Good Practices on Vulnerable Ecosystem Restoration in China

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Abbreviations

CAS	Chinese Academy of Sciences
CERN	Chinese Ecosystem Research Network
CNY	Chinese renminbi
GPS	Global Position System
IMGERS	Inner Mongolia Grassland Ecosystem Research Station
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
RCEES	Research Center for Eco-Environmental Sciences
RS	Remote Sensing
STERE	Stepwise ecological restoration theory
UN Decade	United Nations Decade on Ecosystem Restoration
UNEP	United Nations Environment Programme
UNEP-IEMP	United Nations Environment Programme-International Ecosystem Management Partnership
XIEG	Xinjiang Institute of Ecology and Geography

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Foreword

Healthy ecosystems support all life on Earth. The global call of the UN Decade on Ecosystem Restoration to revive ecosystems worldwide for the benefit of people and nature has been responded to by many nations, international initiatives and civil societies. The goal of this UN Decade on Ecosystem Restoration is to build a strong global movement that seeks to promote ecosystem restoration efforts and create thousands of initiatives on the ground. These efforts are particularly important in the Global South, where better policy planning, enhanced capacity, well-tested technology and science-based and traditional knowledge for ecosystem restoration remain underdeveloped.

The ecosystem restoration efforts of China have been widely recognized by the global community. Over the past few decades, it has undertaken remarkable engineering projects, such as the Grain for Green Programme in 23 provinces and the Three-North Shelterbelt Project in arid and semi-arid regions of China. Chinese scientists, particularly those of the Chinese Ecosystem Research Network (CERN) of the Chinese Academy of Sciences (CAS), are devoted to long-term ecological monitoring, research and demonstration in these regions. They have gained rich experiences in vulnerable ecosystem restoration and management in China.

This report was prepared by a team of researchers from the United Nations Environment Programme-International Ecosystem Management Partnership (UNEP-IEMP) and several research institutes of the CAS. It includes integrated management approaches, science-based knowledge and socioeconomic aspects of vulnerable ecosystem restoration to share knowledge and practices on restoring and managing vulnerable ecosystems in China. These ecosystems include deserts, degraded grasslands, sandy lands in the agriculture-pasture transition area, drylands, mountain gully areas and urban rivers. The case studies on the restoration of these ecosystems put local livelihoods and community development at the core of integrated ecosystem management approaches. We expect this report will be used as a technical reference for local practitioners, civil societies, policymakers and government officials within a similar context. We recommend developing the capacities of local men and women to ensure they can be effectively involved to restore vulnerable local ecosystems.

Professor Bojie Fu
Co-Chair of UNEP-IEMP's Science Advisory Group

Introduction

Efficient and sustainable ecosystem restoration, complemented by ecosystem conservation, is uniquely able to make major contributions to all 17 Sustainable Development Goals (International Resource Panel 2019). In this context, the United Nations General Assembly proclaimed 2021–2030 to be the United Nations Decade on Ecosystem Restoration (UN Decade). United Nations Member States are committed to supporting the UN Decade by building new momentum for ecosystem restoration globally, scaling up existing ecosystem restoration efforts, raising awareness of the importance of conservation and restoration, and building synergies. The United Nations Environment Programme (UNEP) and the Food and Agriculture Organization of the United Nations are the lead agencies implementing the UN Decade. Their role will be catalytic, facilitating collaboration between diverse stakeholders, leveraging funding and providing information (United Nations 2020).

Ecosystem restoration includes restoring converted lands back into healthy ecosystems and restoring degraded ecosystems (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2018). Restoring ecosystems increases the supply and quality of ecosystem services over time, contributing towards desired outcomes supporting national sustainable development priorities, including ending poverty, conserving biodiversity, combating climate change and improving livelihoods for everyone, everywhere (United Nations 2020).

Studies from Asia and Africa indicate that the cost of inaction in the face of land degradation is at least three times higher than the cost of action (IPBES 2018), as less developed countries are more dependent on ecosystem services for their daily supply. Of the 10 significant ecological problems associated with ecosystem degradation identified in China by Cui *et al.* (2021), decreased resource-carrying capacity is one of the most common issues. The 2018 IPBES report also showed that the net primary productivity of ecosystem biomass and agriculture is presently lower than it would have been under natural state on 23 % of the global terrestrial area, amounting to a 5 % reduction in total global net primary productivity. In this context, enhancing the essential ecosystem goods and supply services through large-scale restoration remains a high priority for most developing countries.

A recent study by Chen (2019) showed that China alone accounted for 25 % of the global net increase in leaf area between 2000 and 2017, with only 6.6 % of the global vegetated area, and human land-use management is an important driver of such greening. This is mainly thanks to key ecological restoration programmes, such as the Three-North Natural Forest and Grain for Green programmes, with significant investment from the Chinese Government. Between 2006 and 2015, 214 key ecosystem restoration technologies were recorded in China. Afforestation, soil and water conservation, and contour hedgerow systems were the best received technologies on the ground and were most often scaled up. Although there have been many ecological restoration projects in China, an ecological restoration database has not yet been established (Cui *et al.* 2021). Related good practices and lessons learned could be shared further.

There are many stakeholders involved in restoration in China. The CERN, founded in 1988 and led by the CAS, is one such stakeholder. It has conducted continuous experiments and monitoring of the hydrological, pedological, atmospheric and biological elements of typical ecosystems to meet scientific research and societal needs (Li *et al.* 2015). The CERN is committed to exploring the development paths of optimizing ecosystem structure and function while ensuring human well-being. Many ecological field stations located in vulnerable drylands were established before 1988 to meet socioeconomic needs, for example, protecting the railway from wind and sand, improving the productivity of low-yield agricultural areas and restoring vegetation (Zhao, Yu and Xu 2021). As a founding member of the International Long-Term Ecosystem Research Network, CERN's experiences of ecosystem restoration and long-term monitoring and research over the past three decades are invaluable to the world.

To address global restoration barriers to technical capacity, scientific research and public awareness, both the IPBES (2018) and the UN Decade strategy (United Nations 2020) identified pathways to strengthen the role of science, indigenous knowledge and traditional practices, apply best technical knowledge and practice, and invest in long-term research.

In this context, the UNEP-IEMP, together with Chinese scientists, complied relevant good-practice case studies on ecosystem restoration in China. The selected case studies present different vulnerable ecosystems, including deserts, degraded grasslands, sandy lands in the agriculture-pasture transition area, drylands, mountain gully areas and urban rivers. Most of these cases are based on major ecosystem restoration programmes initiated by the Chinese Government in the past three decades, including the Three-North Natural Forest, the Grain for Green programme and the Beijing-Tianjin Sandstorm Control Programme. The cases presented have therefore been thoroughly tested and are regionally representative. Noting that restoration is site-specific and driven by the local ecological and socioeconomic context, the report provides not only specific intervention approaches and techniques and restoration outcomes but also cost-benefit analyses, related policy contexts and their potential application scope and lessons learned.

The Science and Technology Service Network Initiative contributed greatly to this report. Sponsored by the CAS, it aims to provide easy access to science-technology services for sustainable socioeconomic development through joint demonstrations and capacity-building with local communities and private sectors. Based on successful upscaling projects under this initiative, 41 ecological restoration cases in the key ecologically vulnerable regions were selected and summarized (Wang *et al.* 2019). From those 41, this report selected 10 good practices based on the representativeness of the vulnerable ecosystem types, technology transferability, scientific bases, local knowledge and buy-in and cost-effectiveness.

This report is part of the UNEP Climate, Ecosystems and Livelihoods flagship programme, which is the 10-year strategy of UNEP-IEMP aimed at improving livelihoods through ecosystem restoration and conservation for better ecosystem service delivery in a changing climate. Since this flagship programme is the major South-South cooperation initiative between the UNEP and the Chinese Government, sharing Chinese restoration experiences is a good way of promoting South-South cooperation under both the UN Decade and the UNEP Strategy for South-South and Triangular Cooperation.

This report is expected to complement the Ecosystem Restoration Playbook by providing more technical references for interventions on the ground in different ecosystem types. Since most of the cases selected are cost-effective and thoroughly tested in China, the report will guide readers on the short- and long-term benefits of restoration and stimulate more scaling up. It will also provide input for the Task Force led by the Food and Agriculture Organization of the United Nations, collating best practices on ecosystem restoration.

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Case 1. Establishing perennial artificial grassland in degraded areas

Brief Overview

Here we introduce an ecosystem management approach aimed at revitalizing degraded grasslands by sowing perennial forage species(Figure 1.1). It was developed based on extensive long-term, site-based research conducted within the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) of the CAS. This approach is applicable to areas with annual precipitation greater than 280 mm or areas with accessible groundwater, including hilly lowlands with fertile soils and sufficient precipitation suitable for planting artificial grassland and abandoned flat farmlands that can be converted to irrigated artificial grassland. This approach should be useful and of interest to those working in the grassland management and land resource sectors for further upscaling.

Figure 1.1 High-yield perennial artificial grassland in degraded areas established by IMGERS in 2000

Source: IMGERS, CAS

1. Background

In arid and semi-arid areas of China, grassland agriculture is constrained by the low productivity and degradation of natural grasslands and the limited scale and stability of artificial grassland (Bai, Pan and Xing 2016). Managing artificial grasslands is essential for restoring degraded grasslands, ensuring forage production for livestock and developing a robust local industry within pastoral areas.

In this context, the IMGERS has been developing an approach to establish perennial artificial grasslands since the early 2000s. This approach is based on niche theory, plant compensation and plant community succession theory. The model covers a series of technical solutions, including site selection and preparation, species/variety selection, sowing technique, field management and harvesting.

