

Ecological compensation for desertification control: A review

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Abstract: Desertification control is a crucial way to enhancing the ecological conditions of arid and semi-arid regions, and maintaining sustainable development globally. Designing and improving an ecological compensation mechanism for desertification control has great significance related to achieving balance amongst the needs of different economic subjects and the assurance of a sustained and stable supply of desert ecosystem services. In this paper, (1) the theoretical bases of ecological compensation for desertification control were re-analyzed; (2) the research status and challenges of three important topics related to ecological compensation for desertification control were systemically discussed, including compensation standards, ecosystem service supply-consumption process and multi-scale effects, and resource-environment basis and policy orientation; (3) a research framework of ecological compensation for desertification control based on the process of desert ecosystem service supply-flow-consumption was proposed; (4) and finally, seven priority research issues were discussed, which aimed to support ecological compensation policy-making and ecological engineering implementation for desertification control.

Keywords: desertification control; ecosystem service; ecological compensation; evaluation system; scale

1 Introduction

Desertification is a land degradation process that is mainly caused by climate change and human activities in arid, semi-arid and some sub-humid regions (Wang, 2004; Adamo and Crews-Meyer, 2006; D'Odorico *et al.*, 2013; Chasek *et al.*, 2015; Salvati *et al.*, 2015; Wijitkosum, 2016). Desertification has caused a loss of soil nutrients, a decline in land productivity and degradation of the environment. This leads to a decline or degradation of sand-stabilization, soil conservation, water resource regulation, carbon sequestration and other desert ecosystem services, and endangers both regional and national econ-

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omy-society-environmental security (Glenn *et al.*, 1998; Unkovich and Nan, 2008; Xue *et al.*, 2012; Martínez-Valderrama *et al.*, 2016; Sutton *et al.*, 2016). Research sponsored by the United Nations Environment Programme shows that the global economic losses caused by desertification and drought were as high as US $\$4.2 \times 10^{10}$ each year, which was equivalent to all official aid to Africa in 2009 (United Nations Convention to Combat Desertification (UNCCD), 2011).

Effective control of desertification requires long-term systematic efforts aimed at restoring the functions of desert ecosystem services and to realize the securing of both ecological and economic benefits. This will not only require the investment of large amounts of money and new technologies, but also get a relatively slow return. Particularly, the initial stage of desertification control will only require investments with very little or no initial return. In addition, other problems may arise during the final stage of desertification control such as the separation of investments and returns (Zhang, 2015). Therefore, it is essential to coordinate the interest-balancing among stakeholders in desertification control and improve the enthusiasm of those tasked with controlling desertification, to realize sustained control of desertification. United Nations Conference on Sustainable Development (Rio+20) in 2012 proposed establishing and achieving the goal of “Zero Net Land Degradation” by 2030, and regarded ecological compensation as an important measure that can be used to address land degradation (UNCCD, 2012). The “2030 Agenda for Sustainable Development,” officially launched in January 1, 2016, established the goals of desertification control along with the suppression and reversal of land degradation, and proposed that participants should protect, restore and promote the sustainable use of land by using ecological compensation (OWG, 2014).

Ecological compensation can be treated as an integrated economic policy measure or a benefit compensation mechanism for realizing the interest-balancing of different economic subjects in environmental protection by constructing standard systems (Wunder, 2005; Lv *et al.*, 2009; Home *et al.*, 2014; Bennett and Gosnell, 2015; Wunder, 2015; Curran *et al.*, 2016; Galati *et al.*, 2016). As early as the 1870s, Larson and Mazzarse (1994) had proposed a rapid assessment model for wetlands for the issue of wetland development compensation permits, which initiated the preliminary study of ecological compensation. The Millennium Ecosystem Assessment (MA) has played a role as a milestone in the study of ecosystem services. It defined the framework of ecosystem services assessment, and resulted in an increase in

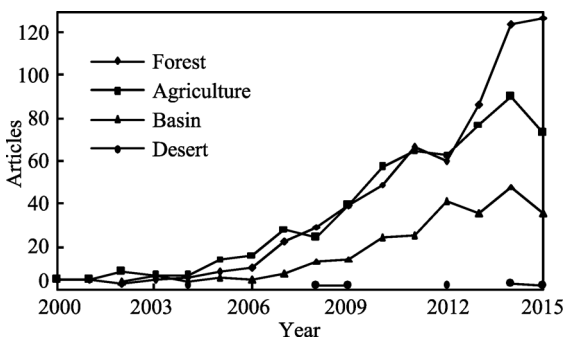


Figure 1 Research on ecological compensation in different areas of foreign countries in 2000–2015

theoretical and practical research worldwide on the problem of services and compensation for different ecosystems, including desert ecosystems (MA, 2003). However, many previous studies have mainly focused on ecological compensation for forests, agriculture, basins and other areas (Clements *et al.*, 2010; Nguyen *et al.*, 2013; Wünscher and Engel, 2012; Bennett *et al.*, 2014; Kwayu *et al.*, 2014; Hofstad *et al.*, 2015), while relatively little research has been conducted

on ecological compensation for desertification control (Figure 1).

