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REVIEW

HIGH QUALITY DEVELOPMENTAL APPROACH FOR SOIL AND WATER CONSERVATION AND ECOLOGICAL PROTECTION ON THE LOESS PLATEAU

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KEYWORDS

ecological management, high quality development, industrial structure, soil erosion, soil and water conservation, Loess Plateau

HIGHLIGHTS

- Analyse the effects of ecological management measures undertaken so far.
- Point out the main problems that confront effective ecological management.
- Suggest some measures to guide ecological management and high-quality development.
- Develop some models to improve the quality of clear waters and green mountains.
- Provide scientific and technological support for green and eco-friendly development.

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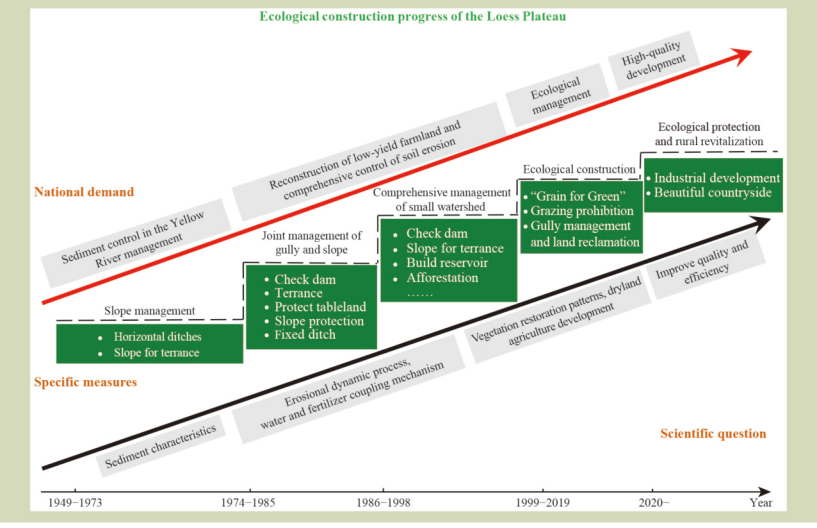
GRAPHICAL ABSTRACT



ABSTRACT

The Loess Plateau is the core area in the Yellow River basin for implementing environmental protection and high-quality development strategies. A series of ecological projects has implemented aimed at soil and water conservation and ecological management on the Loess Plateau over the past 70 years. The effects of the ecological projects are apparent mainly through a marked increase in vegetation cover, controlled soil erosion and reduced flow of sediment into the Yellow River, continual optimization of the industrial structure and increased production from arable land, poverty alleviation and greater prosperity, and optimal allocation of space for biological organisms. Major problems have also been analyzed in ecological management including the fragile ecosystem of the region, maintaining the stability of vegetation, lower agricultural productivity and continued risk from natural disasters. Some suitable schemes and models have been developed for the coordinated development of the region through research and demonstration, striking the optimum balance between rural industry and ecology, and increased regional

capacity to supply high-quality ecological products. Countermeasures to address the problems are suggested to guide ecological management and high-quality development in the future.

1 INTRODUCTION

The Loess Plateau lies in north-central China and covers, fully or partly, seven provinces (regions), namely Gansu, Henan, Inner Mongolia, Ningxia, Qinghai, Shaanxi and Shanxi, with a total area of 640,000 km^2, accounting for 6.7% of the total land area of China[1,2]. The Plateau is considered the birthplace of Chinese civilization, an important energy base with an ecological barrier, an area most severely affected by soil erosion, and a key area for soil and water conservation and ecological reconstruction[3,4].

The health of the natural environment on the Loess Plateau affects both the survival and well-being of more than 100 million people and also affects the safety of their lives and property in the upper and middle reaches of the Yellow River. Since the establishment of the People's Republic of China in 1949 a series of projects have been implemented on the Loess Plateau for ecological protection and soil and water conservation including the 'Grain for Green' program, construction of check dams and modifications to sloping farmlands. These projects have helped to control soil erosion, boost the productivity of dryland farming and control the natural environment[5,6]. Although the extent of anthropogenic disturbance to the environment has decreased gradually with socioeconomic development and greater urbanization, the region's ecological vulnerability and exposure to risk from natural disasters have seen little change[7]. The development of soil and water conservation and the natural environment on the Loess Plateau are therefore matters of concern to the international community[8,9]. The plateau is also a major focus for international research in ecology, geology, forestry, and the humanities and social sciences, with distinct multidisciplinary integration that is comprehensive, periodic, and practical[1,7]. In the social and economically sustainable development of the Loess Plateau it is important to optimize and integrate every element and draw up a blueprint and implementation roadmap for soil and water conservation and ecology specifically tailored to the biological resources, the geographical environment, and the economic conditions and developmental objectives.