2. The intervention approach and implementation plan

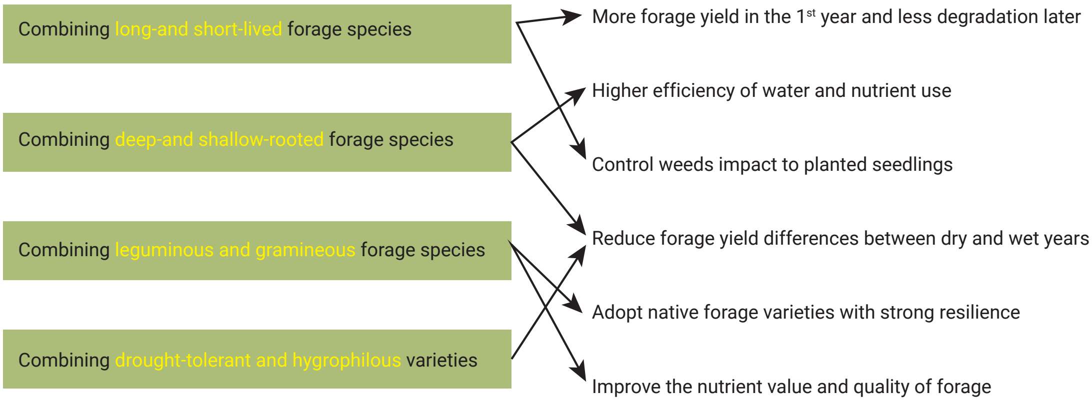
The core part of this intervention approach is the selection of perennial forage species and varieties. The four suggested combinations of species, as shown in Figure 1.2, include: 1) long- and short-lived forage species; 2) deep- and shallow-rooted forage species; 3) leguminous and gramineous forage species; and 4) drought-tolerant and hygrophilous forage species (Bai and Wang 2017).

Combining long- and short-lived forage species can make the total forage yield more sustainable. For example, we combined *Rhizome graminoid* and *Caespitose graminoid* at one plantation site. This strategy solves the key issues surrounding low grass yield in the early stages of succession and serious degradation in the later stages. The negative impacts of weeds on perennial forage species during the early planting season can be effectively controlled, and certain grass yields can be maintained in the year of sowing. As such, this enhances the sustainable utility of artificial grasslands.

Combining deep- and shallow-rooted forage species can leverage the complementary roles of different forage varieties in terms of water usage. Likewise, combing nitrogen-fixing and non-nitrogen-fixing species is known to enhance nutrient utilization. Combined, these strategies lead to the highly efficient use of both water and soil-nutrient resources and improves the overall economic benefit.

Combining drought-tolerant and hygrophilous varieties can maintain forage yield during both wet and dry

Figure 1.2 Schematic diagram of developing a perennial artificial grassland by combining diverse species



years. This enhances the stability and overall yield of artificial grasslands affected by unpredictable extreme weather.

Selecting targeted forage species and varieties makes it possible to tailor grassland species' composition to maximize species' adaptability to specific eco-environmental conditions. This strategy thus enhances drought resistance and overwintering survival rates and helps to avoid ecological disasters induced by alien species invasions and extreme weather.

Besides species selection, applying different management practices is also crucial to establishing artificial grasslands cost-effectively and for improving forage quality and utilization rate(Figure 1.3). Advisable management practices include compaction during the sowing process, precise fertilizer and water application, weeding and pest control during the ploughing stage, mechanized mowing and grass compacting and microbial fermentation during harvesting. The appropriate sowing period should be determined according to climatic conditions and soil moisture. The sowing period for typical grassland areas in Inner Mongolia is generally from June to July (Li *et al.* 2000). The sowing depth is generally 2–3 cm, but it can be slightly deeper, reaching about 3–5 cm for large seeds.

In our experiment in 2015 in the Wulagai Management Area of Inner Mongolia, we sowed different varieties of annual and perennial forages using the above-mentioned methods to establish a perennial artificial grassland of both leguminous and gramineous forage species. A precision sowing machine was used with a sowing row spacing of 20 cm and a sowing depth of 4–5 cm. Fertilizer ($N:P_2O_5:K_2O$=12:18:15) was applied at 300 kg/ha. Three planting options were used in this experiment: Option 1 – *Avena nuda L. and Vicia sativa L.*; Option 2 – *Avena nuda L., Elymus nutans Griseb., Bromus inermis Leyss., Leymus chinensis (Trin.) Tzvel* and *Medicago sativa Linn. (Aohan);* and Option 3 – millet, *Elymus nutans Griseb., Bromus inermis Leyss., Leymus chinensis (Trin.) Tzvel and Medicago lupulina L.*

Additional fertilizer was applied during the rainy season, which coincided with rapid plant growth. Grasses were then harvested using mowing and grass-compacting machinery, with stems and leaves dried synchronously.

Figure 1.3 Demonstration management practices of perennial artificial grassland in degraded areas in Wulagai Management Area, Inner Mongolia

Source: IMGERS, CAS

3. Restoration outcomes

Since 2000, this approach has been expanded across Xilingol in Inner Mongolia, and both local herders and local governments have fully recognized its beneficial effects(Figure 1.4).

Since 2015, this approach has been used in abandoned farmlands in the Wulagai Management Area of Inner Mongolia within a 1,200 mu[1] (80 ha) grassland. In the first year of sowing during the experiment, the yield of Option 1 was highest, while perennial grasses in Options 2 and 3 germinated late in the first year after sowing, and the plants grew more slowly. This affected their overall yield in the first year. The yield of natural grasslands in the Wulagai Management Area was about 185 kg/mu (2,775 kg/ha), and the yield of the three artificial grasslands after the second year reached 336–800 kg/mu (5,040–12,000 kg/ha), which was 1.8–4.3 times that of the natural grasslands. Together, we found that such artificial grassland can increase grassland production and enhance ecosystem functions.

Our results showed that after applying this management approach, forage yield increases by 5–10 times that of natural grasslands. Furthermore, such approaches can lead to forage yield that is 10–20 times greater than that of degraded grasslands and about 50 times that of severely desertified grasslands (Du 2006). This means that planting one hectare of artificial high-yield grassland with mixed sowing can help restore 10 hectares of degraded grasslands and 50 hectares of severely desertified grassland. Compared with the single sowing of one forage species, the combined sowing of four species can significantly improve ecosystem resilience and, in turn, enhance the yield of artificial grasslands. Where late spring frost occurs, the overwinter survival rate of single-species artificial grassland is very low. Our demonstration sites with mixed species showed much higher survival rates.

From a gender perspective, this practice had positive impacts on women. With ecosystem restoration, both men and women received positive health and economic benefits. With established perennial artificial grasslands using standardized machinery, women should be less exposed to unfavourable outdoor working conditions and able to turn more to intensive indoor animal husbandry work.

4. Demonstration and upscaling

Since 2015, this mixed-planting approach for perennial artificial grassland has been promoted and demonstrated on a large scale in several counties of Xilingol, including the Wulagai Management Area, Xiwu and Zhenglan, with a total area of more than 2,000 mu (133 ha).

Figure 1.4 Restored landscape through perennial artificial grassland in Inner Mongolia

Source: IMGERS, CAS

[1] Mu is a traditional unit of land area in China. 15 mu =1 hectare.

5. Estimate of investment and investment payback period

The initial investment, annual forage yield and net income in the second year for Options 1, 2 and 3 are shown in Table 1.1, based on the average market price of hay (1.2 CNY/kg) in recent years.

This indicates that the perennial mixed-sowing option can generate a better income and provide high-quality forage while ensuring more sustainable grassland management practices. It is expected that the investment for Options 1 and 2 will be paid back in 1–2 years.

Table 1.1 Investment and income in the second year of the three perennial mixed-sowing options (Unit: CNY/mu)

	Option 1	Option 2	Option 3
Initial investment	285	250	236
Forage yield incomes	528	396	240
Annual net incomes	243	146	4

6. Challenges and potential issues

Although the yield of artificial grasslands was high, the production sustainability for different annual precipitations remains unclear. In addition, the increased yield is based on a greater nutrient and water uptake. This needs to be studied in more detail from the perspective of water and nutrient cycling. Understanding how to maintain the soil fertility and long-term production of artificial grasslands is thus an important area of future research and debate.

There are three main potential technical issues for scaling up such practices. Firstly, we need to determine a reasonable ratio of artificial grassland according to the overall habitat of grassland areas to meet the regional development requirement while conserving the remaining natural grassland. Secondly, the science-based design of artificial grassland according to the water and heat supply can ensure its long-term sustainability. Last but not least, the local community must transform their behaviour from a traditional animal husbandry model to a more intensive model (Bai, Pan and Xing 2016).

7. Prospects for commercial transformation and promotion of findings

Our study shows that planting 10 % of an area with artificial grassland can ensure the conservation of the remaining 90 % of natural grassland (Bai, Pan and Xing 2016). The approach discussed above can be used at a large scale in the northern grassland areas of China, where it proved to be cost-effective. Our study, based a 24-year experiment on Inner Mongolia grassland, showed that undisturbed mature steppe ecosystems seem to culminate with high biodiversity, productivity and ecosystem stability concurrently (Bai *et al.* 2004). Establishing perennial artificial grassland provides an effective means to balance the trade-off between ecological functions and development concerns in northern grassland areas of China.

Because these areas are typical of many grassland regions across the globe, these findings have broad implications outside of northern China. As such, they have already attracted the attention of government bodies and practitioners interested in sustaining such grassland ecosystems.

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Case 2. A rotational mowing system for natural grasslands

Brief Overview

This chapter aims to introduce a more sustainable rotational mowing system for managing regularly mowed natural grassland ecosystems. The sustainable mowing system involves rotationally reserving some grassland areas to conserve nutrients, water and a seed bank. It was developed based on extensive site-based research conducted by the IMGERS. This management approach specifically applies to mowed natural grasslands in semi-arid, semi-humid and humid areas of Inner Mongolia, China. However, our results are likely applicable to other similar ecosystems with the following conditions 1) generally flat terrain with a slope of less than 15°; 2) land that is free of stones and shrubs, 3) experiences with mechanized operations such as mowing; and 4) an average grass height of at least 35 cm and overall coverage of no less than 50 %. Ecosystems that do not meet these criteria are likely not suitable for mechanical harvesting, or it would not be cost-effective to do so. This approach should be useful and of interest to those working in grassland and land resources management sectors for upscaling.

Figure 2.1. Rotational mowing approach in Wulagai Management Area, Inner Mongolia, China.

Source: IMGERS, CAS

1. Background

Inner Mongolia has 87 million ha of natural grassland that makes up a large part of the Eurasian Steppe — the largest contiguous biome in the world (Wu and Loucks 1992). Significant increases in the numbers of livestock and pastoralist households (11- and 9-fold, respectively) over the past 60 years have caused variously degradation in the majority of grasslands in Inner Mongolia (78 million ha), jeopardizing the livelihoods of 24 million human inhabitants (Briske *et al*. 2015). Apart from grazing, clipping is another management practice commonly used by local inhabitants for haymaking (Zhong *et al*. 2017). Haymaking areas are in relatively good condition due to grazing exclusion but are facing a continuous loss of nutrients in the harvested biomass (Schönbach *et al*. 2011).

