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The Evolution of Desertification Control and Restoration Technology in Typical Ecologically Vulnerable Regions

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Abstract: Global economic development and increasing human activities have brought great challenges to fragile ecosystems. In order to avoid, reduce, and reverse desertification, Chinese and foreign scientists and ecological governance institutions have developed a series of ecological restoration technologies (ERTs) and models in the past few decades. These technologies can improve residents' livelihoods, strengthen disaster resilience, and launch a comprehensive review of degraded ecosystems in desertification regions. However, some studies and practices have limited the selection and promotion of good technologies and the assessments of these technologies, resulting in the waste and loss of funds and manpower. The objective of this study is to identify desertification control and restoration technologies and models, summarize the evolutionary features and trends of these technologies under different natural conditions, and evaluate the various ERTs that are now available. The data sources of this study include the databases of international organizations, CNKI, related literature and reports, and questionnaires from institutions and experts. First, the three stages of ERTs evolution were summarized, and the key events and social-economic developments were identified as the driving forces of evolution. Then, the four categories of ERTs were identified as biological, engineering, agricultural, and management ERTs. Finally, the key ERTs were evaluated in the five dimensions of the degree of difficulty, the degree of maturity, effectiveness, suitability, and potential for transfer. The management ERTs scores for the degree of difficulty, the degree of maturity, and potential for transfer are higher. This study provides a reference for adapting to local conditions, the comprehensive management, rational development, and utilization of dryland resources, improving the application of ecological technologies, and promoting the export and import of the excellent technologies.

Key words: combating desertification; ecological restoration technologies; technology evolution; technology evaluation; ecologically vulnerable regions

1 Introduction

According to the Millennium Ecosystem Assessment (MA), the degraded area of the world's arid land is 10%–20%, with a desertification area of 6–12 million km^2 (MA, 2005). The data from the United Nations Sustainable Development Goals showed that drought and desertification land are increasing by 12 million ha every year, at a rate of 23 ha per minute. Globally, land degradation directly affects 74% of the land area (United Nations, 2015). Desertification is one of the major triggers for frequent droughts and sandstorms, the reduction of biodiversity, the loss of land productivity, and a weakened ability of the sustainable use of ecosystem services by local residents, on both regional and global scales (Dobie, 2001). The level of human well-being of the

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impoverished populations in desertification areas is lagging that in other areas, so those populations cannot play a role in social and political decision-making and are increasingly threatened by natural disasters (MA, 2005). There is a long history of combating desertification by humans, especially since the 1990s. It is necessary to step up efforts to tackle the desertification, land degradation, erosion, drought, biodiversity loss, water shortages, and other issues. These issues are considered as the main environmental, economic, and social challenges to global sustainable development. The United Nations Conference on Sustainable Development adopted the 2030 Agenda for Sustainable Development in September 2015, which announced the 17 Sustainable Development Goals (SDGs) and 169 targets (United Nations, 2015). The SDGs put forward higher requirements for combating desertification and coping with its complexity, not only reducing the area of degraded land, but also improving the underlying social, economic, and environmental systems (Reynolds et al., 2007; Cherlet et al., 2018; Zhen et al., 2020). These goals include no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6), decent work and economic growth (SDG 8) and other SDGs. One specific goal, SDG 15.3, refers to combating desertification and restoring degraded land and soil.

China is one of the UNCCD contracting parties, and the coverage of desertified land had reached 2.61×10^6 km^2 (27.20% of the total land) by 2014. It is one of the countries with the largest desertified land area and the most severe sandstorms in the world (Dobie, 2001). In the past 30 years, major national ecological system protection and restoration project initiatives have led to the development of many ecosystem restoration modes and technologies, such as the Grain for Green Program and the Beijing-Tianjin Sandstorm Source Control Program (Zhen et al., 2017). However, the lack of systematic theory and research on ecological technologies has been far out of touch with the practice and effective application of these technologies (Zhen et al., 2020). For example, there were some major issues in the artificial afforestation programmes in the Loess Plateau in recent decades, including the introduction of high-water-consuming species and a dry soil layer (Jia et al., 2017), loss of biodiversity (Wang and Shao, 2013), and ecological water demand deficit and water resources balance issues (Yang, 2001; Feng et al., 2016). On the one hand, such problems have led to repeated investments in technology research and development (R&D), resulting in a waste of funds (Zhang and Shao, 2001; Chen et al., 2007). On the other hand, they have caused re-degradation and unstable results of ecological governance, or the simultaneous destruction of the program (Cheng et al., 2000; Zhen et al., 2017). As a result, the urgency of the global combat against desertification and the problems in technology application have been very challenging topics.