For the blueprint and roadmap mentioned above it is necessary to undertake an in-depth study of ecological management, to formulate a management plan scientifically and to chart the path to ecological industrialization on the Loess Plateau to achieve the coordinated development envisaged in the plan to protect the ecology, boost productivity and improve the living standards of the region's inhabitants. Such planning is of great practical significance to demonstrate the validity of the ecological civilization theory that maintains that "clear waters and green mountains are as good as mountains of gold and silver"[7,10]. Accordingly, the present study sought to develop some schemes and models aimed at improving quality and increasing efficiency to make the waters clearer and the mountains greener, and revitalizing the rural areas. We did this by analyzing the effects of soil and water conservation and ecological management measures undertaken so far, and of the main problems that confront effective ecological management of the Loess Plateau. The study also suggested some measures to guide ecological management and high-quality development of the region in the future, thereby providing scientific and technological support for green and ecologically friendly development of the Loess Plateau.

2 EFFECTS OF SOIL AND WATER CONSERVATION AND ECOLOGICAL MANAGEMENT

Since 1949, ecological governance of the Loess Plateau has gone through several stages including the following: slope management, joint management of gullies and slopes, comprehensive management of small watersheds, the "Grain for Green" program (which involved restoring agricultural land to forests and grasslands), and ecological protection and high-quality development (Fig. 1). These measures have achieved remarkable results in regional ecological construction and restoration of ecological functions on the Loess Plateau.

2.1 Vegetation restoration has achieved remarkable results and regional ecology has begun to develop healthily

Since the implementation of the "Grain for Green" program, the area under forests and grasses on the Loess Plateau has

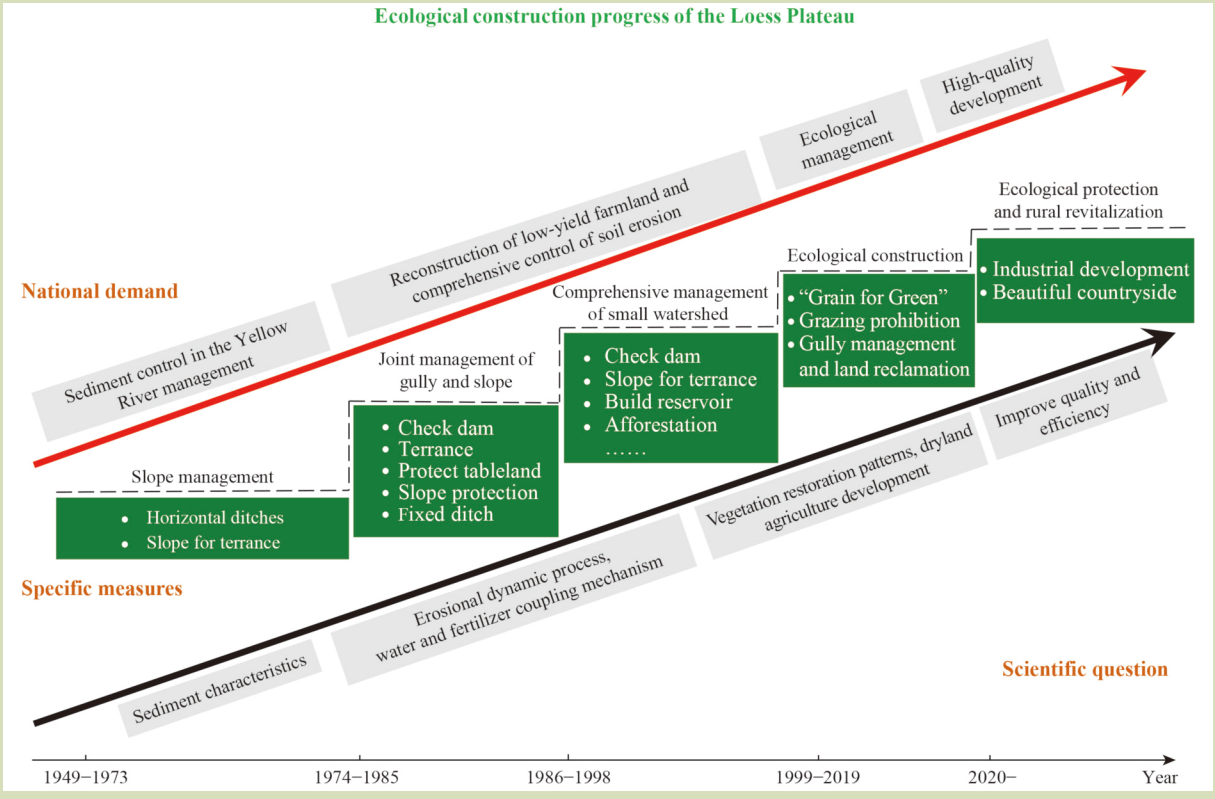


Fig. 1 Progress of ecological governance on the Loess Plateau since the establishment of the People's Republic of China in 1949.