In the study region in the Wulagai Management Area in Inner Mongolia, mowing is generally conducted yearly, which removes nutrients without effectively replacing them. This destroys the balance of nutrients and causes grassland degradation. Yearly mowing also affects the density of seeds in the soil seed bank and reduces the number of viable seeds. Leaving certain grasslands free from mowing in a rotational management system helps preserve water (or snow in winter) and the seed bank. Furthermore, during rotational mowing, fertilization can be applied to supplement soil nutrient loss, which will help promote the long-term sustainability of these systems.

2. The intervention approach and implementation plan

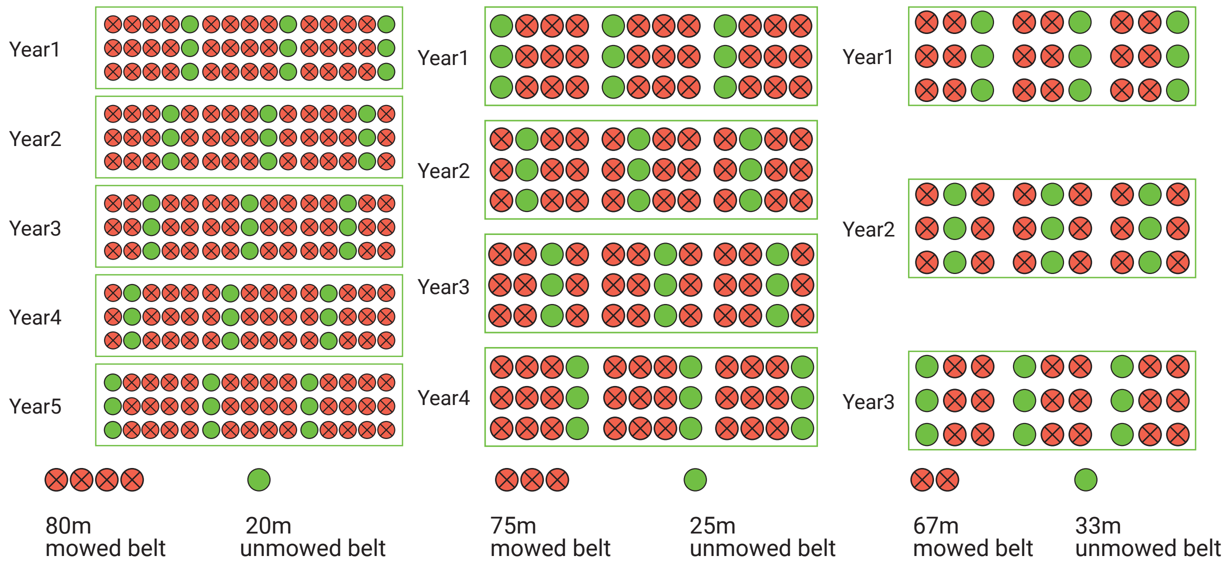
This intervention mainly referred to the Technical Regulation For Rotational Mowing On Natural Grassland (GB/T 27515-2011) released by the Chinese Government in 2011. A rotational mowing system was applied in the Wulagai Management Area in Inner Mongolia in 2016. Two natural grasslands were selected for mowing treatments, each with an area of about 33 ha.

The suggested width of the unmowed grass area is 15–30 m. This allows for convenient mechanized operations and the effective ecological conservation of nutrients, water and viable seeds rotationally. The direction of mowing should be perpendicular to the prevailing wind direction in winter. This strategy is conducive to spreading the snow and seeds, so the mowed grassland will benefit from the accumulated snow and preserve the seed bank of the unmowed areas.

In our theory for designing this intervention, the exact width of the grass belt is determined according to the intended term of the management plan, as shown in Figure 2.2. The planned term (for example, N years) for one rotational management cycle determines the percentage for conservation (1/N for unmowed areas and (N-1)/N for mowed areas) each year. For example, for a 5-year rotational management cycle experiment covering 100 metres, the mowing belt width should be 80 metres and the unmowed restoration rotation belt width 20 metres. This means that each 1/5 of the grassland would have one year of conservation in the 5-year rotational cycle.

The residual stubble height (vegetation height after

Figure 2.2. Schematic of the rotational management strategy in grasslands



clipping) is the most direct indicator of mowing intensity. Stubble heights during harvesting affect forage yield and quality, regeneration and overwintering survival rate. In hay production, yield is often hindered due to relatively high stubble. However, too short stubble often leads to the root crowns freezing in northern areas of China, which results in a decrease in the overwinter survival rate the following year, incurring huge economic losses. In our study, the suggested suitable residual stubble height of warm grasslands, lowland meadows and swamps, and mowed grasslands is suggested to be no less than 12 cm, 9 cm and 7 cm, respectively.

The suggested mowing time varies according to the climate characteristics of different regions, as well as the structure of the grassland community. For example, mowed grasslands containing *Stipa capillata* as the dominant species should be mowed before the formation of awns, while *Artemisia sp.*-dominated grasslands should be mowed after the first frost. At the latest, mowing should occur one month before the end of the growing season.

3. Restoration outcomes

Our experiments in recent years have shown that snow thickness in the unmowed belt reached 19.2–22.5 cm, which was 2–2.5 times that of the mowed belt. In addition, the average soil moisture of the unmowed belt in spring was 23.6 %, compared with 15.15 % in the mowed belt.

A similar long-term study between 2003 and 2011 at the IMGERS showed that, during the growing season, as compared to unmowed plots, mowed grassland's soil moisture was 47.5 % lower (Shao *et al.* 2012). The heavily mowed plots' soil surface temperature was 7.4 °C higher at midday and 2.2 °C lower at predawn, with a 4.2 °C greater diurnal soil temperature range at 2 cm depth compared to the unmowed plots (Shao *et al.* 2012). The absence of mowing might alleviate the stress of high temperatures and drought during the hot and dry periods, leading to vegetation that is highly resistant to environmental changes.

Another six-year (2012–2018) field experiment examined the responses of soil seed banks and plant communities to an annual mowing system at the Inner Mongolia grassland. Investigating seed richness at 0–10 cm depth soil showed that compared to a no-mow approach, the mowing practice suppressed 0.4 species and forb seed density by 208.0 m^{-2} and plant cover by 11.5 % (Miao *et al.* 2020).

4. Demonstration and upscaling

Between 2016 and 2019, rotational mowing was implemented in the Wulagai Management Area, in a total area of about 66 ha. This strategy is applicable to many managed natural grasslands in the central and eastern parts of Inner Mongolia and beyond.

5. Estimation of investment and investment payback cycle

Since this is a management practice adjustment, there is no additional investment. Instead, there is a slight decrease in mechanized operations and labour costs. However, this also decreases herder income and provides less forage production in the short term. When fertilizer is applied during mowing, the additional cost is around 750 CNY/ha. Due to the short-term nature of this study, there is no data for a long-term cost-benefit analysis. It is estimated that herders' income will increase after one rotational cycle (3-5 years).

6. Challenges and potential issues

One of the potential issues for upscaling lies in how herders perceive trade-offs between the short- and long-term benefits of rotational mowing. This approach will increase the total and average per unit forage yield in the long term. However, in the short term, income will likely decrease due to reduced harvesting from unmowed belts. Still, further experiments are required to test the effectiveness of rotational mowing operations under a variety of ecological conditions. To do this, the government or local civil societies need to establish a management mechanism (such as an eco-payment and monitoring system) in the early stages of such projects to supplement the incomes of local herders, as well as develop awareness and capacity for such implementation.

Sharing new knowledge with both women and men and building their capacities in improved management of grasslands are critical ingredients in driving environmental sustainability and livelihood improvements. The entire local community is expected to benefit from this intervention in the longer term.

7. Prospects for commercial transformation and promotion of findings

According to the official website of the Inner Mongolian Government, the total area of mowed natural grasslands in Xilingol in 2018 was 2.23 million ha, accounting for 67.1 % of the total area of mowed grasslands. The unmowed belts reserved for restoration covered 63,600 ha, an increase of 25,800 ha compared to 2017. This accounts for only 4.25 % of the actual mowed grassland area. Despite these improvements, the proportion of restoration rotation belts in mowed grasslands remains low. Therefore, significant areas of growth remain for promoting this approach throughout Inner Mongolia.

Between 2018 and 2021, some counties in Inner Mongolia released government regulations for natural grassland management, requiring 20–25 % of an area to be reserved rotationally or at least 7 % area reserved for seed banks if grassland habitat does not allow restricted rotational mowing. This regulation is supported by the government monitoring system and payment for the ecosystem service programme, allowing for better up-scaling our intervention within Inner Mongolia.

By referring to the Chinese National Technical Regulation For Rotational Mowing On Natural Grassland (GB/T 27515-2011), this approach could also be applied elsewhere.

Further information	
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Case 3. Restoration of degraded grassland using biophysical methods

Brief Overview

This chapter introduces a grassland restoration practice using biophysical methods in the Hunshandake sandy region in China. It was developed by the IMGERS based on over 20 years of research and experiments. The interventions were based on the different land types (etching pits, steep and gentle slopes, inter-dune flat lands and lowlands). They introduced issue-based comprehensive restoration approaches, such as engineering measures, physical sand barriers, planting and natural restoration(Fig. 3.1). This approach was upscaled through public and private partnerships by engaging multiple stakeholders. This can be used as a reference by the grassland management sectors.