In this paper, desertification combating and ecological restoration technologies (ERTs) refers to the measures and modes used in the process of prevention and/or reduction of desertified land, or in the restoration and rehabilitation of the ecosystem. ERTs can continue promoting the restoration of ecosystem structure and improving ecosystem function, and they can save energy and natural resources. They are acceptable to the public, and conducive to regional economic development. ERTs can directly produce ecological benefits, considering both social and economic benefits (Hu et al., 2018; Zhen et al., 2020). The current research on ERTs mainly focuses on the following aspects: the process of combating desertification (Qi and Zhao, 2006; Bao et al., 2018; Qu et al., 2019); the effectiveness of individual technologies, such as sand fixation by grass and trees (Yang et al., 2008; Zhang et al., 2012), sand barriers (Ning et al., 2017; Hong et al., 2020), sand-fixing agents (Hu and Zhou, 1990); the evaluation of programs and projects (Feng et al., 2017; Gong et al., 2014; Shao et al., 2017; Zhou and Zhao, 2017; Wei et al., 2020); the concept of governance and restoration (Wang, 2016; Fu et al., 2019); and the governance system (Li et al., 2017; You et al., 2018). However, there is still a lack of research which analyzes the evolution and trends of desertification combating and ecological restoration technologies from a global perspective, although it is an important issue in the promotion and introduction of these technologies.

The objectives of this study are to identify the technologies and modes for combating desertification, to summarize the evolutionary features and trends of these technologies under different natural and social-economic conditions (i.e., technologies with different operating principles in different stages), and to conduct multi-dimensional evaluations on the technologies and modes. This study is intended to provide a theoretical basis for combating desertification and ecological restoration in China, and also a reference for the construction of an ecological civilization and green community of common destiny, in order to promote sustainable governance and restoration.

2 Data and methods

There are two main sources of information on the desertification combating and ecological restoration technologies. One source is the UNCCD and WOCAT databases, and technologies involved in CNKI documents and related international organization reports (MA, 2005; WOCAT, 2012; UNEP, 2016a; UNEP, 2016b; UNCCD, 2017; Bazza et al., 2018; IPBES, 2018); while the other is questionnaire surveys such as institution discussions, field investigations, conference investigations, etc. The questionnaires include the status quo of the application of technology, existing problems, the evaluations, etc. We conducted this study according to the method framework shown in Fig. 1.

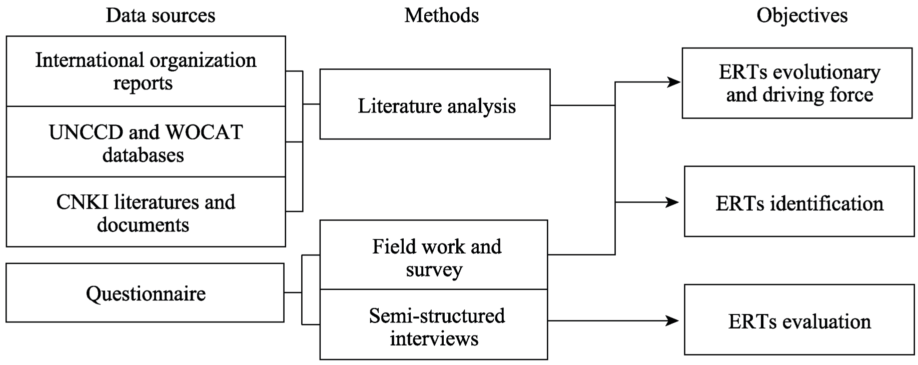

Fig. 1 The framework of data and methods in this study

2.1 Technology identification

We conducted semi-structured interviews by convenience sampling, at the 13th Session of the Conference of the Parties to the UNCCD (COP13) in Ordos, China on September 6–16, 2017 and the Global Land Programme 4th Open Science Meeting in Berne, Switzerland on April 24–26, 2019. The interviewees represented various countries and included representatives of relevant government departments, researchers, and non-governmental organization staff participating in the conferences. We obtained information on their evaluations of ecological technology by face-to-face in-depth interactions. The interviews yielded 35 valid questionnaires from 20 countries: Kenya, Zambia, Ethiopia, Namibia, Australia, The Philippines, Thailand, India, Turkey, Iran, Kazakhstan, Jordan, Israel, Nepal, Mongolia, Russia, the United States, Germany, France, and Japan.