increased substantially, transforming the landscape from yellow to green (Fig. 2). Compared to the period 1982–1999 the normalized difference vegetation index (NDVI) of > 21% of the area of the Loess Plateau has changed from low (0–0.4) to high (0.4–0.8) during the period 2000–2015[12]. The trend toward the greening of vegetation has been more obvious in the southeastern Loess Plateau[12]. The vegetation cover as a whole increased from 32% in 1999 to 64% in 2019, with the Loess Hilly and Gully Region showing the maximum increase[13]. Even the restoration of vegetation in the Mu Us Sandy Land has been well managed. More than 2.2 Mha have been afforested, reversing the trend of expansion of sandy lands. This effort comprised a complete set of management technologies and models that integrated the techniques of air planting, enclosures, artificial afforestation and fixing sands by erecting barriers to control desertification in the Mu Us Sandy Land, providing a Chinese model for controlling desertification worldwide[14]. The Loess Plateau's natural environment underwent benign development, captured by the slogan, "Overall better and local well".

Fig. 2 Vegetation cover: before and after the "Grain for Green" program in Wuqi, Shaanxi, on the Loess Plateau[11] (with permission from Yingfei Bai, Forest and Grass Science and Technology Innovation Alliance).

2.2 Soil erosion has been effectively controlled and the sediment flow into the Yellow River has decreased significantly

More than 56,000 check dams have been built on the Loess Plateau, serving more than 220,000 ha of cultivated land and preventing more than 21 Gt of sediment from flowing into the

Yellow River[15], thereby effectively controlling the loss of soil and water. Since 2000, the intensity of soil erosion has generally been decreasing, although with marked regional differences. The amount of sediment flowing into the Yellow River has decreased annually from 1.6 Gt in the mid-1970s to about 0.2 Gt by 2020 (Fig. 3)[16]. Especially on the Loess Hilly and Gully Region the erosion modulus has fallen by > 50% over most of the area[17]. Before the "Grain for Green" program was implemented, decreased rainfall and controlling sand movement by building large reservoirs each lowered the amount of sediment flowing into the Yellow River by 30%, and soil and water conservation projects (e.g., check dams, terraced fields, forests and grass cover) lowered the flow by 40%. After the program the contribution of the three measures amounted to 19%, 22% and 59%, respectively, that of forests and grass cover increased by about 20%[2]. Therefore, the influence of such measures as soil and water conservation on the change in sediment volume increased gradually, whereas the effect of rainfall waned following the implementation of the "Grain for Green" program on the Loess Plateau.

2.3 Industrial structure has been continually optimized and arable land has been made significantly more productive

The Loess Plateau is a core area that connects farming and pastoral areas. It is also an important ecological barrier to central and eastern China. Historically, it was the traditional organic agriculture on the Loess Plateau that spawned Chinese civilization. The complex ecology has led to a series of different types of farming, or modes of agricultural development, through long-term exploration, represented by such forms of productive ecological agriculture as dryland agriculture, organic agriculture, sustainable agriculture, low-carbon agriculture, dimensional agriculture, facilities agriculture and precision agriculture. Also, depending on local conditions, some areas have developed integrated ecological forms of agriculture such as leisure and sightseeing agriculture, urban agriculture, white agriculture, and soil and water conservation agriculture[7]. The developments on the Loess Plateau have led the rest of the country in ecological protection and sustainable development of agriculture.

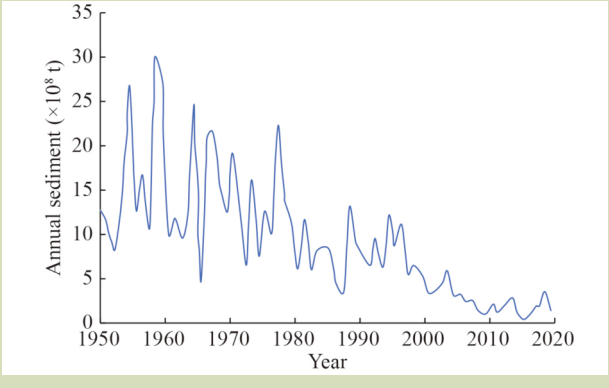


Fig. 3 Annual sediment discharge at Tongguan station of the Yellow River[16] (with permission from the Chinese Journal of *Bulletin of Soil and Water Conservation*).

Developments on the Loess Plateau have optimized community structure and function, made full use of the limited water resources, and maximized the use of light and heat by way of breeding and using improved varieties, regulating planting density and sowing time, following rational fertilizer regimes, increasing soil temperature, reducing the evaporation of soil moisture (e.g., by mulching with plastic film) and other measures. As a result, the yields of grain and cash crops have been steadily increasing and the water and nutrient use efficiencies have increased significantly, leading to high yield and high efficiency agriculture that can guarantee food supply to the people of the Loess Plateau. For example, the average yield of maize increased from 1 t·ha^{-1} in 1949 to currently about 6 t·ha^{-1} (Fig. 4). One high yield model of 21 ha farmland reported that maize yields in Yulin, in Shaanxi Province, can reach nearly 22 t·ha^{-1}[18].