China is one of the countries that have seriously suffered from desertification in the world, and the desertified lands are mainly distributed in Inner Mongolia, Ningxia, Gansu, Xinjiang, Qinghai, Shaanxi, Shanxi, Hebei and other provinces. According to the fifth national desertification survey statistics (SFA, 2015), the area of desertified land in China had reached 1,721,200 km² in 2014, which was reduced by 9900 km² in 2009; and the desertification in some regions, like Erdos, North Shaanxi Province etc., had been reversed significantly. These desertification reversions can be attributed to the implementation of ecological protection projects and ecological compensation policies in recent years. For example, the cumulative input of ecological compensation from the Project of Returning Farmland to Forests and the Project of Sandstorm Sources of Beijing and Tianjin etc. reached about 800 billion yuan. Although the ecological compensation policy had been implemented about 10 years, less attention had been paid to systematically discussing the basic theory and key problems related to ecological compensation in support of desertification control. Therefore, based on reviewing the related literature, this paper aimed to re-analyze the theoretical basis and key problems related to ecological compensation, and propose a research framework and prioritize issues related to ecological compensation in support of desertification control.

2 Theoretical basis of ecological compensation for desertification control

The essence of desertification control is using engineering, biological, chemical and other measures to increase soil quality and vegetation coverage (Xu, 2003; Portnov and Safriel, 2004; Amiraslani and Dragovich, 2011). This can improve the level of ecosystem services provided by desert habitats and eventually realize an improvement in regional environmental quality. The result of desertification control has the characteristics of integrity, liquidity, positive externalities and regional differences. In addition, ecosystem service value theory, externality theory and public goods theory can be used as the theoretical basis for desertification control.

2.1 Ecosystem service value theory

Natural ecosystems provide raw materials and products (wood, fiber, etc.) that humans can use directly. Simultaneously, those ecosystems also provide the functions of supply, regulation, culture and support, which is beneficial to the survival and development of human beings (Sodhi *et al.*, 2010; Allendorf and Yang, 2013; Sagie *et al.*, 2013; Matthies *et al.*, 2016; Mouchet *et al.*, 2017). In 1997, Costanza *et al.* (1997) and Daily (1997) estimated the value of global ecosystem services as well as developed the principles and methods used in that valuation, but did not evaluate the value of desert ecosystem services. In 1999, Ouyang (1999) assessed the value of terrestrial ecosystem services in China, including desert ecosystems. Later, Xie *et al.* (2003, 2008) established and improved a service value table for desert ecosystems, which had important guiding significance for later studies. As an important type of terrestrial ecosystem, the value of desert ecosystem services is mainly reflected in the function of sand-stabilization, soil conservation, water resources regulation, biodiversity conservation and landscape-scale recreation, etc., which provides benefits and guarantees for residents living in sandy areas (Bai, 2003; Zhang and Yang, 2007; Gao *et al.*, 2013;

Wang, 2015). The results of desertification control are mainly embodied in the incremental value of these services. For example, a previous study in Yuyang District, Shaanxi Province, China showed that the Project of Returning Farmland to Forest and other ecological measures had led to an increase in the regional sand-stabilization function value of 5.64×10^6 yuan per year from 1988 to 2003 (Mo *et al.*, 2006). Shapotou, a community situated in Zhongwei County, Ningxia Hui Autonomous Region, China, conducted large scale conversion of desertified land into timber and cultivated crop land from 2002 to 2011. The value of food supply, sand-stabilization, soil conservation, carbon sequestration, oxygen release and nutrient cycling functions increased by 7.04×10^6 , 3.00×10^7 , 1.37×10^7 , 9.36×10^6 , 7.51×10^6 and 2.42×10^6 yuan, respectively, in Shapotou over 10 years (Wang, 2015). Although putting a “price tag” on nature might raise inherently thought that the loss of ecosystem services can be replaced by man-made capital, quantitatively estimating and monetizing the value of desert ecosystem services is still critically needed; because this type of data can then be employed as an important reference for formulating the ecological compensation standards of desertification control.