The institutional interviews, expert questionnaires and field investigations were conducted from April 2017 to September 2019 in Ningxia, Gansu and other provinces of China, including the Institute of Desert Manage of Ningxia Academy of Agriculture and Forestry Sciences, Gusha Forest Farm in Zhongwei, Shapotou National Field Station for Scientific Observation and Research of Desert Ecosystem in Ningxia, Yanchi Observation and Research Station of Desertification Ecosystem in Ningxia, Cold and Arid Regions Environmental and Engineering Research Institute of Chinese Academy of Sciences, Gansu Desert Control Research Institute, Gansu Research Academy of Forestry Science and Technology and other institutions. Valid questionnaires were obtained from 15 related researchers, government staff, technical and engineering staff, who were engaged in soil and water conservation, desertification prevention and control, ecology, grassland science, forestry, agronomy, water conservancy engineering, agricultural economics, restoration ecology, etc. We collected information from the questionnaires about the locations of ERTs applications, the type of ecosystem degradation, the degree of degradation, the type and name of the ERTs, and the problems with ERTs application.

2.2 Technology types

This study divides ERTs into four major categories: engineering ERTs, biological ERTs, agricultural ERTs, and management ERTs, according to the principles of the ERTs in existing research and practical applications.

(1) Engineering ERTs refers to the physical technology that changes site conditions, including slope control, gully control, flash flood and debris flow prevention, rainwater collection and water storage, sand control, etc.

(2) Biological ERTs refers to the technology related to vegetation conservation, restoration of aquatic plants, planting trees and grasses combined with economic plants, including artificial afforestation and grass planting, microbial remediation, etc.

(3) Agricultural ERTs refers to the measures which can increase ground roughness and vegetation cover, change slope topography, and enhance soil erosion resistance, for the purposes of water and soil conservation, wind-breaking and sand-fixing, soil and water improvement, and increasing the production, mainly including (dry) farming, soil fertilization, irrigation, etc.

(4) Management ERTs refers to ecological management technologies which are adopted to solve ecosystem degradation and ecological harm, including fence enclosure technology, livestock management, ecological compensation, ecological management policy, etc.

2.3 Technology evaluation

The evaluation questionnaire for desertification combating and ecological technology includes five dimensions: degree of difficulty, degree of maturity, effectiveness, suitability, and potential for transfer (Hu et al., 2018; Zhen et al., 2019). The degree of difficulty refers to the requirements for user skills and the cost of ERTs application. The degree of maturity refers to the development and application level, or the maturity level of the ERTs. The effectiveness refers to the ecological, economic, and social effectiveness of the ERTs application. The suitability refers to the degree of consistency between the application of the ERTs and the implementation of regional development goals, site conditions, economic needs, and policies and laws. The potential for transfer refers to the advantages of the ERTs for use in other regions in the future.

The Likert 5-point scale was used to score each dimension, in which degree of difficulty levels are 1=very difficult, 2=difficult, 3=medium, 4=easy, 5=very easy; degree of maturity levels are 1=key functions are verified, 2=verified, 3=risks are acceptable, 4=successful application, 5=fully mature; and effectiveness/suitability/potential to transfer levels are 1=very low, 2=low, 3=medium, 4=high, 5=very high.

3 Characteristics and driving forces of ERTs evolution

3.1 Characteristics of ERTs evolution

3.1.1 Characteristics of temporal and spatial evolution

Since the 19th century, the evolution and development of desertification combating ERTs can be divided into three stages (Table 1).

(1) Stage I (from the 1800s to the 1950s)

ERTs of this stage mainly included afforestation and grass planting in sandy land, combined with a small amount of engineering technology. The early sand barriers appeared, as well as systematic observations and sand control experiments. To ensure normal life and safety, developed countries had planned to combat desertification, for example, shelter forests in the United States, and beach/dune protection systems in Japan, the United Kingdom, and other coastal countries.

People began to use passive control for the basic survival needs at Stage I, but only after severe desertification and damaged ecosystems occurred. The ERTs transitioned from the single vegetation planting to "vegetation + engineering" compound measures. The exploration of the formation and mechanism of desertification was still in the experimental stage. Most applications of desertification combating ERTs were simply blind measures, and some of them caused huge economic losses, e.g., the shrinking of the Aral Sea caused in part by irrigation and canal construction.

(2) Stage II (from the 1950s to 2000)

Many biological ERTs, engineering ERTs and early management ERTs emerged at this stage, supplemented by agricultural ERTs. In Saudi Arabia and Iran, people began to spray petroleum products and seeds to combat desertification in the process of constructing the infrastructure driven by oil exploitation. With the new discoveries in the chemical industry and materials, the number of new sand fixation agents and water retention agents increased dramatically.