2.4 Rural areas have escaped poverty and the spaces for "ecology, production and life" have been continuously improved

The policy introduced through the "Grain for Green" program on the Loess Plateau in parallel with adjustments in agricultural structure and urbanization has promoted specialization in agricultural production and the development of non-agricultural surplus labor force, as well as multiplied the channels through which farmers can increase their income[8]; especially by strengthening the construction of ecological economic forests, involving industrial crops such as apple, Chinese prickly ash, potato and wolfberry. Following the implementation of the "Grain for Green" program, average farm income more than doubled, and non-agricultural income increased to 60%[2]. At the same time, the regional "ecology, production and life" spaces have been optimized. Instead of slopping land, farming is now concentrated on wide terraces, dam lands and in valleys, whereas people have gradually moved from hillsides to towns. These changes have promoted the transformation from traditional agriculture to large-scale and mechanized agriculture, a shift that has achieved distinct ecological, economic and social benefits.

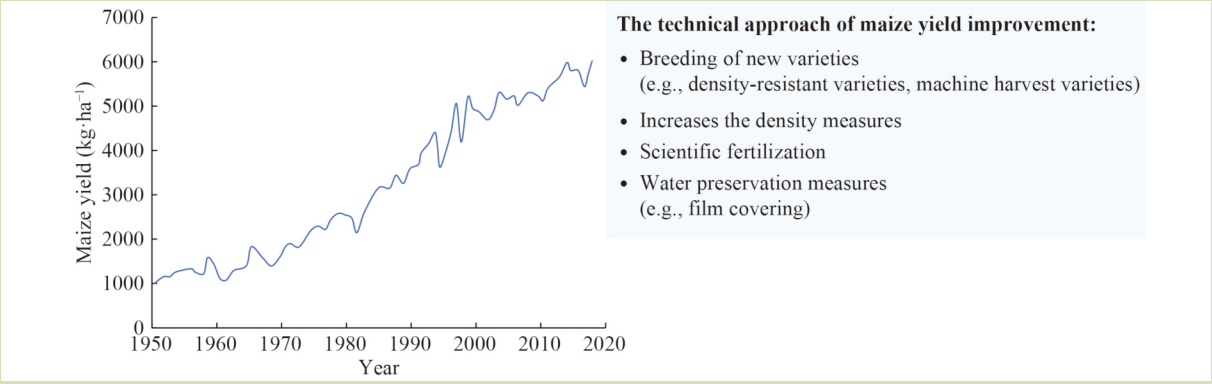


Fig. 4 Changes in maize yield and major technical approaches that have contributed to higher maize yields on the Loess Plateau in the past 70 years.

3 MAIN DIFFICULTIES IN SOIL AND WATER CONSERVATION AND ECOLOGICAL MANAGEMENT

Despite decades of managing the natural environment it continues to remain fragile. Specifically, aggregate risks from disasters, weak livelihood security and adverse impacts of development are significant challenges, in addition to several other complex problems.

3.1 The fragile natural environment has not changed fundamentally

The natural characteristics of the loess create severe soil erosion risks and make the area prone to geological disasters. Reviewing the process of ecological management of the Loess Plateau over the past 70 years, it becomes apparent that the process has been focused on biological and engineering management[1]. Ecological management has not been fully combined with adjusting the local industrial structure, economic development and livelihood security[9]. The process also lacked the comprehensive management of zoning classification and its faithful implementation. The central area comprising rough sediment in the middle reaches of the Yellow River is 188,000 km^2, accounting for less than a third of the whole area of the Loess Plateau. Even so, the central area produces 219 Mt of sand[19], accounting for 73% of the total amount of sand coming from the Yellow River. Therefore, despite some good results from periodic ecological management, soil erosion continues to be severe and the natural environment on the Loess Plateau continues to be fragile.

3.2 Disaster risks remain high

Landslides, subsidence, unstable slopes, ground fissures, and other geological disasters are very common on the Loess Plateau. For example, areas categorized as either extremely high risk or high risk from geological disasters in the Shaanxi-Gansu-Ningxia region amount to about 180,000 km^2. The area prone to geological disasters in Yan'an City is about 30,000 km^2, includes 737 geological disaster risk points, and has witnessed 324 landslides and 314 subsidence events. Also, floods and droughts caused by extreme climate will aggravate the situation. Large and medium-sized dams that are considered dangerous account for more than two-thirds of the total number of check dams on the Loess Plateau. The risk from check dams increases as extreme climate events become more frequent. On 16 July 2017, once-in-a-century torrential rains and floods ravaged Suide County, Shaanxi Province, damaging 337 check dams. Of the 432,700 people made vulnerable, 12 died. The direct economic loss was 6.9 billion CNY[17]. The dams rendered dangerous seriously affected regional ecological and livelihood security. Thus, not only the likely risk from disasters but also actual damage from disasters remains a reality on the Loess Plateau.