2.2 Externality theory

Externality theory provides an important theoretical basis for determining losses and beneficiaries during ecological compensation. According to Marshall’s “Principles of Economics” (Marshall, 1890), externality is the economic effects of different interests that occur when a producer’s own interests generate external influences to others who are outside the economic exchange during the process of conducting economic activities. However, the influence of externality will not result in corresponding compensation from the marketplace or payment of the equal costs. Ecological compensation can serve as an important tool used to provide a favorable correction for this external influence. Generally, in the external economy, external beneficiaries are taxed or charged; while in the external diseconomy, the external losers are provided with subsidies to compensate them for their losses. The increased level of ecosystem services provided by controlling desertification always has a significant positive externality. This is especially true for sand-stabilization and soil conservation. Previous studies have shown that dust storms affecting eastern China were closely related to the control of desertification in western China (Gou *et al.*, 2012; Chen, 2013). For example, with an increase in vegetation coverage in some sandy areas of northern China over the past 30 years, as measured by the Normalized Difference Vegetation Index (NDVI), the number and intensity of dust storm days in Beijing showed a decreasing trend from 2001 to 2010 (Figure 2). Meanwhile, some studies also found vegetation restoration in the Loess Plateau and in desert regions of western Inner Mongolia had effectively reduced soil erosion, which can enhance the soil conservation and the safety of residents in lower reaches of the Yellow River (Peng, 2013). Hartter and Goldman (2011) indicated that local precipitation and air quality of forest park in western Uganda had been improved as a result of efforts to protect forest ecosystems. It is easy to document the significantly positive externalities of sand-stabilization, soil conservation etc. in the process of controlling desertification, which will lead to inequalities of the investment and income of the entity controlling desertification. Therefore, levying a tax on beneficiaries to compensate the entity that controls desertification is indispensable, which will make ecological compensation an environmental economics instrument for the inter-

nalization of external cost (Mao *et al.*, 2002; Bartczak and Metel-ska-Szaniawska, 2015; Rodrí-guez-de-Francisco and Budds, 2015).

2.3 Public goods theory

Desert ecosystem services are non-exclusive and non-competitive, and can be classified in the category of public goods. In addition, controlling desertification also produces tradable goods, such as wood, herbs and industrial raw materials, etc., so

treating it as a quasi-public good would be more accurate. This attribute of public goods in desertification ecosystem services might lead to excessive consumption of natural resources without supervision, and finally result in desertification, which is also called “Tragedy of the Commons”. Take North China as an example, over the past few hundred years, especially in the past decades, the population growth and the excessively use of grassland and farm land had changed the traditional nomadic culture and resources using patterns (Zhang *et al.*, 2017), which destroyed the ecological balance and led to rapid expansion of desertification (Figure 3). As another example of “Tragedy of the Commons” in Shiyang River of China, the over exploitation of groundwater had led to the death of oasis vegetation and a large-area of desertification in the periphery of the oasis (Ni *et al.*, 2013).

From this perspective, the subject of desertification ecosystem services’ supply should be the government. Due to the limited resources of government, it is often difficult to realize a sustained and effective supply of desert ecosystem services. Hence, many individuals or firms were expected to participate in desertification control. However, the result of these desertification control activities that conducted by individuals or firms cannot exclude others who enjoy the benefits, which might result in the creation of “free riders” and lead to a deficiency of ecosystem service supply (Hardin, 1968; Gatiso *et al.*, 2015; Hu, 2015). The restoration of desertified land provides public goods that can be enjoyed by all the people in a

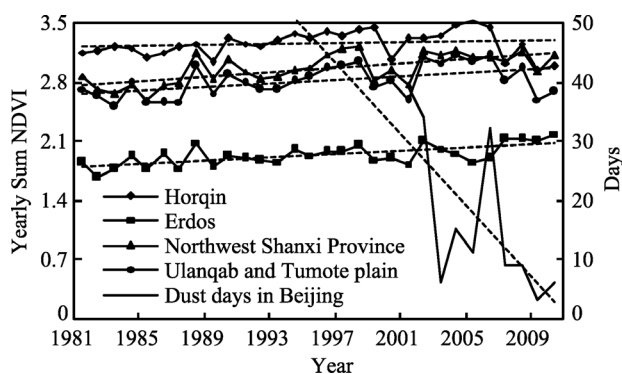


Figure 2 Changes of dust days in Beijing and NDVI in desert area

sandy area and the adjoining region, so the government needs to use service-purchasing or other market mechanisms to maximize the generation and expansion of these services. However, when the entity tasked with controlling desertification was an individual or firm, that entity must solve the problem of recovering the costs of controlling desertification. Therefore, it is necessary to reduce the high cost of



Figure 3 Photographs of desertification expansion: (a) Trees had died and removed in the next year after planting due to the absence of management. (b) Grassland desertification is serious due to the excavation of village road. (Photo credit: Duanyang Xu obtained the pictures in October 2011 (a) and August 2016 (b))

controlling desertification during the initial stage by using ecological compensation, which would create effective incentives for desertification control and eventually realize a sustained supply of desert ecosystem services.