The aim to desertification control ERTs and modes at

Table 1 The evolution of desertification combating and ERTs

Stage	1800s–1950s	1950s–2000	Since 2000
Targets	Beach/dunes Railway Farmland/grassland	Farmland/grassland Urban/railway/highway	Farmland/grassland ecosystem
Biological ERTs	Sand fixation by grass Sand fixation by trees Afforestation and grass planting Mechanical/aerial seeding Indigenous plants Sand fixation by shrubs Container seedlings	Planting grass Deep seedling Soil moisture preservation by surface cover Rainy season afforestation Stand improvement Drought-resistant afforestation Stress tolerance selection	Artificial biological crusts Airflow/UAV tree planting Domestication Stress tolerance breeding Seed banks
Engineering ERTs	Upright sand barriers Reeds and sleepers Gravel/clay Crude oil	Movable sand barrier Straw/stone-checkerboard Clay sand barrier Water-harvesting afforestation Artificial trees Sand fixation by oil products Chemical sand fixation agents НЭРОЗИН (an oil shale agent)	High density polyethylene sand barriers Stereo sand-fixation equipment
Agricultural ERTs	Rotation Contour farming Rotation of crop and grass	Water saving irrigation Water retention agents Drought-resistant agents	Ecological organic soil amendments
Management ERTs	Systematic observations/experiments The Grain for Green	Grazing prohibition Forage-livestock balance Rotation grazing House feeding Fencing	Photovoltaics
Integrated modes	Arbor-shrub-herb +Engineering Land reclamation by sluicing sand Shelter forest system	Fixation-shelter integrated mode Water saving efficient agriculture Artificial oases Engineering + development Shrub+windbreak+economic fruit+forage-animal husbandry+tourism	Kubuqi model Low coverage sand barriers

stage II focused on the prevention of desertification. There were many comprehensive modes combining biological and engineering ERTs for the purpose of prevention and control. Examples include the shelter forests system that consisted of farmland, forests, road, and water which formed the scientific spatial pattern, preventing the wind and sand, and the secondary salinization of the soil. The core of this system was a narrow forest belt with a small network, and it had the guarantee of high efficiency by combining trees-shrubs-grass, farmland, road, and irrigation system (Ci et al., 2007).

(3) Stage III (since 2000)

According to the UNCCD, combating desertification emphasizes the concept of near-natural restoration, ecological and environmental conservation, and regional cooperation, for the comprehensive benefits of ecological restoration. The assessment report of UNCCD indicated that since the Great Green Wall of Africa was launched in 2007 to combat drought and desertification, 11 countries along the green wall had rehabilitated nearly 4 million hectares of degraded land and created 350000 jobs in the process, which currently affect around 45% of Africa’s land area (Editorial, 2020). In 2008, the Northeast Asia Forest Network, a trilateral ministerial cooperation platform joining China, Mongolia, and the Republic of Korea, adopted the Northeast Asia Sub-Regional Action Programme to Combat Desertification and Dust and Sandstorms (NEASRAP). It is a framework plan for the network to implement its future cooperation activities under the UNCCD and relies heavily on the principles of partnership building. In order to achieve the improvement of ecological functions and the restoration of land productivity, some traditional ERTs have also been reused, such as reduced tillage, no tillage, green mulch planting, crop rotation, and other conservation tillage techniques.

Figure 2 shows that the center of ERTs application and combating desertification transferred from the United States, Japan, and Europe to developing countries in three stages. Developed countries had their desertification problems disturbed by unreasonable human activities in the process of industrialization, for example, destructive sandstorms in the United States and land desertification in the Mediterranean regions. These countries and regions carried out very early efforts in combating desertification and the R&D of ERTs (Stage I and Stage II). Europe and the United States are currently focusing on the R&D of new materials. The key areas of ERTs application are now in developing countries, and Africa and Central Asia will be the key regions of governance in the future.

Figure 2 shows the spatially heterogeneous distribution of technology R&D and applications, with a gap in the degree of desertification and governance needs. The areas most vulnerable to desertification are the sub-Saharan, Central Asian, and West Asian drylands. For example, a severe drought has occurred every 30 years in the Sahel region, and the southern and southeastern region of Africa (MA, 2005). However, the scope and sustainability of ERTs applications have been limited in Africa due to economic constraints. There were fewer new technologies and modes, and most funding and technical assistance was provided by other countries. In Stage III, China has shifted from being a follower to a leader in the desertification combating and ERTs R&D and applications. Although there is still a gap in the R&D level between China and developed countries, China has taken the lead in desertification control ERTs in