Figure 3.1 Comparison of changes before the restoration in 2015 (a,b,c) and after the restoration in 2016(d,e,f), in 2018(g,h,i) and 2019(j,k,l)

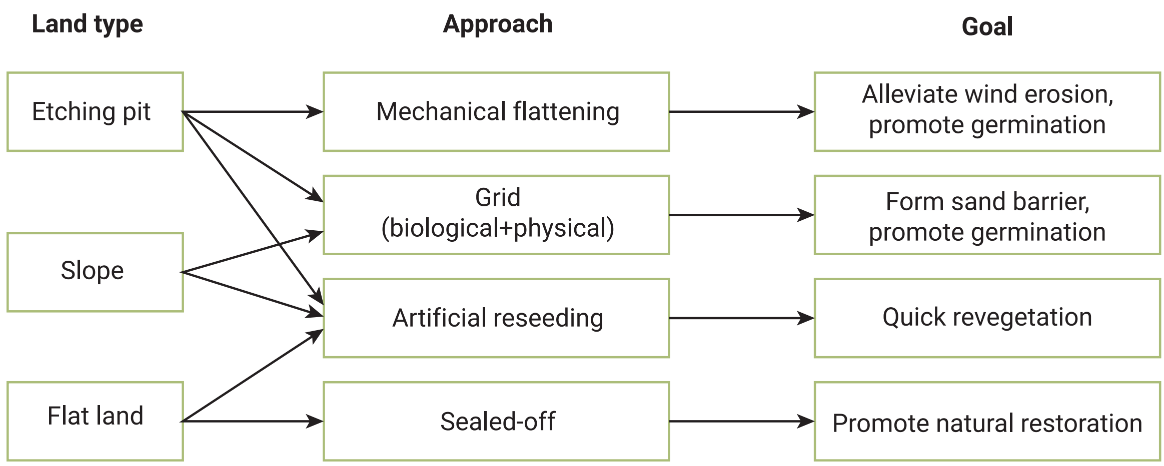
Source: IMGERS, CAS

1. Background

China has a grassland area of nearly 4 million km², approximately 41.7 % of the total terrestrial land mass, 3.2 times that of domestic cropland, and 2.5 times that of domestic forest (Du 2006). Ninety per cent of that grassland area is showing some form of deterioration, and 60% of that is facing severe deterioration (Akiyama and Kawamura 2007). This potentially affects 400 million people, and the direct economic loss is estimated at 54 billion CNY per annum (Akiyama and Kawamura 2007). For centuries, the rangelands of northern China have provided forage for livestock, but they are also facing degradation. Anthropogenic activities, particularly those caused by unfit rangeland management policies and outdated management practices, on top of arid climatic conditions, have been the major causes of rangeland deterioration in arid areas of Northern China.

Due to the ecological challenges facing the Chinese pasture industry, the CAS set up the IMGERS in 1979 to explore sustainable rangeland development and management schemes. The IMGERS sits in the Xilin river basin, a representative temperate grassland in China. The IMGERS is a crucial CERN station and has dedicated the last 40 years to studying key issues vital to national and global ecosystem development. Many of its research findings have been successfully adopted in rangeland conservation and have seen both ecological and economic benefits.

Figure 3.2 Restoration procedures carried out for various land types in the Hunshandake sandy region



2. The intervention approach, implementation plan and restoration outcomes

One such example is a rangeland recovery programme carried out in the Hunshandake sandy region. The Hunshandake region is in the central part of Inner Mongolia. Occupying an area of 52,000 km^2 with an average elevation of 1,100 m, it is one of the 10 largest sandy lands in China and the nearest to the nation's capital. Studies in the Hunshandake region showed that the dunes and etching pits constitute approximately one-third of the total area and require active restoration. The remaining two-thirds consist of inter-dune flat lands and lowlands, where some vegetation is still intact, and the soil seed bank has been partly preserved. These land types can be treated with prohibited or intermittent grazing procedures, utilizing natural succession to recover vegetation. After an extended period of research, a management scheme was implemented in the region in 2015 that can be described as one-third active management, two-thirds sealed-off natural restoration, which was very effective (Fig. 3.1).

The overall intervention approach based on the different land types is shown in Figure 3.2. Firstly, the active management of etching pits involves flattening them using engineering measures (Fig. 3.3) and then creating physical sand barriers combined with revegetation. The physical barriers were made using *Phragmites communis* reed straws buried in the ground in diamond formations. Mixed annual and perennial, deep- and shallow-rooted seeds were used for revegetation. The annual/perennial combination matches fast revegetation with subsequent long-term colonization, while the deep/shallow-root combination matches varied water requirement levels to minimize risk from drought. Restoration procedures have proven useful just one year after implementation (Fig. 3.1, Fig. 3.3).

Figure 3.3 Flattening of etching pits using engineering measures (Source: IMGERS, CAS)

Source: IMGERS, CAS

Secondly, for steep slopes, physical sand barriers were fixed to the ground, in which mixed vegetation was planted (Fig. 3.4). Additional fixture was needed in extremely windy seasons to prevent erosion. For gentle slopes, biological sand barriers were created using shrubs such as desert willow (*Salix psammophila*), *Hedysarum laeve* and sand sagebrush (*Artemisia desertorum*). Mixed vegetation was planted inside the barriers with reed straws fixed on top to block the excessive wind. Restoration of these land types also proved useful after one year (Fig. 3.1, Fig. 3.4, and Fig 3.5).

Thirdly, sealed-off or fenced natural restoration was applied to the inter-dune flat lands and lowlands, which emphasizes the self-colonizing abilities of the surviving seed and vegetation. Additional re-seeding was done in areas with suboptimal vegetation. Visible changes in vegetation coverage could be seen in 4 years (Fig. 3.1).

Results indicate that within three years of the restoration practices, terrains with etching pits and movable sand dunes were noticeably improved. Adding subsequent self-sustaining vegetation after the initial treatment successfully maintained ground cover.

After two years of restoration, the vegetation recovery was highly successful in the project areas. Even during the 2016 drought, these areas still demonstrated abundant vegetation. Aside from the ecological benefits, these restoration trials provide empirical evidence and data for the nation's restoration projects in other rangelands and sandy-regions. Prominent government officials at various levels have visited on many occasions to see the restoration results and have spoken highly of the project.

3. Demonstration and upscaling

In 2015, the dedicated research team in the IMGERS initiated the experimental "1/3 restoration and 2/3 recovery" programme. The initial trial area covered 15,000 ha in the Hunshandake sandy region where the IMGERS was located. Following this successful demonstration, the IMGERS continued cooperating with the Inner Mongolia M-Grass Ecology and Environment Company and the Wulagai regional government – the Xilingol League of Inner Mongolia – to restore degenerated grassland in Xilingol, adapting the restoration programme to more than 2,000 ha of sandy land. The restoration programme was supported by the Ministry of Science and Technology of China (under the Comprehensive Restoration of Desertification Area project, 2012BAD16B00). The IMGERS supervised the execution of the subproject rangeland recovery programme in the Hunshandake sandy region. Based on the programme, the IMGERS has been able to duplicate the recovery practice in multiple counties in Xilingol.

The local government/league and the herders were the most important stakeholders in the restoration programme. Throughout the restoration project, the project management team leased rangeland from the local herders to ensure their basic interests. Meanwhile, the project team offered labour contracts, management opportunities and technology training

Figure 3.4 Conditions of steep slopes before (left) and after (right) restoration

Source: IMGERS, CAS

Figure 3.5 Conditions of gentle slopes before (near) and after (far) restoration (Source: IMGERS, CAS)

Source: IMGERS, CAS

to the local community, building up local capacities and ensuring their continuous participation in the restoration process. The IMGERS cooperated closely with the Inner Mongolia M-Grass Ecology and Environment Company in research and technology transfer, and was further enabled by the company's human resources and rangeland management experiences. The local government also has a strong interest in ecological restoration and the development of a green economy. The combined effort of these relevant parties made the deteriorated grassland restoration project in Xilingol possible.

4. Challenges and potential issues

The most prominent obstacle the restoration project faced was the technological adjustment of the revegetation practices to accommodate different conditions in different areas. For example, desert willow branches initially had very low survival rates and caused problems when constructing sand barriers. The IMGERS conducted extensive greenhouse rooting and winter-storage experiments to improve its field-survival rate. A continuous and large-scale restoration effort would require large quantities of desert willow branches, but the current mass harvest based on cutting and subsequent transplantation may have unfavourable effects on the ecosystem. The IMGERS has started experimenting with tissue culture techniques to achieve large-scale desert willow production and alleviate detrimental impacts on the ecosystem.

Another lesson learned from the restoration practices is that subsequent protection and management are just as important as the initial construction, especially in cases of desertification where continuous deterioration is of concern.

5. Prospects for commercial transformation and promotion of findings

The sandy-area restoration project demonstrated in the Hunshandake region is not only successful in controlling desertification processes but also highly economically efficient as it relies heavily on natural succession and less on human input. The idea of utilizing ecological niche theory and biological complementation to generate ground vegetation that relies on semi-natural succession considerably benefits on-site ecological restoration and enhances the vegetative community's stability and resilience to negative disturbances. The core principle behind the restoration process can be turned into site-specific restoration practices suitable for regional requirements.

Although the initial restoration and construction in the Hunshandake region are dependent on national and regional funds, the continued management of the sites requires little input. The on-site restoration practices are mostly performed by the local communities and industries with guidance from technological advisers. Successful restoration and prevention of desertification considerably benefits local communities, especially the livelihoods of those who rely on rangeland productivity, such as herders and livestock industries. The continuous participation of local stakeholders is thus guaranteed.

Ensuring that economic benefits reach both local women and men is crucial. Empowering women through related restoration activities ensures that they are included in productive work, further reducing the gender gap and leading to progress towards environmental sustainability.

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Case 4. Natural regeneration of sandy lands at the ecological transition zone

Brief Overview

In this chapter, we introduce an ecosystem management approach to develop human-assisted natural regeneration in degraded sandy lands while enhancing local alternative livelihoods with livestock farms in the semi-arid and arid areas of an ecological transition zone. The local Forestry Bureau in Inner Mongolia, China, developed this approach based on long-term local traditional practices and long-term research in the Mu Us Desert, China. The approach is applicable to both degraded arid and semi-arid ecozones that utilize irrigation for agricultural and livestock development. This ecosystem management approach should be useful and of interest to those working in the agriculture, forestry and livestock sectors.

Figure 4.1. Before-after comparison of natural regeneration with fencing in the Mu Us Desert

Source: Forestry Bureau in Inner Mongolia, China

1. Background

Located in the transitional zone between agricultural farming and animal grazing in the southern Ordos Plateau, the Maowusu Sandy Land (Mu Us Desert) is bordered by the Kubuqi (Hobq) Desert to the north and the Yellow River to the east and west. It is one of 12 major dune fields in northern China and belongs to the 'sandy lands', with an area of 32,100 km^2 (Yang, Li and Conacher 2012). Research shows that a total of 1,680 km^2 of sandy lands affected by desertification were managed during 1990–2017 in the Mu Us Desert. This can be divided into three stages of desertification: development (1990–2000), rapid reversal (2000–2010), and stable reversal (2010–2017) (Han *et al.* 2020). The environmental protection policies and human efforts designed to prevent and control desertification, together with the warmer and dryer climate, played an important role in reversing desertification (Han *et al.* 2020).