3 Important problems related to ecological compensation for controlling desertification

3.1 Standard accounting for ecological compensation during desertification control

The compensation standard is a critical part of the implementation of ecological compensation for controlling desertification. However, it varied greatly in different regions, which ranging from 1000 to 10,000 yuan/ha·a. Take Britain as an example, the government paid about 1091 yuan/ha·a to farmers who returned farmland to forests for compensation in 30 years (Green, 1989). For the Project of Returning Farmland to Forests launched in China, the compensation standard in the Yellow River basin and its northern region is about 1050 yuan/ha·a (Ning, 2010); and for the Project of Sandstorm Sources of Beijing and Tianjin, the government had provided subsidies about 8250 yuan/ha·a to farmers in the sandy regions (Pan, 2014). The differences of compensation standard are mainly dependent on the value of desert ecosystem services. Generally, three factors affect the ecological compensation standards: the scope of desert ecosystem services, modeling and the method used for valuation. However, different scholars have created different definitions of these three factors, which means their assessment results cannot be easily compared. Meanwhile, some studies have also been carried out to assess the loss value of economic and social system that caused by land degradation or desertification. As illustrated in Table 1, although both Wang (2015) and Yang and Wang (2009) assessed the ecosystem services in Shapotou in China, they placed different values on ecosystem services in their research. Those differences were mainly caused by differences in their assessment of service functions of the desert landscape. In addition, many uncertainties remain related to parameter acquisition and evaluation methods. For instance, Yang *et al.* (2006) calculated the sand-stabilization value of the Hotan River Basin in China based on forest area, while Han *et al.* (2011) calculated the same service value in the downstream region of the Heihe River in China by using the amount of sand-stabilization provided by vegetation.

In 2012, the State Forestry Administration of China promulgated the forestry industry standard “Desert Ecosystem Service Evaluation Norms” (LY/T 2006–2012), which is a useful exploration in constructing an assessment framework of desert ecosystem services. However, it does not consider the spatial heterogeneity of land surface environment and its impact on modeling parameters. To avoid these limitations, some scholars began to combine multi-source and high-resolution remote sensing data to retrieve the parameters at a regional scale (Luo *et al.*, 2014). So, the difference and optimization method of the key parameters should be fully considered at a national scale, such as crop yield, soil organic matter and surface roughness etc.; meanwhile, specific adjustment and correction for parameters and methods are also needed (Chun, 2011). It should also be pointed out that some desert ecosystem services are invisible, such as water purification, biodiversity conservation and landscape recreation, and subjectivity during an evaluation would lead to uncertainties in the accounting compensation standard (Cui, 2009; Gee and Burkhard, 2010; Bidak *et al.*, 2015). In addition, the formation mechanism of desert ecosystem services must be clarified. There-

fore, knowing how to quantitatively identify the individual contribution of human activities and climate change, and how to analyze the marginal effects of different policies, still creates a difficult problem in accounting for ecological compensation standards.

Table 1 Standard of desert ecosystem service value by different scholars

Nation	Study area	Assessment content	Total value (yuan/a)	Unit area value (yuan/a·km ²)	Literature source
USA	California desert	Direct, indirect and passive use values	1.33×10 ⁹ dollars		Richardson (2005)
USA	Mojave desert	Direct, indirect and passive use values	1.42×10 ⁹ dollars		Kroeger and Manalo (2007)
World	World	Loss value of land degradation	6.25×10 ¹³	4.64×10 ⁵	Sutton <i>et al.</i> (2016)
Mexico	Coastal Wetlands	Loss value of land use change	18.44×10 ⁶	7.34×10 ³	Camacho-Valdez <i>et al.</i> (2014)
USA	New Jersey	Loss value of sandy storm	4.4×10 ⁹	5.57×10 ⁴	Hauser <i>et al.</i> (2015)
China	China	Hydrological regulation	5.51×10 ¹²	4.15×10 ⁵	Xiao <i>et al.</i> (2013)
China	China	Carbon fixation and oxygen release; Nutrient cycling; Sand-stabilization; Water and soil conservation; Biodiversity conservation; Tour etc.	2.28×10 ¹¹	1.87×10 ⁵	Cui (2009)
China	China	Sand-stabilization; Soil conservation; Water resources regulation; Carbon fixation; Biodiversity conservation; landscape recreation etc.	3.08×10 ¹³	1.87×10 ⁷	Project group (2014)
China	Western region	Carbon fixation and oxygen release; Soil conservation etc.	5.37×10 ¹¹	0.78×10 ⁵	Ren <i>et al.</i> (2007)
China	Ejin Horo Banner in Inner Mongolia	Soil conservation; Climate regulation etc.	3.3×10 ⁹	5.49×10 ⁵	Bai (2003)
China	Shapotou in Ningxia	Carbon fixation and oxygen release; Nutrient cycling; Food supply; Sand-stabilization; Water and soil conservation etc.	1.55×10 ⁸	1.11×10 ⁶	Wang (2015)
China	Ulan Buh in Inner Mongolia	Sand-stabilization	4.42×10 ⁹	4.87×10 ⁵	Gao <i>et al.</i> (2013)
China	Neiman Banner in Inner Mongolia	Gas regulation; Climate regulation; Water conservation; Soil formation and protection; Waste disposal; Biodiversity conservation; Food production; Raw material; Entertainment culture etc.	1.49×10 ⁹	1.84×10 ⁶	Chun (2011)
China	Qiemo Oasis in Xinjiang	Ditto	2.69×10 ⁸	3.71×10 ⁵	Huang <i>et al.</i> (2007)
China	Qitai Oasis in Xinjiang	Ditto	5.29×10 ⁸	1.23×10 ⁵	Peng <i>et al.</i> (2010)