3.3 Vegetation stability still faces great challenges

Restoration of vegetation, part of the implementation of the "Grain for Green" program, has increased surface evapotranspiration[20]. Water consumption by such vegetation affects the sustainable use of the region's water resources. Excessive consumption of soil water results in a layer of dry soil occurring over large areas[3,21], stunting the growth of trees (resulting in trees that are old and yet small) and even killing them. Large-scale restoration of vegetation has stretched the use of water soil resources beyond what is sustainable[22,23] and a major challenge is to continue to restore and maintain the

present forest and grass vegetation in the future. For example, vegetation in the sandy area changes from sparse scrub grassland to desert steppes owing to excessive exploitation of vegetation and inappropriate restoration of vegetation. The shelterbelt of forests built in the past at Sanbei are severely degraded and their efficiency in protecting the ecology continues to decline, whereas the recently planted vegetation is yet to attain the stage at which it can be an effective replacement for the shelterbelt and has also failed to increase rural incomes because of defective planning.

3.4 Production from integrated agriculture has remained low

The Loess Plateau is a fragile habitat and its soil and water resources are not used systematically. Also, the cultivated land is mostly dry, with extensive holdings and low productivity. Lack of overall planning, inadequate maintenance, and excessive exploitation have degraded the soil, leading to severe soil erosion and secondary salinization in some regions[24]. The overall quality of cultivated land is low. According to the national classification system of cultivated land, less than 7.6% of the cultivated land in the area is of high quality and more than 92% is of medium or low quality[25]. In addition, excessive application of chemical fertilizers and pesticides has greatly damaged the natural environment at the field level, and the region's agricultural ecosystems have been adversely affected by increasing pollution from residues of plastic films, pesticides and fertilizers, livestock manures and wastes.

4 KEY TECHNOLOGIES AND DEMONSTRATIONS TO ATTAIN "CLEAR WATERS AND GREEN MOUNTAINS", AND FOR THE REVITALIZATION OF RURAL AREAS

4.1 Assessing habitat health and demonstrations of improved technology can contribute to achieving "clear waters and green mountains"

A number of key technologies and demonstration projects aimed at attaining "clear waters and green mountains" and revitalizing rural areas have been implemented since 2019 in the Hilly and Gully Region of Yulin in Shaanxi Province, characterized by loess wind and soil. To begin with the process that leads to the formation of clear waters and green mountains was examined using many different techniques including the following: comprehensive monitoring of the ecosystem network by remote sensing, observation stations, sampling and field surveys; deploying the internet of things for real-time monitoring; and compiling large data sets and running simulations based on suitable models. Key technologies were then developed and technical standards formulated tailored to different regions for revitalizing rural areas and alleviating poverty. Coordinated technical programs were drawn up to balance industrial growth and ecological protection and to ensure sustainable use of rural resources to develop "green" industries and an ecologically friendly countryside. The required theoretical, political, and technical support was provided for realizing the vision of sustainable clear waters and green mountains, as well as for implementing "Beautiful China", which sought to build an eco-friendly civilization on the Loess Plateau.

Two years of scientific and technological integration and optimization have led to the following achievements. (1) Obstacles to improving the quality and efficiency of typical vegetation configurations in the windy and sandy region were identified; a collection of native plant germplasms suited for the region was established (because species substitution was the main factor leading to species homogenization); technology was developed to exploit the layer of dry soil using appropriate plant species. (2) Technology was developed for enhancing the conversion of the desert land to fertile land and for maintaining that level of fertility. Technical regulations were compiled to preserve the quality of cultivated land in the loess sandstorm region. (3) A model to improve the quality and to increase the efficiency of plantations and eco-friendly industries based on those plantations was demonstrated. This model was particularly suitable for the windy and sandy region because it made the ecosystem more stable and elastic, achieving a win-win situation for both ecology and economy.

Consequently, the demonstration served primarily as a regional high-quality model to develop the region's ecology and to alleviate poverty (Fig. 5). Technology demonstration zones have been established in Shenmu in Shaanxi and Yanchi in Ningxia to achieve an appropriate balance between economic development and protection of the ecology, captured by the slogan "Turn green to protect green".