Our study area Wushen is part of the hinterlands of the Mu Us Desert, with climate shifts across an arid/semi-arid/humid region. The natural vegetation is dominated by sand-tolerant plants, such as *Artemisia ordosica*. Due to the combined impacts of climate change and overgrazing, the natural vegetation is significantly degraded. Our approach is part of the restoration efforts in the Mu Us Desert aimed at addressing grassland degradation. The approach used primarily involves hillside (i.e. sandy land) fencing and grazing prohibition, supplemented by some grassland restoration measures, with the aim of restoring the overall grassland vegetation. Meanwhile, livestock rearing is enhanced through vegetation restoration.

2. The intervention approach and implementation plan

This approach is composed of four steps: (1) site selection for natural restoration by fencing; (2) fencing methods; (3) measures for natural regeneration and afforestation; and (4) developing alternative livelihoods.

Step 1. Selection of plots for fencing: To ensure effective nature restoration, the site must have a certain capacity for natural regeneration. Plots with more than 7,500 evenly distributed shrubs/ha were selected as natural restoration sites. Site conditions varied considerably, especially in terms of human disturbance, existing plant community, vegetation succession stage and soil seed bank. These factors impact natural restoration speed and results. The two major types of vegetation selected for our study were shrubs and grass with sparse shrubs.

Step 2. Fencing methods: Full fencing within the first 3–5 years of restoration is recommended, followed by semi-fencing and rotational fencing afterwards, varying according to the site conditions and natural regeneration capacity.

Step 3. Human-assisted natural regeneration and afforestation measures: Since most of the plots used for fencing hillsides are characterized by poor habitat and vegetation coverage, natural restoration will take time to make an impact. Therefore, we also introduced human-assisted measures to promote natural regeneration. Afforestation, fencing, aerial sowing, branch burying and shrub and grass planting were

Figure 4.2. Demonstration of livestock farming as an alternative livelihood in the Mu Us Desert

Source: Forestry Bureau in Inner Mongolia, China

implemented to support the overall goal of degraded land restoration.

Step 4. Developing alternative livelihoods: Great efforts were made to promote livestock farming. Forage processing sites were commonly established in high-quality grasslands and forested areas. Livestock farming, rotational grazing and seasonal grazing by ecozone are also commonly implemented in this region. In addition, the livestock structure was adjusted and optimized to increase the proportion of female livestock.

3. Restoration outcomes

After fencing the hillsides to prohibit grazing, natural regeneration soon followed, with scattered plant species spreading rapidly. This shows that fencing clearly plays a positive role in restoring vegetation and sand fixation. In the three years following the introduction of the grazing prohibition, the vegetation coverage continued to increase from 15 % to 25.2 %, 29.23 % and 31.04 %, respectively. In areas left open for grazing, vegetation coverage decreased to 13.04 %, 9.62 % and 6.89 % over the same period.

After two years of grazing prohibition, the biomass and seedling regeneration of *Salix cheilophila* increased significantly. Likewise, the average plant height and canopy width of this species increased by 135 % and 143 %, respectively. The number of one-year-old *Salix cheilophila* seedlings was nine times greater than that observed in the controlled area. Similarly, the average plant height and canopy width of *Caragana korshinskii* increased by 296 % and 143 %, respectively, and the number of one-year-old seedlings was 4.41 times greater than in the controlled area. The average plant height and canopy width of *Artemisia desertorum* increased by 81 % and 100 %, respectively. The number of one-year-old *Artemisia desertorum* seedlings was 4.5 times greater than in the control area.

The number of *Artemisia desertorum* and *Agriophyllum squarrosum* increased significantly after fencing. Similarly, *Psammochloa villosa* and *Sophora alopecuroides* grew rapidly and expanded in clusters. The density of *Agriophyllum squarrosum* individuals grew from 18 plants/m^2 to 44 plants/m^2. Likewise, the density of *Psammochloa villosa* increased from 0.29 plants/m^2 to 5.07 plants/m^2 , and the density of *Artemisia desertorum* increased from 4 plants/m^2 to 18 plants/m^2.

This intervention had a positive impact on women in the region by developing alternative livelihoods and indoor livestock farms and reducing exposure to land degradation and desertification.

4. Demonstration and upscaling

This approach was tested primarily in Wushen and was later expanded to another 3,000 ha surrounding the Mu Us Desert. In the areas where *Sabina vulgaris* and *Salix cheilophila* dominated, branches were buried to promote natural regeneration. This method was used to restore 4 ha of *Sabina vulgaris* and 45 ha of *Salix cheilophila*. Replanting of forest and artificial grasslands was carried out within good habitats (with a good water and energy supply and fertile soil). Afforestation and grass sowing were implemented in moving sandy lands at a large scale. In the past five years, 133.33 ha of afforestation, 100 ha of aerial seeding, 33.33 ha of human-assisted seeding and 120 ha of sand barriers have been undertaken.

5. Estimation of investment and investment payback period

It is estimated that the annual profit from raising one small-tailed sheep as an alternative livelihood is about 1,200 CNY ($180) for the local community for an expected initial infrastructure investment of about 400 CNY ($60) plus an annual investment for grass forage of 300 CNY ($45). This 500 CNY ($75) net profit from each small-tailed sheep can provide some incentive for local communities to adopt natural regeneration practices.

Meanwhile, for the first year, around 170,000 CNY of initial investment is required to build a medium-sized livestock farm with 100 sheep and a natural ecosystem regeneration system. To break this down, it would require 1,000 mu of grassland to support 100 small-tailed sheep. It would then cost around 100 CNY/m to construct fences in the grasslands, resulting in a total investment of 100,000 CNY. Replanting and grassland management costs 30 CNY per mu, with a total annual investment of 30,000 CNY. Additionally, about 40,000 CNY is needed to construct medium-sized livestock farms and other necessary infrastructure to support 100 sheep.

It is expected that in 2–3 years, the aforementioned investment will be paid back through the alternative livelihood of raising small-tailed sheep.

In addition, by planting *Salix cheilophila*, local farmers got government subsidies of 100 CNY/mu, and *Salix cheilophila* biomass can be sold at 160-180 CNY/t.

6. Prospects for commercial transformation and promotion of findings

The Mu Us, Kubuqi and Ulan Buh Deserts and the Yellow River Irrigation Areas are typical ecozones used for agriculture and livestock grazing. However, these ecosystems have become highly fragile due to increased human activities. Animal husbandry in the region is one of the primary income sources for farmers and herders. Fencing, grazing prohibition, assisted planting, livestock farm and livestock structural adjustment are recommended key actions. Meanwhile, some government financial support for initial investment is required. This approach is a promising prospect for sand fixation and natural restoration while improving the livelihoods of local inhabitants.

Further information	
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Case 5. Coupling agricultural crops and livestock rearing at irrigated farmlands

Brief Overview

Coupling agricultural crops and livestock was developed as an alternative approach for irrigated croplands, introducing livestock rearing to promote better resource efficiency and income. The intervention approach included two components: 1) introduce a dual-crop system of grain and grass, instead of the traditional one-crop system, together with improved grass-planting methods; 2) introduce livestock rearing to couple with the planting system and enhance one another. This approach is applicable to semi-arid, semi-humid and humid plain areas. This should be useful and of interest to those working in eco-agricultural economies, the livestock industry and a broad spectrum of land resource sectors.

Figure 5.1. Landscape in the Loess Plateau with animal husbandry surrounded by plantation

Photo source: Cong Ou

1. Background

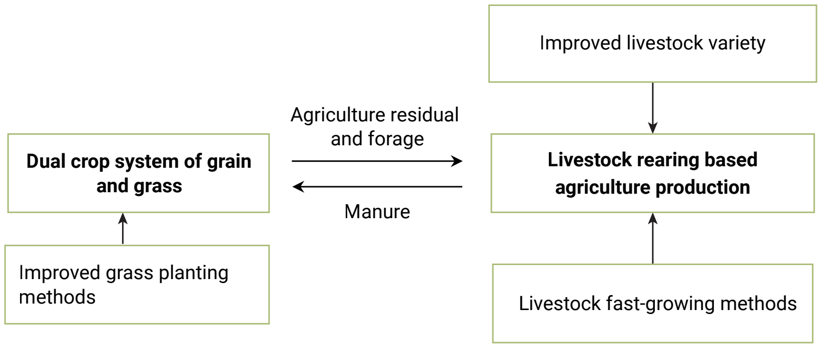
In the dryland agricultural areas of northern China, the current cropping system consists primarily of planting systems that use a single crop per year. In the winter-crop planting area, there are 90–120 days in summer when the land has no crops growing, yet it consumes 25 % of the total annual precipitation. In the spring-crop planting area, there are approximately 200 days in the winter when the land has no crops growing, yet it consumes 27 % of the total annual precipitation. This is a waste of land and water resources. Conservational tilling or soil covering practices can reduce some soil water loss, but water waste remains high.

In the context of climate warming, the northern climate-based boundaries of the double cropping system have moved significantly northward and westward in the Liaoning, Hebei, Gansu, Shaanxi and Shanxi Provinces of China (Gao *et al.* 2019). This provides more opportunities for areas of northern China to make more effective use of natural resources by adjusting their cropping systems.

Livestock production is unevenly distributed in China (Zhang *et al.* 2019). It is concentrated in a few regions, and consequently, manure-nutrient excretion exceeds the nutrient uptake capacity of local cropland in these regions. Uneven distribution of livestock production, in particular high livestock density near urban areas, may lead to a high proportion of the population being exposed to multiple pollutants in the air and watercourses (Bai 2022).

To address these issues, coupling crops and livestock management can be a practical alternative approach for the dryland agricultural areas of northern China. For example, grass can be sowed in the non-crop season for more livestock rearing, and livestock manure can be used as a crop fertilizer and feedstock for other livestock and poultry. Nutrients thus cycle between animals and plants so that they can be more adequately absorbed and utilized by the entire ecosystem. This can solve the problem of manure pollution from the livestock industry, reduce production costs and improve quality, hence increasing overall sustainability.