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Nation	Study area	Assessment content	Total value (yuan/a)	Unit area value (yuan/a·km ²)	Literature source
China	Kuqa River in Xinjiang	Ditto	1.90×10^{10}	3.39×10^6	Zhang <i>et al.</i> (2009)
China	Minqin Oasis in Gansu	Ditto	5.58×10^8	3.72×10^4	Yang and Bai (2009)
China	Shapotou in Ningxia	Sand-stabilization	5.93×10^8	5.29×10^7	Yang and Wang (2009)
China	Hotan River Basin in Xinjiang	Organic matter production; Climate regulation; Soil formation and protection; Water regulation; Cleansing of environmental pollution; Biodiversity conservation; Entertainment culture; Wood products; Industry material etc.	6.72×10^8	2.11×10^6	Yang <i>et al.</i> (2006)
China	Horqin in Inner Mongolia	Waste disposal; Soil formation and protection; Water conservation; Climate regulation; Biodiversity conservation; Gas regulation etc.	1.46×10^{11}	2.82×10^6	Zhang <i>et al.</i> (2007)
China	Heihe River in Inner Mongolia	Sand-stabilization	5.31×10^9	4.78×10^5	Han <i>et al.</i> (2011)

3.2 Spatial-temporal patterns of desert ecosystem service supply-consumption and its multi-scale effect

Identifying the desert ecosystem service supply-consumption subjects at multiple scales is an important prerequisite during the implementation of ecological compensation (De Groot *et al.*, 2002; Kolinjivadi *et al.*, 2014; Liu *et al.*, 2014); in addition, the MA had also emphasized the importance of multi-level ecosystem service assessment (MA, 2005). For example, the food supply function is mainly applicable to the local scale; sand-stabilization, soil conservation and water resource regulation functions are mainly applicable to a regional scale; and climate regulation function is more reflected in national and intercontinental scales (Zhao and Zhang, 2006). Because of the spatial heterogeneity and multi-scale effect on the supply-consumption subjects of desert ecosystem services (Figure 4), it is crucial to analyze the spatial path of the ecosystem service flow and its influence on the ecological compensation policies at different scales.

With the spatial mobility of the results of controlling desertification, the geographical locations of the providers and beneficiaries of desertification control are not necessarily the same. This also brings some difficulties in determining who are the stakeholders in ecological compensation efforts. Generally, at a continental scale, compensation always occurs in different nations, such as developed countries may compensate developing countries because desertification can be induced by global climate change. For instance, Zambia and Zimbabwe, two signatories of the UNCCD, both suffer from the adverse effects of climate change, resulting in poor and even economic contraction in the agricultural sector (Twomlow *et al.*, 2008). At a national scale, compensation should be focused on different regions

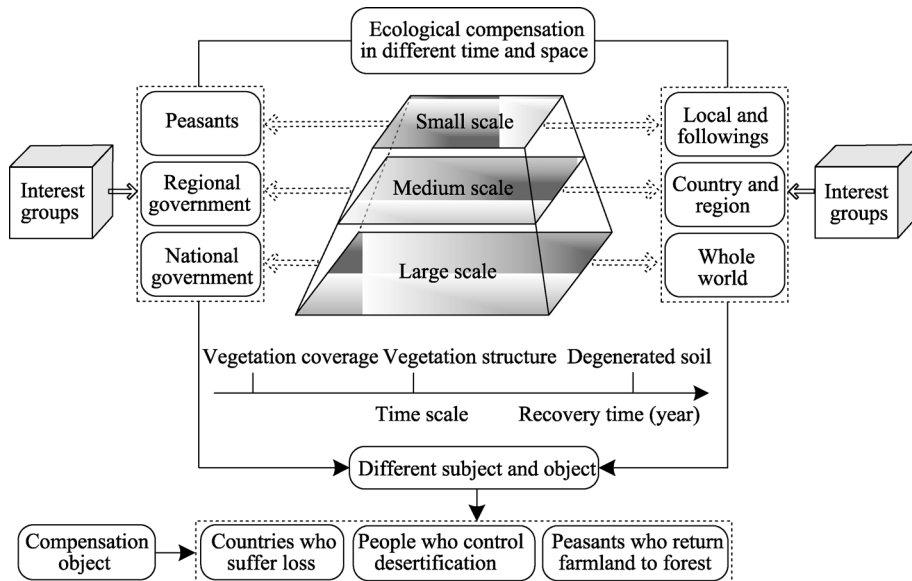


Figure 4 The difference of the supply-consumption subjects of desert ecosystem services at different scales