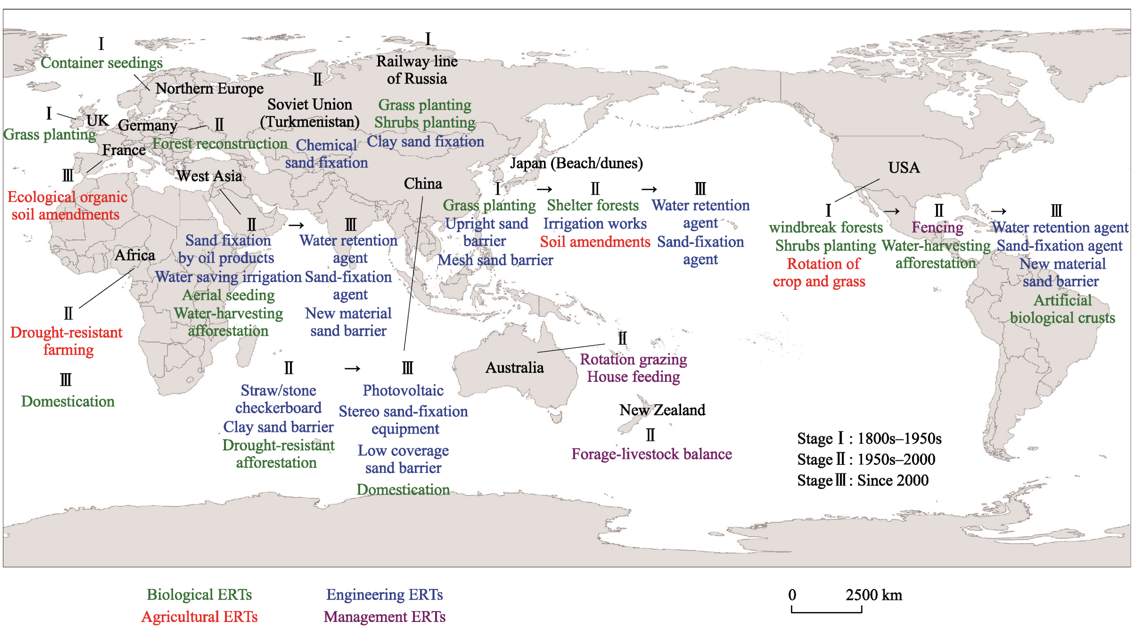

Fig. 2 The distribution of key desertification ERTs in three development stages

ecologically fragile areas. More than 90% o the ERTs such as drought-resistant afforestation and biological fences have been widely used. The sand industry, such as medicinal and biomass energy development technologies, has been an emerging economy for local development (ETFGC, 2015). China has strived to contribute Chinese wisdom to the combating of desertification and global governance.

3.1.2 Characteristics of the different types of ERTs

Biological ERTs pay more attention to the comprehensive improvement of ecosystem functions. The early vegetation measures with the addition of arbor, shrub and grass improved vegetation coverage, and soil and sand fixation. Biological ERTs have focused on the R&D of afforestation and land preparation technologies, and in Stage III, they have focused on the stability and suitability of artificial planting, the responses of multiple ecological functions to climate change (Li et al., 2018), as well as reducing environmental pollution. However, we still need newer ERTs, such as the screening and domestication of stress-resistant species, artificial biological crusts, and microbial soil amendments.

The evolution of engineering ERTs has been highly dependent on the R&D of new materials. Taking sand barriers as an example, initially, the early sand barriers used traditional biomass and on-site materials such as branches, wheatgrass, and reed poles; then came *Salix gordejevii*, *Salix psammophila*, *Caragana Fabr.*, *Hedysarum scoparium* and other living plants; and later the use of gravel and clay and other mineral materials for firmness; then with the development of science and technology, nylon mesh, plastic warp knitting mesh and other non-environment-friendly materials; for the purpose of environmental benefit, high-tech environmental protection materials such as polylactic acid fiber and polyester fiber; and most recently in order to improve labor productivity and reduce costs, sand-fixation equipment and low coverage sand barriers are currently used. In addition, dams and cellars with new materials are also in high demand.

Agricultural ERTs refer to farming techniques in the process of agricultural production to improve crop quality and increase economic benefits, under the premises of ensuring food security and sustainable land use. For example, no-tillage and reduced-tillage can effectively improve the physical structure of the soil and the external environment. Straw mulching can improve the ability of soil to store water and moisture. Leaving stubble and returning green manure to the field can increase the organic matter content, and intercropping can increase the yield.

Management ERTs have been paid more attention in recent years. For the comprehensive benefits of ecological, social, and economic aspects, the bottom-up approach with multi-stakeholder participation is emphasized, in addition to the top-down plans and programmes. This approach can motivate residents and communities, and inspire them to participate in best practices. The long-term mechanism for combating desertification and ecological restoration includes effective system and organizational innovations, public participation, and the effective combination of government and market, which is necessity for sustainable development.