Figure 5.2. Coupled cycle by combining crop planting and livestock rearing



2. The intervention approach, implementation plan and restoration outcomes

Figure 5.2 shows the intervention approach used in our case study and how crop planting and livestock rearing enhance one another. The intervention approach includes two main components: 1) introducing a dual-crop system of grain and grass, instead of the traditional one-crop system, together with improved grass-planting methods; 2) introducing livestock rearing to couple with the planting system to enhance one another.

2.1 Promoting and experimenting with a dual-cropping system, and their restoration outcomes

We sought to determine the feasibility of a dual-cropping system in semi-arid areas. To do this, we examined two cropping system designs: 1) a winter wheat with a summer crop and 2) an overwintering forage with a spring sowing crop.

The first design was carried out using multiple sowings of corn, soybeans, millet and *Amaranthus spp*. in summer, following the winter-wheat harvesting. Our experiments showed that additional summer crops can significantly improve land productivity and water utilization. In particular, summer crops such as soybeans and maize can even induce an increased yield of winter wheat. Meanwhile, the dual-crop system used 28.7 mm more water than the one-crop system.

In the second design, we sowed winter-rye grass during the crop-free winter period, followed by the usual autumn-harvest crops like maize. The land productivity was up to 49.7 % higher than the maize monoculture system, while it consumed 101.5 mm more water.

2.2 Improving grass-planting methods

After three years of experiments, a set of approaches to improve grass planting was developed, consisting of the following four aspects: selecting suitable grass species, improving grass-planting methods, sowing a mix of different forage and crop species, and sowing drought-resistant species. In our studies, all these aspects resulted in higher ecosystem productivity, efficient water use, effective land resources use and more drought resilience.

Regarding suitable grass species selection, 54 herb varieties were introduced and tested. Among them, 11 species with good drought resistance, fast growth and high yield were selected after two years. Among the best-performing species, *Cichorium intybus* had the highest fresh grass yield of 77,983 kg/ha, followed by the legumes *Astragalus honghenensis* and *Onobrychis viciifolia*, which yielded 61,552 kg/ha and 30,297 kg/ha, respectively. The production of *Medicago sativa L*. ranged from 29,697 kg/ha to 21,622 kg/ha, while that of the Gramineae forage *Bromus* Dukang and *Bromus inermis L*. ranged from 25,567 kg/ha to 20,232 kg/ha.

Grass-planting methods were optimized for different topographies. For areas containing a gentle slope (≤ 10°) and abandoned farmland, it is recommended to complete ploughing in autumn, followed by planting *Medicago* on shady (north-east) slopes and *Onobrychis viciifolia* on sunny (south) slopes in spring. In the second year, the coverage of this sowed grassland can reach 100 % and a height of 60–80 cm. Fresh grass yield in this scenario can reach 37,500 kg/ha.

For grasslands on slopes steeper than 15°, it is recommended that grasses are planted according to the contour interval. We recommend digging to make a 0.8–1.0 m-wide flat area along the contour

Figure 5.3. a) chipped crop residues as forage, b) sheep fed by crop residues and planted grass

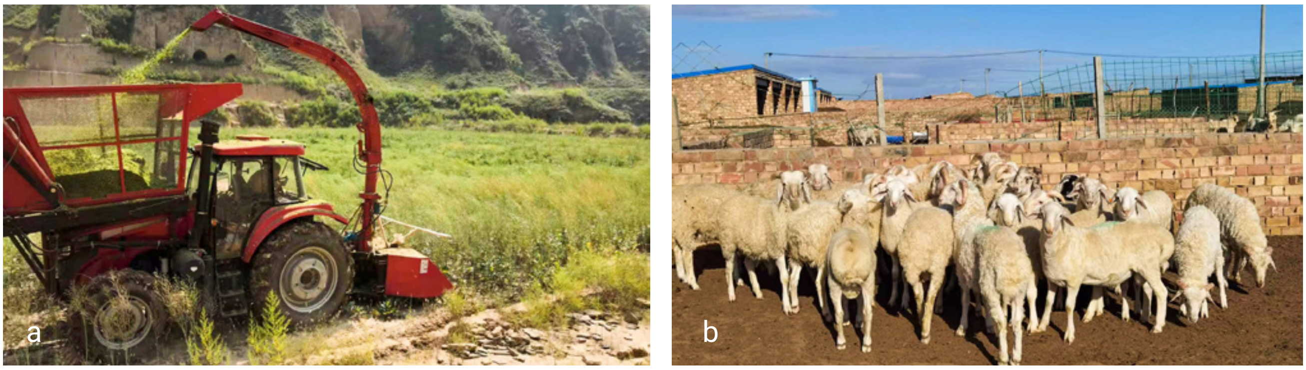


Photo source: Yurui Li

line for planting grass species in the first year, while a distance of 1.0–1.5 m should be kept in between two planting belts. For broken terrain, fish-scale pits can be dug, where seeds should be sown in the following spring. On south-facing slopes, *Astragalus adsurgens* is most commonly cultivated, while *Medicago sativa* is more common on shady slopes. This species can also be mixed with *Lespedeza bicolor* and *Caragana korshinskii*, especially if grazing is restricted for half a year after sowing. In the second year, the coverage of these grasslands was 85.2 %, with a fresh grass yield of 18,450 kg/ha.

In areas with heavy rainfall or mountainous areas with thick soil layers, grasses like *Astragalus adsurgens* can be sown during the rainy season. In the second year after sowing, the vegetation coverage rate reached 79.8 %, and 11,550 kg/ha of fresh grass was produced.

Mixed sowing of leguminous and gramineous species is recommended. Our results show that this can significantly improve the overall yield and quality of forage. The best ratio of leguminous and gramineous forages is 2:1. This strategy resulted in production 7.3 % higher than that of single sowing with one leguminous species and 74.5 % higher than that of single sowing with one gramineous species.

With regards to drought-resistant sowing, our results indicated that in dry years, mulching with straw can overcome drought-associated problems on barren slope land. For example, covering drylands dominated by *Coronilla varia* with straw can help the grass sprout three days earlier than in non-mulched barren fields and can increase the germination rate by 38 %.

This approach has been used in an area of 200 ha. Planted grasslands on original cropland can produce yields of over 37,500 kg/ha, while the yield of sowed grasslands on these original grasslands can reach 12,000-18,000 kg/ha. The crude protein content, crude fat content and crude ash contents of improved grasslands were estimated to be 13.4 %, 2.4 % and 8.3 %, respectively, which were 8.3 %, 0.2 % and 2.1 % higher than those from original grasslands. The crude fibre content was reduced by 9.1 %, and the surface run-off and land erosion were reduced by up to 21.6 % and 26.3 %, respectively.

2.3 Introducing livestock rearing to couple with the planting system

In this case-study area with a semi-arid climate, forage production is abundant in summer and falls in winter. In this context, we introduced fast-growing lambs to match with the forage production time. The main aims were to crossbreed and improve livestock varieties to increase meat productivity and shorten the livestock rearing period. This included introducing non-native sheep such as Dorset and Suffolk sheep and crossbreeding them with native sheep.

According to the physiological and nutritional needs of the livestock, two kinds of sheep-feed additives and three kinds of rabbit-feed additives were applied for experimental observation. This ensured the productivity of the livestock sector, and that the forage was consumed in a more efficient way. It also created more job opportunities for women working at home.

3. Demonstration and upscaling

This approach has been experimented with in an area of 200 ha in China, mainly within the Loess Plateau. Making full use of land resources by coupling agriculture and livestock sectors allows for integrated economic, ecological and social sustainability and promotes sustainable and stable rural development. Meanwhile, combining crops and livestock can help promote the development of community-based enterprises. Such enterprises are engaged in processing agricultural and poultry products, establishing an integrated eco-farm system and creating organic fertilizers, thus boosting the rural economy.

4. Estimate of investment and investment payback period

The following is an estimate based on a mixed crop and livestock project.

The total cost of the small-scale project was 100,000 CNY, including 33,000 CNY for purchasing calves, lambs and young medicinal earthworms; 27,000 CNY for transporting raw materials such as crop straw, fertilizers and forage; 35,000 CNY for the salaries of people engaged in agricultural production and management of forage processing etc.; and 5,000 CNY for technical training.

It is expected that in three years, such small investments at the household level will be paid back by livestock-based benefits.

5. Prospects for commercial transformation and promotion of findings

This kind of dual-cropping system can be expanded due to climate warming. The yield of the dual-cropping system is projected to increase by 11.6–86.2 % with different irrigations in northern China (Gao *et al.* 2019). With the water shortage in northern China, multiple-cropping practices that include innovative water-saving techniques and breeding technologies will need to be developed.

Recent research indicates that relocating livestock closer to croplands could increase opportunities for manure recycling and reduce the need for synthetic fertilizer, facilitating nitrogen pollution abatement and reducing the impacts of nitrogen pollution on human health (Gu 2022). Bai *et al.* (2022) demonstrated that relocating one-third of livestock in China to match the distribution of croplands would reduce manure nitrogen pollution by two-thirds and halve the number of people exposed to high NH_3 emissions from manure. Relocating two-thirds of livestock could further reduce NH_3 exposure for 90 % of the population of China (Bai *et al.* 2022). This kind of coupled livestock-cropland system has great potential to support the implementation of the United Nations Environment Assembly Resolution on Sustainable Nitrogen Management (UNEP./EA.5/Res.2). For effective implementation, a new coupled livestock-cropland system must increase agricultural productivity and farmer income by increasing the size of farm and cropping systems (Gu 2022).

From a community perspective, this approach can help guide local farmers to meet market demand and adjust their agricultural production system while increasing their income. Compared with traditional models that separate crops and livestock, this alternative approach can help improve the environment by saving fertilizer and water and optimizing overall resource allocation. In addition, the approach promotes upscaling of new technologies and products, increases local residents' incomes, nourishes community-based enterprises and establishes a favourable socioeconomic development practice. Therefore, it is an important approach for promoting the sustainable growth of the rural economy. As such, this approach provides many opportunities for both commercialization and environmental sustainability.

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Case 6. Ecological restoration in mountain gully areas for soil and water conservation and poverty reduction

Brief Overview

This case study serves to introduce an effective multi-objective tree-planting approach, mainly to improve local livelihoods and ecological function. This work is part of the Grain for Green Programme in the Loess Plateau of China, one of the largest ecological construction programmes in the world. It has been successfully applied in river valleys, plains, hilly and gully areas and soil and water conservation areas. It is recommended for similar landscape areas requiring restoration and for the agriculture, forestry, and land resources sector.