within the interior of a nation, and the majority of stakeholders are the agents of the supply of ecosystem services, such as regional governments. At a local scale, attention should focus on the interaction of ecological compensation and farmers' livelihoods, including the degree of participation by farmers, the enthusiasm of farmers in participating in a project and the entire lifecycle accounting of the opportunity costs in desertification control. Studies of the Sahel region of Africa suggest that poverty alleviation through the carbon sink projects effectively increase the income of local residents, and market-oriented measures can strengthen the potential for sustainable development in small scale agricultural systems (Tschakert, 2007). On a time scale, the control of desertification is a long-term project, and it generates revenue relatively slowly. More concretely, during efforts to control desertification the restoration of vegetation coverage and structure will take more than 10 years, and the restoration of degraded soil will require at least a few decades or may even require more than 100 years (Wuriga, 2013). Hence, the beneficiaries of desertification control include people who have yet to be born, and the determination of stakeholders often includes the problem of intergenerational compensation. Because different descendants of the present generation will enjoy different ecosystem services, the determination of compensation standards needs to take full account of the allocation and reduction of the control costs at different time scales (Kosoy *et al.*, 2008).

3.3 Resource-environmental basis and policy of sustained desert ecosystem services supply

Because of the public ownership of desertification control, problems such as those related to the "Tragedy of the Commons" and "free-riders" always exist and will lead to an insufficient supply of ecosystem services. The purpose of ecological compensation is to ensure a sustained supply of desert ecosystem services, with the goal of ultimately achieving continuous improvement of the regional environment. In recent decades, many policies or projects have been launched to control desertification all over the world. The most representative one is

the Conservation Reserve Program (CRP) in United States, which offered 10–15 year contracts for retirement of land from crop production, and provided cost-sharing for establishment of cover (usually grass or trees) and an annual payment (Claassen *et al.*, 2008). Furthermore, the Forests Absorbing Carbon-dioxide Emissions Forestation Program (PROFAFOR) in Ecuador (Wunder and Albán, 2008), the Payment for Hydrological Environmental Services (PSAH) in Mexico (Muñoz-Piña *et al.*, 2008), and the Project of Returning Farmland to Forest in China (Li and Shi, 2015) are also the favorable paradigms for ecological compensation policy. However, in view of the spatial heterogeneity of desertification control, to realize a sustainable supply of ecosystem services and reduce the dependence on a direct compensation fund, a balance also needs to be achieved among desertification control, environmental resources and economic development at national and regional scales.

Specifically, at a national scale, by considering the regional differences in resource availability and bearing capacity, desertification control in different forms and intensity are carried out, which would realize an indirect reduction of ecological compensation expenses. However, regional differences in resource-environmental capacity have not been fully considered in previous desertification control efforts. We take the afforestation activities in northern China as an example. Although statistical data had matched the regional natural conditions quite well, some areas still suffered from excessive or insufficient afforestation, which was likely to result in regional ecological risk or a waste of resources (Figure 5). Some studies show that afforestation will have significant effects on the regional water balance and ecological security. For example, Feng *et al.* (2016) found that although afforestation resulted in an increase in net primary production (NPP) and evapotranspiration (ET), it also resulted in the decrease in annual precipitation in a catchment area. Cao *et al.* (2007) found that large-scale afforestation in the Loess Plateau of China is likely to lead to excessive consumption of soil moisture, and ultimately increase the risk of desertification and economic losses. The studies of Lu *et al.* (2016) and Zhang *et al.* (2016) reached similar conclusions. Therefore, it is crucial to scientifically plan and develop ecological restoration projects based on regional resource endowment, which can ensure a sustained supply of ecosystem services and reduce the cost of ecological compensation for desertification control.

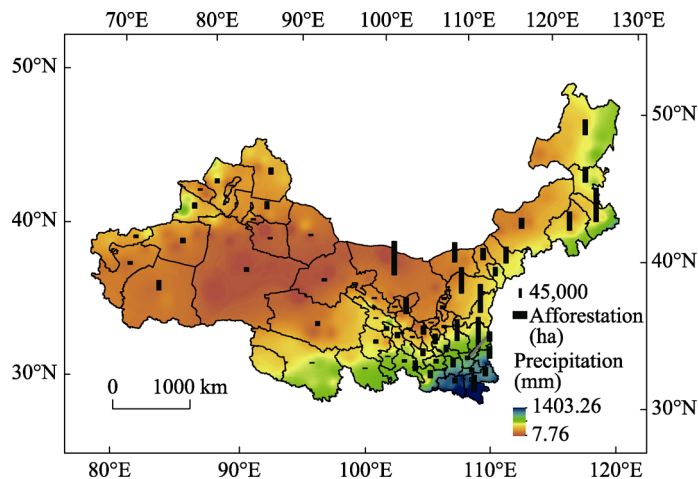


Figure 5 Distribution of precipitation and afforestation in arid and semi-arid areas of northern China