4.2 Evaluation and promotion of ecosystem carbon sequestration by the ecosystem was ensured

Since the implementation of the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05060300) in 2010, attention was focused on the national need to assess scientifically the benefits of carbon sequestration achieved through the "Grain for Green" program and the dynamic relationship between regional ecological restoration and carbon sources and sinks. As the first step an internationally

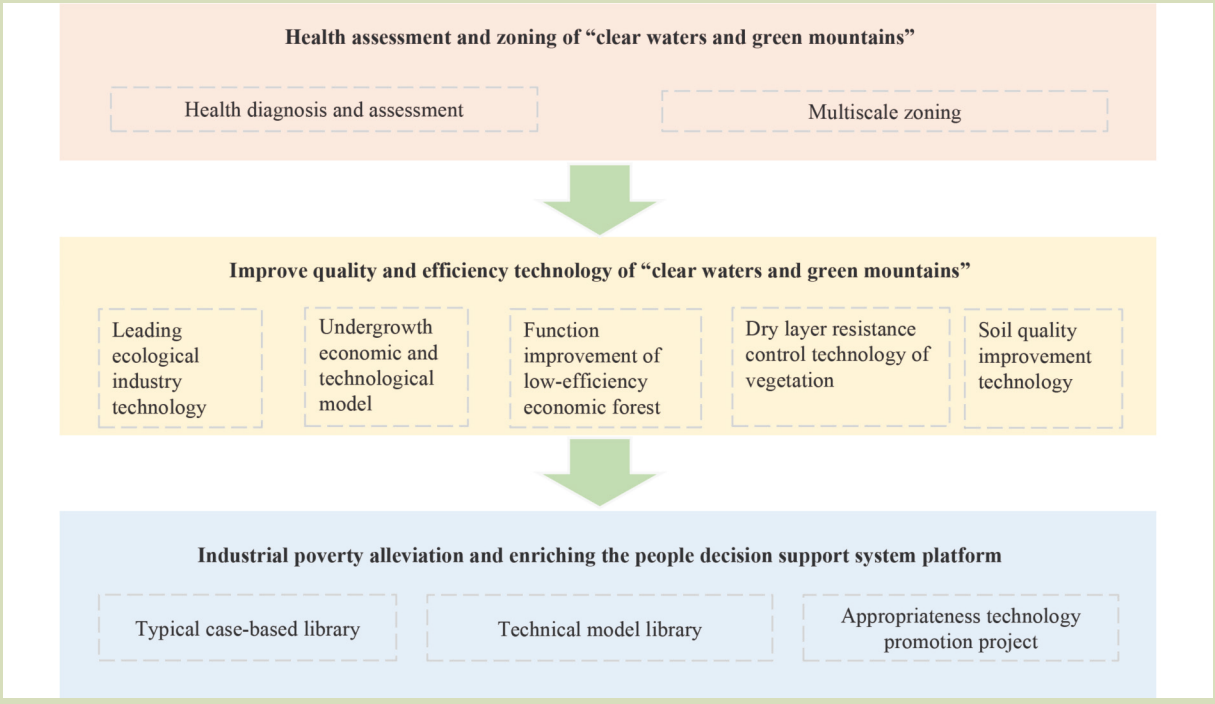


Fig. 5 Health assessment and demonstration of technologies for improving quality and efficiency of "Clear waters and green mountains" in the sandy and windy region of the Loess Plateau.

recognized method of evaluating the benefits of carbon sequestration was chosen. This was followed by evaluating the current situation and the potential for and the rates of carbon sequestration. The relationship between changes in land use and the carbon budget of the soil was also clarified, revealing the dynamics and the drivers of carbon sequestration in the ecosystem under the "Grain for Green" program on the Loess Plateau. The approaches for increasing ecosystem capacity for carbon sequestration are described below. These advances provided a scientific basis and quantitative evidence of guiding ecological restoration, and regulating the capacity of the carbon pool of the Loess Plateau. These technologies are particularly significant to promote ecological protection and high-quality development of the Loess Plateau, and will also help to improve the strategy for the development of regional ecology in the future.

As the first step, three models were set up based on the following inputs: accurately verified dates during which the "Grain for Green" program was implemented, the area covered, baseline value of carbon storage, tree species used for afforestation, percentage survival of the plants and the area afforested annually. The three models were the vegetation carbon fixation allometric model, the soil carbon fixation dynamic model and the litter carbon storage dynamic model[5]. The benefits of carbon sequestration accrued, or likely to accrue, from the project from 1999 to 2060 were quantified, taking into account four carbon pools: aboveground biomass, roots, litter, and soil. For the whole ecosystem, the total carbon sequestered by the "Grain for Green" program was 322 Mt in 2020 and projected to be 501 Mt in 2030 and 906 Mt in 2060 (Fig. 6). Therefore, the implementation of the "Grain for Green" program on the Loess Plateau was conducive to improving the capacity of the carbon sink of the terrestrial ecosystem and could guide afforestation projects worldwide.

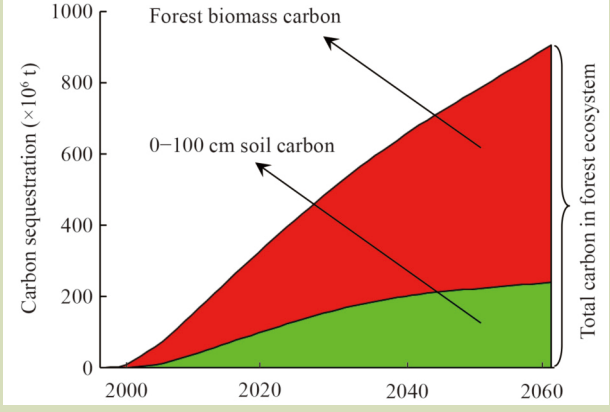


Fig. 6 Net cumulative carbon sequestration by forest ecosystems (forest biomass and soil) under the "Grain for Green" program on the Loess Plateau: 2000–2060.