3.2 The driving forces of ERTs evolution

3.2.1 Driven by events

The occurrence of ecological and environmental disasters, such as sandstorms and severe droughts, has prompted people to propose countermeasures in a short period, stimulating the R&D of ERTs. Ecological environmental events have occurred in the context of the process of industrialization and urbanization. The disasters caused by human development have transferred from developed countries to developing countries, and the same spatial evolutionary trend has involved the transfer of the center of desertification control and the application scope of ERTs. Governments and organizations generally lead the activities to combat desertification after ecological environmental events, such as by issuing relevant policies and regulations, setting up relevant institutions, and proposing short-term and long-term plans (Table 2).

3.2.2 Driven by social-economic development

The evolution of desertification combating and ERTs has also been affected by social-economic development, including the process of resource development and utilization, policies, and technological progress. Taking the sand barrier as an example, in the past, the evolutionary driving force of technology has changed from the demand of desertification control, to demand + economy + technology, to the SDG-related ERTs. Today, people combat desertification for the comprehensive benefits of low pollution and minimized interference with the ecosystem, not only for governance with low cost and longevity.

Taking China as an example (Table 3), the share of China's GDP in the world's total GDP decreased sharply after the industrial revolution. China's economy began to lag major European countries from the first half of the 18th Century. Since the reform and opening up in the 1980s, the share of China's GDP in the world's total quickly increased, and reached 18.2% in 2017 (Jin et al., 2019). Promoting eco-civilization is an important part of China's overall plan for the modernization of construction and human well-being. Since 2000, China has moved up in the ranking of national science and technology innovation capacity, from below 10th place to 3rd place. The Soviet Union and the United States were in the first rank of national science and technology innovation capacity in Stage II and Stage III, respectively (Duan et al., 2019)

In 2015, the State Forestry Administration of China announced that the overall expansion trend of desertified land had been initially reversed in China, shifting from greater

Table 2 The case of combating desertification driven by desertification control

Period	Site	Natural disaster or human activity	Measurement	Driver type
1934	Western America	Black storm	Shelterbelt Project of Roosevelt Federal Conservation Program Soil Erosion Act of 1935	Natural disaster
1950s	Shapotou of Ningxia, China	Construction of Baolan railway	Artificial sand fixation vegetation protection system	Human activity (+)
1960s	West Asia (Saudi Arabia, Iran)	Oil extraction and construction of desert roads	Sand fixation with oil and its by-products	Human activity (+)
1970s	New Zealand	Deforestation, over grazing	Forage-livestock balance	Human activity (–)
1968–1973	Sahel, Africa	Severe drought	Declaration of the United Nations Conference on the Human Environment (1972) United Nations Convention to Combat Desertification (1994)	Natural disaster
1990	Mediterranean coast of Europe	Sandification caused by farming modernization and Intensive management	Mediterranean Desertification and Land Use Project (European Union, 1990)	Human activity (–)
1980s–1990s	Soviet Union (Turkmenistan)	Construction of the Karakum Canal, the Aral Sea shrinking, and sandification	Economic and Ecological Restructuring of Land and Water Use in the Region Khorezm (ZEM/UNESCO, 2001–2011)	Human activity (–)
2000	North China	Severe sandstorm	Beijing-Tianjin Sandstorm Source Control	Natural disaster

Note: "+"= Active governance; "–"= Passive control.

Table 3 The economic situation of the main countries or regions in different stages

Stage of technological evolution	Country/region	Proportion of major economies in the world GDP [a]
Stage I (1800s–1950s)	Japan Europe The United States	3.2%–3.4% 28.1%–29.3% 1.7%–27.5%
Stage II (1950s–2000)	Soviet Union The United States	From 9.2% to 3.8% From 27.5% to 20.6%
Stage III (Since 2000)	China The United States	15.1% (2003), 17.5% (2008), 18.2% (2017) 20.6% (2003), 18.6% (2008), 15.2% (2017)

Note: Stage I, Stage II, and Stage III for the proportions of major economies in the world GDP refer to 1820–1952, 1952–2003, 2003–2017, respectively. Stage II and Stage III of the ranking of national science and technology innovation capacity refer to 1990–2000, and 2000–2014, respectively. Before the establishment of the Soviet Union (1922) and after the disintegration of the Soviet Union (1991), the data of the Soviet Union were replaced by data of the boundaries of the Soviet Union. [a] Jin et al., 2019.

damage to more governance. Reports indicate that desertified land in China is being reduced by 1283 km^2 each year, while it is increasing with an average annual expansion of 3436 km^2 at the end of the 20th century (SFA, 2015). In contrast, most parts of Africa are mainly reliant on external assistance, and the application and R&D of ERTs are insufficient, due to the poor economy and technological support. At the same time, the global technological innovation system is shifting from the Atlantic to the Pacific, and East Asia has become the new growth pole (Duan et al., 2019).