At a regional scale, more attention should be focused on the balance between desertification control and economic development. Based on the basic framework of ecological compensation, direct financial compensation provided by regions benefiting from ecosystem services is an important guarantee for supporting the control of desertification. However, fundamentally solving the problems related to long-term sustained control of desertification is difficult when using this compensation method. To realize a “win-win” situation related to both desertification control and sustainable economic development, it is necessary to stimulate the enthusiasm of local farmers and enterprises and gain their participation and cooperation in these efforts. In recent years, Inner Mongolia, Qinghai and Ningxia in China have begun to develop the concept of desert-based industry to combat desertification (Zhang *et al.*, 2007; Xie *et al.*, 2013; Liu *et al.*, 2015). For instance, in Alashan, Inner Mongolia, China, by developing the farming of *Haloxylon-Cistanche*, two genera of useful plants, the yield of *Cistanche* increased from 200 to 800–1000 tons per year in Inner Mongolia, which not only increased the income of farmers, but also achieved the goal of combating desertification (Tian and Gao, 2013). Therefore, government agencies need to explore methods of diversifying ecological compensation, with a certain amount of funds and related policies used to compensate for the major costs to farmers along with corporate governance of projects during the initial stage of investment. Ultimately, government agencies need to promote the formation of a desertification control industry and stimulate healthy economic development in the same region simultaneously.

4 Research framework and priority issues related to ecological compensation for desertification control

4.1 Research framework of ecological compensation for desertification control

Although a considerable amount of progress has been made in the field of ecological compensation for desertification control, it is still necessary to develop a research framework that covers priority issues from basic research to comprehensive decision making (Figure 6). Based on related theory and the key problems, ecological compensation for desertification control should be examined from the perspective of regionality, comprehensiveness and scale correlation. The improvement of the desert ecosystem services classification system should be based on the supply-flow-consumption of desert ecosystem services. The goal is to improve the key service functions related to the formation of those services, the process of service flow, and to understand the relationship between the internal and external economic and social impact of desert ecosystem services at different spatial and temporal scales. It is crucial to clarify the resource environment basis and policy orientation of sustained supply of desert ecosystem services, which can provide comprehensive support for innovation based on theories and help policy makers develop practical methods of ecological compensation related to desertification control.

4.2 Priority issues related to ecological compensation for desertification control

(1) A desert ecosystem service classification system with integrated function-demand and its definition. Currently, most definitions of desert ecosystem service functions are based on the MA classification system that highlights the components, structures and processes of

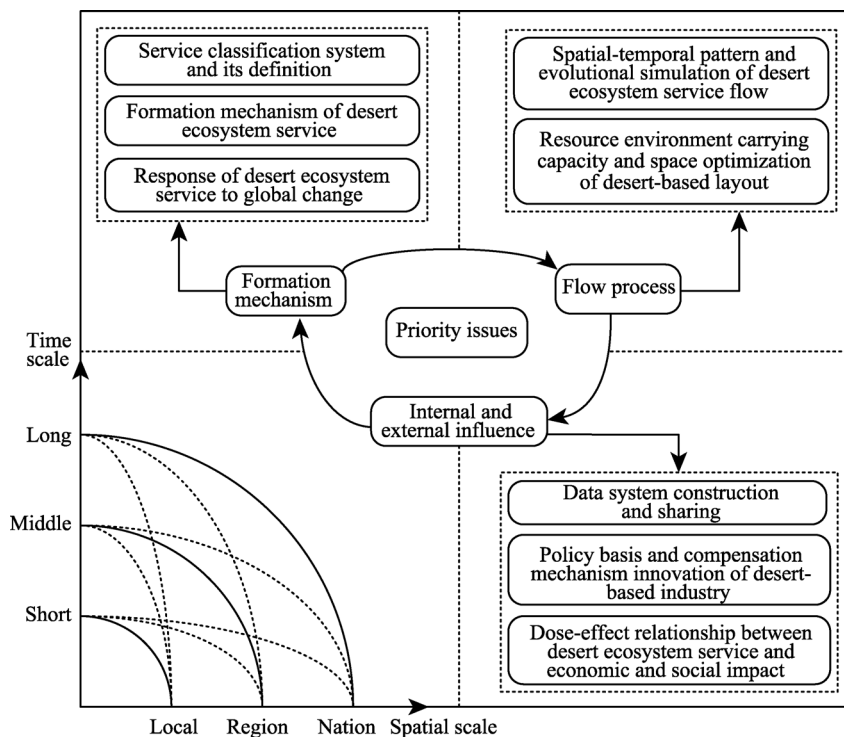


Figure 6 Research framework of ecological compensation for desertification control

desert ecosystem services from the supply perspective. However, less consideration has been given to the actual needs of human society and well-being (Zhang *et al.*, 2010). Therefore, the spatial heterogeneity of the ecosystem service supply and consumption requires more attention. It is crucial to systematically review the relationship between desertification ecosystem functions and human needs during different stages of economic development. Human health, ecological security, water supply, etc., should be considered and a new desert ecosystem services classification system should be established.