Second, 5 years of effort aimed at the integration and optimization of science and technology show that the carbon sequestration capacity of the ecosystem was increased by the following measures: application of fertilizers to forests, replacement of non-native species with native tree species, and a three-pronged technology of afforestation comprising moderate and rotational grazing, thinning and removal of shrubs from grasslands (Fig. 7). Sites to demonstrate the technology have been set up in Shenmu and Ansai in Shaanxi and Yanchi in Ningxia. The technology has effectively increased the carbon sequestration capacity of the ecosystem of the Loess Plateau.

5 COUNTERMEASURES AND SUGGESTIONS FOR DEVELOPING ECOLOGICAL MANAGEMENT

5.1 An experimental demonstration area for ecological management and green development needs to be established

The Loess Plateau has three state-level city clusters designated, namely Guanzhong Plain, Hohhot-Baotou-Ordos-Yulin and Lanzhou-Xining. These clusters are an important base for the development of energy, the chemical industry, agriculture and animal husbandry sectors, as well as an urban-rural economic transition area in China. The area should (1) strengthen regional cooperation, ecological cooperation, economic complementarity and win-win ventures on the Loess Plateau; (2) comprehensively revitalize the upper and middle reaches of the Yellow River; and (3) promote high quality development of the region. Also, the clusters should lead in launching a scientific plan for comprehensive ecological and environmental management of the Loess Plateau and compile a systematic plan for the ecological and economic development of the Plateau as part of the Fourteenth Five-Year Plan. In addition, the area should introduce innovative regional models of ecological conservation, poverty alleviation, rural revitalization, and green development scientifically and set up extensive demonstrations of the integrated management of natural resources, ecological and environmental protection, and transformation of resource-based cities. These steps will take the country farther along the path of poverty alleviation and prosperity. Lastly, such integrated development of mountains, rivers, forests, fields, lakes and grasslands will enrich the community and attain an optimum balance between cities and villages.

5.2 Promote comprehensive ecological management projects and innovate ecological management

Ecological management of the different zones on the Loess Plateau needs to be improved, and the following measures are suggested to achieve this[26]. (1) Consolidating gullies and