Figure 6.1. Comparison before (1990s) and after (2010s) afforestation through the Grain for Green Programme in the Loess Plateau of China

Photo source: IGSNRR, CAS

1. Background

The Loess Plateau of China, located in central China, is the largest and deepest loess deposit in the world, covering an area of 640,000 km^2 (Fu *et al.* 2017). It is characterized by a continental monsoon climate with an average annual precipitation of 400 mm, which mainly falls in July and August at relatively high intensity. Most of the plateau is located in a semi-arid zone, based on the aridity index. Its predominant sediment is loose loess. As a result of thousands of years of anthropic impact, the Loess Plateau suffers from soil erosion, land degradation, natural disasters and extreme poverty (Fu *et al.* 2017). In addition, river erosion (or flowing water erosion) makes the terrain fragmented, forming numerous gullies. Carried by flowing water, a large amount of soil has accumulated in a relatively flat area to form river valleys and plains, severely damaging the surface vegetation and ecosystems.

Given these adverse conditions and the local socioeconomic development context, we suggested this tree-planting practice to increase local greenery, improve livelihoods and reduce poverty. This tree planting is adapted to local conditions and designed to alleviate soil loss, improve ecosystem function, boost forestry development and support income increases for farmers and foresters. This endeavour is expected to achieve the goal of "identifying the land use rights related to mountains, restoring land with trees, and settling people in peace and contentment."

2. Intervention approach and implementation plan

Our interventions are based on the Grain for Green Programme in the Loess Plateau of China, which is backed strongly by government policies on afforestation and poverty reduction. Meanwhile, different research institutions, local governments and their partners work together with communities to develop and implement technical approaches and methods.

2.1 Afforestation policy for poverty reduction

In 2018, the Chinese Government issued the Work Plan of Eco-poverty Alleviation aimed at reducing rural poverty by implementing a new round of ecological construction programmes. The Grain for Green Programme, one of the largest ecological construction programmes in the world, is reconsidered and included in the workplan's tasks (Wu *et al.* 2021). This strategy is implemented through four key means used in ecological programmes for poverty reduction, including 1) payment for ecosystem restoration project participation; 2) stable wage through ecological public welfare posts; 3) income through ecological industries; and 4) income through policies such as eco-compensation, making it a more powerful policy instrument to support such practices.

Local governments implemented this kind of afforestation policy through the procurement of tree-planting services. In particular, governments formulated plans and standards, while afforestation cooperatives, 80 % of which consisted of low-income households, signed contracts for tree planting on assigned lands. Once afforestation results pass review, the Government will also procure forest management tasks in the form of social services. This promotes multi-level participatory tree planting and afforestation by low-income households and increases their income stability. The demonstration zone adopted an eco-poverty alleviation approach with five measures: returning farmland to forests, ecosystem management, ecosystem conservation, economic forest quality and productivity improvement, and forestry industry-based poverty alleviation. This enabled the forestry development to be transformed from a simple ecological endeavour to a close integration of ecological conservation and poverty alleviation.

2.2 Afforestation methods for multiple objectives

2.2.1 Multi-species selection and nursery

To meet the multiple goals of ecosystem services stability, poverty reduction and local industry development, our afforestation approach integrated these objectives through science-based species selection. The key species selected for afforestation included *Pinus sylvestris* and *Hippophae rhamnoides Linn*.

2.2.2 Prepare land for afforestation and soil and water conservation

Preparing land in advance is an important process for increasing the survival rate of vegetation and improving the habitat for young trees. In our context, combining afforestation with water and soil conservation engineering is the most synergistic approach. Specifically, we prepared land one or two quarters ahead of afforestation using two approaches, namely horizontal trenches and fish-scale pits. Practices have shown that such land preparation can accumulate water resources, increase soil moisture content and fertility, kill insect pests, reduce soil-borne diseases and improve the light and ventilation conditions of forest land.

A horizontal trench should be constructed along the contour line with the following dimensions: 0.8–1.2 m wide at the top, 0.5 m wide at the bottom, 0.6–0.7 m deep and 2–3 m long with 3–5 m spacing between the upper and lower trenches and 0.3–0.5 m spacing between the left and right trenches. Backfilling the topsoil is essential, and a soil ridge should be built around the ditch. The ridge should be 0.4 m high, 0.9 m wide at the top, and 0.8–1 m wide at the bottom before the soil is tamped.

The fish-scale pit should be 0.8 m long and 0.5–0.6 m deep, with a half-moon-shaped soil ridge built under the pits. Pits should be 2–3 m apart.

2.2.3 Seedling planting

When seedlings are planted, their young root systems are vulnerable. In order to mitigate seedling mortality, robust seedlings must be selected. High-quality seedlings that have well-developed root systems and strong drought resistance will increase the survival rate of afforestation. Seedlings should be planted shortly after lifting to reduce evaporation of water from the root system. Seedlings that have undergone temporary planting and long-distance transportation should be immersed in water for 24 hours prior to afforestation. If water loss is substantial, soaking time can be extended to 2–3 days. When seedlings are planted, the following three methods have been tested and are recommended according to the local environmental conditions.

- Planting method 1: Soil and water conservation planting

Seedlings are generally planted in spring and the rainy seasons. It is recommended to choose 3- or 4-year-old seedlings with a robust container or mycorrhizal seedlings. For example, 2-year-old seedlings are prepared with nutrient mycorrhizal soil in bags, and they may be kept for 1 to 2 growing seasons in a container before planting. When planting, ensure that seedlings are lifted, transported and planted in a coordinated way that ensures they get enough moisture. Take off the container bag immediately before planting the seedlings and ensure that the seedlings are in close contact with the nutrient soil when taken out. Planting steps include 1) digging holes in the horizontal ditch; 2) planting seedlings against the ditch wall; 3) maintaining the root system naturally; and 4) refilling the soil and treading down the earth around the root. Instead of planting a pure *Pinus sylvestris* forest, *Pinus sylvestris* and *Hippophae rhamnoides Linn* can be mixed when planting.

- Planting method 2: film mulching

Film mulching is also an effective afforestation technique to improve the survival rates of seedlings. The implementation steps are as follows: 1) cut a slit along one side of the film towards the centre; 2) make the planting hole (tree pit) into a shallow pot-bottom shape with the edge of the hole slightly lower than the ground; 3) mulch the seedlings with the film after planting to make the seedling stems pass through the centre of the film; and 4) use soil to compact the surroundings of the film and the slit. The covering soil should be about 4 cm wide and thick. The soil between the seedling stems and the mulching film should be slightly thicker (~6 cm) so that the film has no voids and vents, forming an inverted umbrella shape, which allows rainwater to flow into the seedling soil as quickly as possible. This mulching technique increases soil temperature, prevents evaporation and reduces weeds.

- Planting method 3: stem-cutting

Due to the windy, dry spring, low temperature and low lignification of the branch tips of most planted seedlings, the survival rate of newly planted seedlings is very low with high evapotranspiration and weak root functioning. Hence, we suggest stem-cutting to reduce the transpiration of the aboveground part of the trees, promote the growth of underground lateral roots and effectively improve the survival rate of plantations. The height for cutting is generally not more than 10–15 cm, and 20–30 cm is suitable for mountain apricots and mountain peaches, which is good for tree shape and early fruiting. However, this is not advised for cash tree species. For coniferous trees, especially Chinese pine, cutting stems may destroy the seedling growth tips and cause them to stop growing. Precautions for stem-cutting afforestation are: 1) do not break the stems by pulling the bark when cutting, so as not to affect germination and growth; 2) leave the soil pile around the stem and ensure stems are 2–3 cm above the ground to avoid air drying. The soil pile is removed only after new leaves break out from the soil. Alternatively, soil piles can be retained year-round, which can delay budding time and prevent herbivores from gnawing on the young trees.

2.2.4 Young forest management

To conserve all newly planted young trees, strict enclosures should be used to prevent destruction by humans and animals. While trees are young, legume pastures can be planted between the upper and lower horizontal trenches to achieve short-term benefits while improving soil fertility and promoting forest growth.

3. Restoration outcomes

These restoration practices have been continuously promoted and applied widely in the soil conservation and water storage area in Linfen's hilly and gully region of the Loess Plateau(Fig. 6.1).

Soil erosion intensity in the river valleys and plains is much less intense after these integrated interventions. Since the implementation of this approach, forests have developed in the gully areas. Forest coverage, annual precipitation and the relative humidity of the air have increased.

Low-income households were employed to implement ecological conservation measures, including 2,727 forest rangers, 2,558 ecological forest rangers and 559 young seedling guardians. To improve ecosystem management, 515 professional afforestation cooperatives have completed 307,300 mu of afforestation tasks through bidding.

4. Demonstration and upscaling

Thanks to the Grain for Green conservation programme's efforts, 46,000 mu of land was returned from farmland to forests in one year. Thus far, 365,800 mu has been afforested. Through the implementation of an economic forest quality and productivity improvement project, 103,000 mu of cash forest was realized for 2017, in addition to 198,000 mu of

Hippophae rhamnoides Linn forest transformation. The forestry industry-based poverty alleviation project focused on 210,000 mu of *Hippophae rhamnoides Linn* forest in shallow, hilly areas in 11 counties.

5. Estimate of investment and payback period

To implement tree-planting projects, the cost of labour is about 800 CNY/mu/day. Except for looking after the seedlings at the early stage, there is basically no need for further labour. Meanwhile, afforestation will help create jobs, forest coverage and economic output.

It is expected that in 5–6 years, these initial investments will be paid back by income from new livelihoods.

6. Prospects for commercial transformation and promotion of findings

This integrated approach has greatly improved the ecosystem function in the demonstration area, reduced soil erosion, increased local residents' income and established a proven approach for social and economic development. Thus, this initiative has positive prospects for commercial transformation and promotion.

In 2020, the Chinese Government released the Master Plan for National Key Ecosystem Protection and Restoration Major Projects (2021–2035), which indicated that forest coverage will increase to 26 % of the terrestrial area of China, and 56.4 million hectares of degraded land will be newly treated in the next 15 years (Sino-German Environmental Partnership II, 2020). This Master Plan provides new opportunities for government-supported restoration, as its key projects cover the main ecological regions of the Yellow River, including the ecological barrier of the Loess Plateau. Sharing knowledge and building the capacities of local men and women is considered crucial for progress towards environmental sustainability. Including women in financial initiatives will enable more empowerment for women who are heads of households.