(2) Formation mechanism of desert ecosystem services and its response to global change. On-site field observations, controlled experiments in both indoor and outdoor settings, model simulation and other related measures should be fully used to study the mechanisms involved during the formation of the most important desert ecosystem services, including sand-stabilization, soil conservation, carbon sequestration and water resource regulation, etc. It is essential to explore dynamic models of the formation and evolution of desert ecosystem services, and analyze the response of desert ecosystems to climate change and human activities at different scales. Quantitatively separating and identifying the marginal benefits of individual human factors in the formation of desert ecosystem services are also needed, which can provide the basis for the scientific establishment of compensation standards.

(3) Spatial-temporal pattern and evolutionary simulation of desert ecosystem service flow on different scales. Cross-coupling application of test methods (including isotopic geochemical tracer techniques and fluorescent labeling), spatial analysis of geo-information and remote sensing observation should be focused to scientifically define the source, spatial flow path, attenuation rate and occurrence law, etc. of desert ecosystem services. Meanwhile, it is

necessary to improve our ability to spatially and temporally simulate the flow of desert ecosystem services under different environmental conditions and policy scenarios, and accurately identify the regions benefiting from desert ecosystem services to help policy makers to develop reasonable ecological compensation plans.

(4) Compensation standard and dose-effect relationship between desert ecosystem services and economic-social impact. Because a result of avoiding loss is equivalent to the benefits obtained, it is needed to quantitatively evaluate the contribution of desertification control to the entire human economic-social system from the perspective of service-revenue-welfare (Li *et al.*, 2013), propose the suitable scope of compensation standard in different areas and analyze its impact on the livelihoods of farmers, government expenditure and the formation of ecosystem services. To this end, researchers should thoroughly study the effect mechanisms, and constantly improve the quantitative methods used to manage revenues. Policy making should actively introduce a substitute market method and simulation market method, such as using the willingness-to-pay and hedonic price methods (Dai *et al.*, 2012; Zhao and Zhu, 2015). Meanwhile, scientific accounting of desertification control costs should be strengthened to provide a sound basis for ecological compensation standards.

(5) Resource and environment carrying capacity and space optimization layout of desertification control. According to the typical water demand characteristics of vegetation and the influence of afforestation on soil moisture, the limited role of water resources in desertification control and the formation of ecosystem services should be fully considered. The goal here is to improve research related to resources and environmental carrying capacity related to desertification control in arid and semi-arid regions. Based on available resources and environmental carrying capacity, the level of economic development, the comprehensive control of cost and other factors, planners need to optimize the spatial layout of desertification control, and from the perspective of regional balance to indirectly improve control efficiency and reduce the cost of ecological compensation.

(6) Policy basis and compensation mechanism innovation of desert-based industry. Relying on the advantages of regional resources, the comprehensive technological-economic-ecological benefits evaluation model should be developed to select the advantaged desert-based industry. What's more, it is essential to conduct a study of the policy system related to innovation-driven development in desert-based industry, and explore the diversified compensation methods of technical assistance, talent introduction, cooperative R&D, carbon trading, etc., which can weaken our dependence on direct subsidies and create new channels for the development of the desertification control industry and ecological compensation.

(7) Data system construction and sharing for supporting ecological compensation related to desertification control. The development of integrated satellite and on-the-ground observation network should be paid more attention to retrieve key elements of the land surface in arid and semi-arid areas. Meanwhile, additional efforts should be implemented to optimize joint inversion and assimilation algorithms using multi-source remote sensing data, and scale correction factors of parametric estimation to overcome the estimation error of single scale and single data sources. In addition, the inversion precision of surface roughness, vegetation coverage, soil moisture and other important parameters need to be improved. Finally, developing and sharing high-resolution data products should be strengthened on a

global scale to support scientific research and practice of ecological compensation for desertification control.

5 Conclusions

(1) A scientific evaluation of the value of desert ecosystem services provides the basis for the establishment of an ecological compensation standard. Currently, the estimation of the volume of the desert ecosystem services is relatively accurate, while knowing the value of those services is still the weak link in future evaluation work.

(2) Based on the full consideration of ecosystem services value theory, externality theory and public goods theory, the spatial-temporal scale is introduced into the definition of an ecological compensation standard. This allows the definition of the flow path of desertification control results as well as resources and environment foundation, and provides a basis for the scientific control of desertification control activities and policy-making related to ecological compensation.

(3) It can easily be noticed that ecological compensation for desertification control should take full consideration of the characteristic difference and dominant factors in different regions, tightly around the main line of desert ecosystem service supply-flow-consumption. A research framework should be formed for ecological compensation for desertification control from basic research to comprehensive decision making, and finally inform the public about the positive effects of a desert ecosystem.

(4) With the inter-science crossing and integrated innovation of economics, ecology, geography and other disciplines, and a wide application of a variety of mathematical models in the desert ecosystem services assessment, there are more possibilities to scientifically construct ecological compensation standards.

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