4 Evaluation of typical ERTs

According to the analysis of the questionnaires in this study, we obtained the evaluation results of four typical ERTs. Biological ERTs mainly include tree/grass planting and agroforestry planting. Engineering ERTs mainly include straw checkerboard barriers and efficient water saving irrigation. Agricultural ERTs mainly include conservation tillage, dry farming, and soil amendments. Management ERTs mainly include fencing, rotation grazing and rest grazing, and herder community co-management. For the four categories of ERTs, the score ranking of the degree of difficulty is: management ERTs (4.1) > engineering ERTs (3.7) > agricultural ERTs (3.3) > biological ERTs (3.2). The score ranking of the degree of maturity is: management ERTs (4.3) > agricultural ERTs (4.2) > engineering ERTs (4.0) > biological ERTs (3.7). The score ranking of the effectiveness is: agricultural ERTs (3.8) > biological ERTs (3.5) > engineering ERTs (3.3) > management ERTs (3.1). The score ranking of suitability is: engineering ERTs (4.5) > management ERTs (4.1) > agricultural ERTs (3.3) > biological ERTs (3.0). The score ranking of potential for transfer is: management ERTs (4.3) > biological ERTs (4.2) > engineering ERTs (4.0) > agricultural ERTs (3.7). For the specific ERTs, the potential for transfer of tree/grass planting is relatively high (*Mean*=4.25), but the effectiveness is not high (*Mean*=3.50). The degree of maturity, the suitability, and the potential for transfer of straw checkerboard barriers are relatively high (*Mean*=5.00). The suitability of efficient water saving irrigation is relatively high (*Mean*=4.25). The effectiveness and potential for transfer of conservation tillage are medium (*Mean*=3.50, and *Mean*=3.00, respectively). The potential for transfer of dry farming is relatively high (*Mean*=4.50), but the degree of difficulty score is low (*Mean*=2.50). The effectiveness of fencing is low (*Mean*=3.50), while the scores of other indicators are high. The effectiveness of rotation grazing and rest grazing is low (*Mean*=2.67), while the degree of maturity and suitability are relatively high (*Mean*=4.33) (Fig. 3).

Type of ERTs	Name of ERTs	Country	Degree of difficulty	Degree of maturity	Effectiveness	Suitability	Potential to transfer
Biological ERTs	Biological ERTs		3.2	3.7	3.5	3.0	4.2
	Planting trees and grass	Jordan	4	3	3	3	4
		Kenya	3	3	3	3	3
		India	3	4	3	3	5
		Ethiopia	3	4	5	3	5
	Agroforestry planting	Zambia	3	5	4	3	4
		Australia	3	3	3	3	4
Engineering ERTs	Engineering ERTs		3.7	4.0	3.3	4.5	4.0
	Straw checkerboard barrier	Kazakhstan	4	5	3	5	5
		China	3	5	4	5	5
	Water saving irrigation	Jordan	4	3	3	4	4
		Iran	2	3	3	3	3
		Turkey	5	3	4	5	3
		Israel	4	5	3	5	4
Agricultural ERTs	Agricultural ERTs		3.3	4.2	3.8	3.3	3.7
	Conservation tillage	Kenya	5	3	4	4	3
		Zambia	4	5	3	4	3
	Dry farming	Zambia	2	4	4	3	5
		China	3	4	5	5	4
	Soil amendments	Russia	2	5	4	2	4
		Zambia	4	4	3	2	3
Management ERTs	Management ERTs		4.1	4.3	3.1	4.1	4.3
	Fencing	Kazakhstan	5	5	4	4	5
		China	5	5	3	5	5
		The United States	4	4	4	4	4
	Rotation grazing & rest grazing	Mongolia	4	5	3	4	5
		Australia	3	4	3	4	4
		Turkey	3	4	2	5	3
	Herder community co-management	Mongolia	4	4	2	3	5
		Iran	5	3	4	4	3

Fig. 3 The evaluation of typical desertification ERTs

Note: Data source: The questionnaires of this study.

5 Discussion

The governments and scientists are aware of the consequences of desertification and land degradation, and they understand the principles of ecological restoration. A considerable number of ERTs have been applied, demonstrated, and promoted in various countries and regions, however, there are some cases of ecological restoration that have failed or produced poor effects (Bekele and Holden, 1999; Pender, 2004). Desertification is still one of the main threats to the global ecological environment (United Nations, 2019). In some countries and regions, there is a lack of appropriate technologies and modes for ecological restoration, caused by either the lack of knowledge and technology of ERTs, or by insufficient land, labor, investment, and other resources. Research on the evolution of desertification combating ERTs could provide a basis for successful practices of ERTs application. Such research also could assist decision makers and ERTs users to work towards more consistent ecosystem management goals, formulate policies and regulations that are suitable for related fields (water, land, energy, and poverty reduction), and expand new funding sources. We summarize the trend of ERTs application as follows.