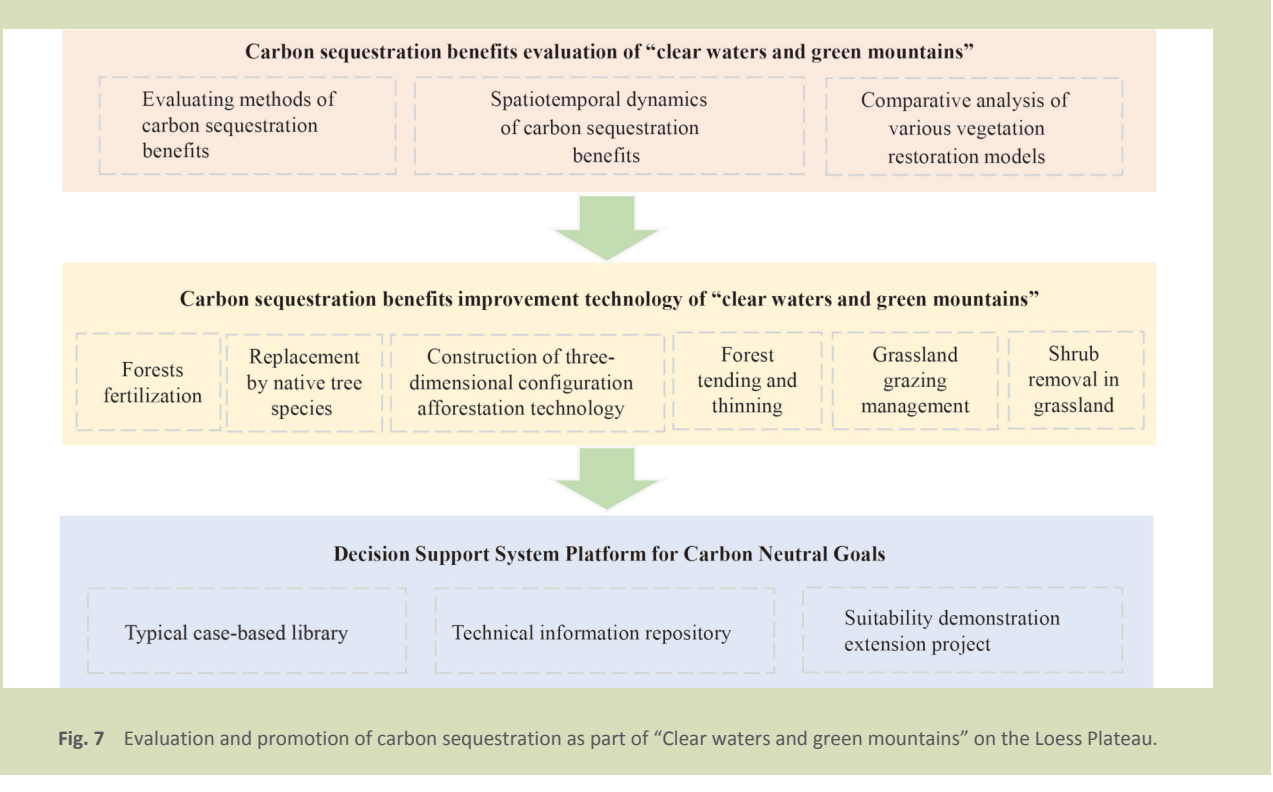


Fig. 7 Evaluation and promotion of carbon sequestration as part of "Clear waters and green mountains" on the Loess Plateau.

protecting land in the tableland area. This can be achieved by setting up four lines of defense, namely controlling soil runoff from the tableland, reinforcing ditches and their banks, restoring the vegetation on slopes, and collecting and storing water and sand. These measures will check the spread of soil erosion in the valley, protect the high-quality arable land resources, and promote the coordinated development of ecology and economy. (2) Restoring the farmland to forests and grassland on the slopes. For steep lands with a slope greater than 25° or, for vital catchment areas, a slope between 15° and 25°, it will be necessary to continue implementing the "Grain for Green" program to maintain the stability of vegetation through such biological treatments as selecting suitable native plants to stabilize the slope and to check soil erosion. (3) Stop runoff and build land in the valley. Depending on the characteristics of water and the sediment in the valley, construction of the check dam system could be improved; building of ditches and projects of land reclamation should continue, and the capacity to block the incursion of sand and to control floods should be consolidated and increased. All these measures will comprehensively improve the quality of land. (4) Arrest sand encroachment and restore shrubs and grasses in sandy areas. Water and soil resources should be allocated scientifically to such sandy areas. Finally, measures should be enforced to improve and rehabilitate degraded lands and to grow plants suited to local conditions.

5.3 Realizing the vision of "clear water and green mountains" and focusing on eco-based industries has promoted an ecology-conscious civilization and rural revitalization

Following the implementation of the "Grain for Green" program and the development of the regional economy, vegetation cover of the Loess Plateau increased significantly to extend the green map of Shaanxi Province 400 km northwards. Implementing this and similar projects aimed at attaining "clear waters and green mountains" and centered on eco-based industries can solve the three major facets of ecological reconstruction, namely ushering in qualitative change instead of quantitative change, improving ecological functions, and upgrading the development path to the "green" approach. That approach involves building an economic complex, including a system of dams and taking into account the rural characteristics, switching to clean production in watersheds and strengthening agricultural development by modernizing agriculture. In this process, the capacity to offer environment friendly and long-term scientific and technological support would keep increasing. Also, the projects can promote green development, breakthrough technologies, and ways of converting "clean waters and green mountains" to "mountains of gold and silver".

5.4 Monitoring and supervision of soil and water conservation should be strengthened, and innovative mechanisms and an ecological management system should be encouraged on the Loess Plateau

It is necessary to build a cloud-based intelligent soil and water conservation monitoring and evaluation technology for the Loess Plateau, as such technology would improve the level of water and soil conservation monitoring and evaluation. For that purpose, it is suggested that an airspace-earth coordinated ecological monitoring network and data center to be established on the Loess Plateau; this infrastructure will also (1) develop such related systems as automatic and intelligent monitoring systems to monitor water and sediment in the watershed, (2) investigate and evaluate soil erosion, and (3) sense in real-time the impacts of soil and water conservation measures. Essentially, a modern technology platform will thus be set up to monitor soil erosion, water resources and sediment. Each government department must conscientiously perform its management and protection duties, strictly implement related laws and regulations, and fully implement the river and the lake chief systems for better protection of water and soil resources, curbing excessive development and exploiting water resources and controlling the increasing soil erosion due to anthropogenic activity. At the same time, it is also necessary to (1) promote innovation in ecological regulation systems and top-level design of related systems for the Loess Plateau; (2) improve the funding mechanism and the departmental coordination mechanism; (3) unify the management of natural resources and develop innovative mechanisms for compensating for ecological damages; (4) undertake a comprehensive evaluation of the effectiveness of such measures; and (5) to set a value to natural resources. These measures can provide major support to rural revitalization and to build a "Beautiful China".

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Compliance with ethics guidelines

Lei Deng and Zhouping Shangguan declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any study with human or animal subjects performed by any of the authors.

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