(1) More interdisciplinary methods are essential, including new intelligent decision-making tools and an effective information exchange mechanism for diagnosing ecological degradation and analyzing the socio-economic feasibility of ERTs. It is necessary to learn from the previous practices and improve the follow-up in promoting the applications (Pastorok et al., 1997). Adaptive management strategies should be adopted, as well as long-term monitoring and evaluation. For example, afforestation in arid areas may aggravate the risk of water shortage (Zastrow, 2019), because many kinds of plants are not native species and consume a lot of water. Therefore, it is necessary to consider the local natural conditions and plant more bushes or grass and other native species with low water consumption.

(2) It is necessary to pay more attention to the social system. In order to upgrade the ERTs, the full range of stakeholders (government + enterprise + NGO + residents) should participate in the entire decision-making process, from the design of the ERTs to the implementation and supervision, and from the initial application to the long-term maintenance. This approach can also increase the possibility for users to accept and apply ERTs. The practice of ecological governance and restoration cannot ignore regional differences, and needs to avoid top-down implementation without the participation of local communities. Special stakeholders need to receive the proper attention in ecological governance and restoration, e.g., smallholders and women (t'Mannetje, 2000; Shames et al., 2013).

(3) It is necessary to pay more attention to the uncertainty of climate change. People should try to apply appropriate adaptive measures to reduce negative impacts when climate change cannot be accurately predicted. In the planning and

design stage of ERTs and programmes, extreme climate events should be considered, not just the normal baseline scenarios, to ensure that species are diversified and adaptable. It is important to provide the necessary technology and infrastructure for the drought early warning system, in order to alleviate the drought and improve water resource utilization and management (Padma, 2019).

(4) Regional cooperation will play an important role in combating desertification. For example, the global mechanism of UNCCD and the Belt and Road Joint Action Initiative for Combating Desertification at the regional and global scales as innovative cooperation models, have promoted communication and pragmatic cooperation, shared governance results, and improved the capabilities of ecological governance and restoration. The cooperation mechanism may include the consensus of all parties, objectives, participants, frameworks, cooperation methods, fund raising and use, strategies, implementation, and evaluation.

6 Conclusions

This paper summarizes the desertification combating ERTs in China and other regions, including both developed countries and developing countries. We identified four categories of ERTs based on questionnaires and literature data. In terms of governance goals, ERTs have changed from passive control to active prevention and comprehensive governance, to regional cooperative prevention and management. In terms of governance methods, biological and engineering ERTs are the key measures, and the trend will be toward integrated modes combined with different ERTs. In terms of governance benefits, the single aim of desertified landscape restoration has turned into the comprehensive improvement of ecosystem functions, and social and economic benefits. The key areas for ERTs application are in developing countries, and they will be especially prominent in Africa and Central Asia in the future. The evolution of desertification combating ERTs is mainly driven by disaster events and the level of socio-economic development. We evaluated ERTs from five dimensions, which are the degree of difficulty, the degree of maturity, effectiveness, suitability, and potential for transfer. Different ERTs have different effects in one region, and one ERT has different effects in different regions. It is necessary to solve the problems in the application of ERTs in practice, and to introduce and recommend the appropriate ERTs.

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典型生态脆弱区荒漠化治理技术演化趋势分析

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摘　要：全球经济发展和日益增强的人类活动给脆弱的生态系统带来了巨大挑战。为避免、减少和扭转荒漠化，帮助改善当地居民生计，加强抗灾能力，近年来，国内外科学家和相关机构研发出了一系列技术体系和技术模式，对生态脆弱区退化生态系统展开了全面的治理和恢复。然而，部分已有研究和实践在很大程度上限制了优良技术的筛选和推广应用及对技术需求的评估，造成了资金和人力的浪费和损失。文章旨在刻画荒漠化治理技术演变规律和发展趋势，识别并评估主要生态技术。数据来源包括国际组织数据库、中国知网、其他文献报告以及机构和专家调查问卷。文章识别了人类防治荒漠化的治理和恢复技术及模式，总结不同自然条件下荒漠化治理技术的三阶段演化规律和趋势，自然灾害、人类活动和社会经济技术发展驱动技术演变。识别并划分了生物、工程、农作和管理 4 类不同作用原理的荒漠化治理技术及模式。最后从难度、成熟度、有效性、适宜性和推广潜力等 5 个维度开展技术评价。研究为因地制宜、综合治理、合理开发利用干旱区资源，提高生态技术应用效果以及促进优良技术的输出和引进提供参考。

关键词：荒漠化治理；生态技术；技术演化；生态脆弱区