With the national Work Plan of Eco-poverty Alleviation policy, this approach can be further upscaled in China. Scholars also suggested that eco-poverty alleviation must activate farmers' utilization of land resources in ways that are both economically effective and ecologically friendly. The following four principles were suggested to safeguard the environment and foster sustainable livelihoods; 1) reform the rural collective property rights system and ensure farmers' accessibility to land resources; 2) capitalize rural land resources by establishing national geographic signs and providing branded ecological products; 3) improve farmers' ability and skill, especially the young generation; and 4) establish a multiparty governance and benefit sharing system for the subsequent management of ecological programmes (Wu *et al.* 2021).

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Case 7. Ecological orchards in slope dryland areas of China

Brief Overview

The Loess Plateau of China is the world's largest apple-producing region, and over 80 % of the orchards are in rain-fed dryland areas (Peng *et al.* 2017). This case study was performed to introduce an ecologically sound, highly cost-effective orchard management approach in the drylands of China to overcome issues like water shortage, low yield, poor fruit quality and low cost-effectiveness. This approach has been developed and tested through the extensive practices of orchard management in China. Its application has been successful in areas with an average precipitation of 450–550 mm, and we recommend it for afforestation and for consideration by poverty alleviation sectors.

Figure 7.1. Demonstration of apple orchard with under canopy *Vulpia myuros* plantation in the Loess Plateau region

Photo sources: RCEES, CAS

1. Background

In the semi-humid regions of northern China, excessive and widespread application of nitrogen and phosphorus fertilizers in apple orchards improved apple yield and quality but intensified deep soil desiccation and restricted the stable and healthy development of the apple industry (Gong, Yan and Wang 2011). Desiccation of the deep soil layer under dryland apple orchards is the main restricting factor for apple production in such regions (Peng *et al.* 2017). Therefore, fruit production in semi-arid areas of northern China generally suffers from low yield, poor quality and low cost-effectiveness.

In the Loess Plateau of China, we developed and tested an ecological orchard management approach for drylands. Our key objectives were to increase the yield per unit area and improve the quality and cost-effectiveness. We used the following key techniques: (1) enhance herbaceous vegetation in the orchard and control evaporation by covering the soil surface and (2) adopt medium-density fruit trees and restrained pruning technology to control the quantity of fruits and branches and reduce ineffective evaporation.

Ecological orchards are defined as any sustainable development production system based on ecology and system sciences. This concept was derived from an orchard industry-driven concept but also benefits from ecological soundness, high cost-effectiveness and energy and material flow efficiency. This technique is established through the scientific allocation of plant, animal and microorganism communities through the strategic use of light, heat, water, soil, nutrients and atmospheric resources in the orchard.

2. Intervention approach and implementation plan

Building an ecological orchard begins with selecting excellent varieties and good habitats with fertile soil. To achieve this goal, we developed an integrated management approach for orchards, livestock and grassland. This strategy included improving soil fertility by expanding planting, increasing surface soil cover of grass and mulch, avoiding over-reliance on chemical fertilizers and pesticides, and using grass and livestock manure. These ecological orchards adhere to the organic pest control strategy and benefit from various agricultural, biological and integrated pest control technologies. This management strategy integrates orchard run-off management, precise fertilization, post-harvest processing for commercialization, processing and storage of fruits, water resource management and orchard and livestock management.

Key takeaways for managing an ecological orchard, as shown in Figure 7.2, include: (1) building natural grass vegetation; (2) controlling tree and branch growth; and (3) adjusting fruit tree managment.

To fully utilize existing natural weed communities, efforts should be made to increase legumes to 20–30 % of the community, using species such as *Medicago sativa* and *Lotus corniculatus* for green manure. Grass should be cut 5–7 times a year to maintain its height at ~15–20 cm year-round while retaining fallen leaves and residual grass to increase coverage.

Medium-density tree-planting strategies should be chosen to reduce the proportion of major branches as much as possible. Tree coverage of the projected area should be limited to 45–50 % at the full fruiting stage, which requires branch thinning, coring, twisting, retracting and removal. These pruning measures limit the total number of auxiliary branches to 600,000~750,000/hm^2 and the effective functional leaves to about 690,000/hm^2.

Fruit numbers should be limited to 1/30~1/40 of the total effective leaves. These care techniques are further supplemented by covering the fruit with bags, reducing leaves, turning fruits to the light and watering during periods of high water demand.

3. Restoration outcomes

3.1 Soil improvement

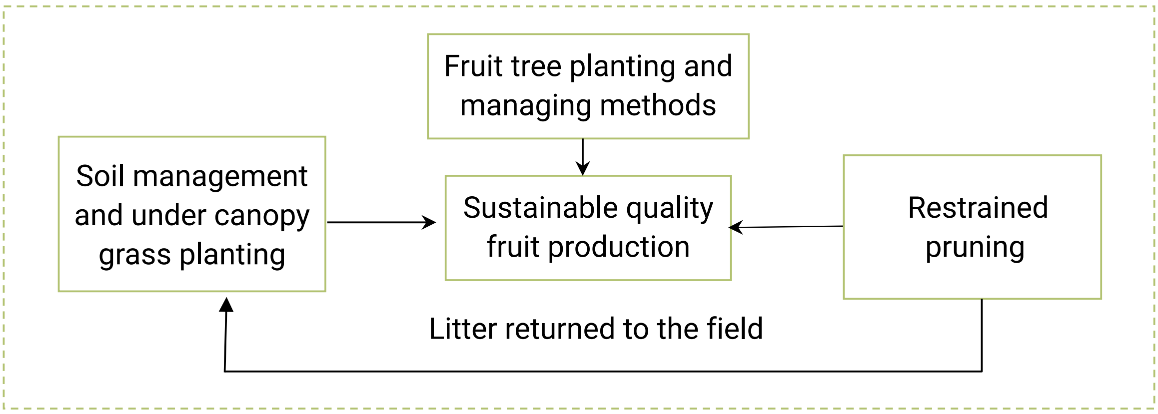
The approach outlined here improves water-use efficiency. Compared with current clean-tilled orchards, the soil's water content in grass-covered orchards was 3.5 %, 2.4 %, and 3.4 % higher at the 0–20, 20–40 and 40–60 cm soil layers, respectively. The organic matter content of the 0–40 cm soil layer was 1.28 % compared to 1.11 % in clean-tilled orchards. Total soil nitrogen was 0.013 % higher, and soil available potassium was 9.1 mg higher per 100 g of soil. The Fe, Ca and Zn contents were much higher than those in clean-tilled orchards. Soil bulk density in orchards covered with grass for four consecutive years decreased by 0.20 g/cm^3, and the pH fell from 8.4 to 8.1 compared to controls.

Compared with clean-tilled orchards, the total evapotranspiration of fruit tree leaves in grass-covered orchards decreased by 42.6–74.4 %. Tree root distribution expanded from 20–60 cm to 20–80 cm. The weight of a single fresh leaf was 0.12 g higher, and the chlorophyll content increased by 0.37 mg/g.

3.2 Improving pest control, fruit quality and income

The number of natural enemies of pests, such as *Chrysopidae* and *Coccinella septempunctata*, increased 3.7- and 2.6-fold, respectively, compared to clean-tilled orchards. In contrast, the number of pests, such as mites and aphids, decreased by 99.8 % and

Figure 7.2. Brief outline of the concept of an ecological orchard in drylands



94.7 %, respectively. The incidence of apple ring rot disease and anthracnose fell by 85.2 % and 76.8 %, respectively.

Average fruit weight (216.7 g), average fruit diameter (75.4 mm), soluble solids content of the pulp (15.2 %), total absorption degree of anthocyanin in the peel (97.4/100 cm^2), and average yield of first-class fruit (27,000 kg/ha) all showed improvements. The economic input-output ratio of the orchard covered with grass was 1:9.25, compared to 1:4.72 for a clean-tilled orchard, increasing the net income by 1,338 CNY/ha.

3.3 Soil and water conservation

Interplanting herbaceous plants in hilly orchards has obvious effects on water and soil conservation. Forage plants have a high root biomass that is widely distributed combined with a high aboveground biomass and coverage rate. For this reason, forage plants are excellent at stabilizing soils, which can effectively slow run-off velocity and prevent erosion. We planted the erect gramineous grass *Digitaria* (South Africa) on the edge of the ridge because it is good at tillering and easily forms a hedge. We sowed *Paspalum notatum*, a grape-based Gramineae, on the ridge because of its characteristic root system that effectively prevents erosion with a reduced run-off of 57-76 % (see Table 7.1).

Table 7.1. Soil and water conservation effects of interplanting forage plants in hilly orchards in the Loess Plateau region

Method of treatments	Coverage rate(%)	Depth of soil loss(mm)	Reduced soil loss depth(mm)	Reduced surface run-off(%)
Bare soil exposed	0	2.8~3.4	/	/
Grass-covered undercanopy	>80	0.92~1.12	1.88~2.28	57~76

Figure 7.2. Landscape of apple orchards in the Loess Plateau region

Photo sources: IGSNRR, CAS

3.4 Social benefits

By making full use of hilly resources, the practices presented here have improved farmers' quality of life and increased their employment opportunities. They also improved farmers' capacity, reduced the surplus rural labour force, effectively mitigated employment pressure (including jobs for women), and developed sustainable economic growth in mountainous rural areas.

4. Demonstration,upscaling and investment payback period

At present, this model is widely used in the Loess Plateau(Fig 7.2). The development of ecological orchards is promising but is also dependent on local natural conditions, climate characteristics, the buy-in of local fruit farmers, and demand for fruits locally and internationally.

It is estimated that the initial investment will be covered in 3 years.

5. Prospects for commercial transformation and promotion of findings

The Weibei Dryland Highlands of Shaanxi are a primary apple-growing region with apple orchards covering a planted area of more than 1.2 million ha (Wang, Wu and Meng 2006). In this region, more than 80 % of the orchards are rain-fed — they are not irrigated and are thus subject to severe soil water over-consumption marked by deep soil desiccation, soil impoverishment and low fertility (Peng *et al.* 2017).

The production model described here has greatly improved the ecosystem function of the demonstration area, reduced soil erosion, increased local residents' income and supported social and economic development. Therefore, it has a high potential for commercialization and improvement of major apple orchard areas with an average precipitation of 450–550 mm.

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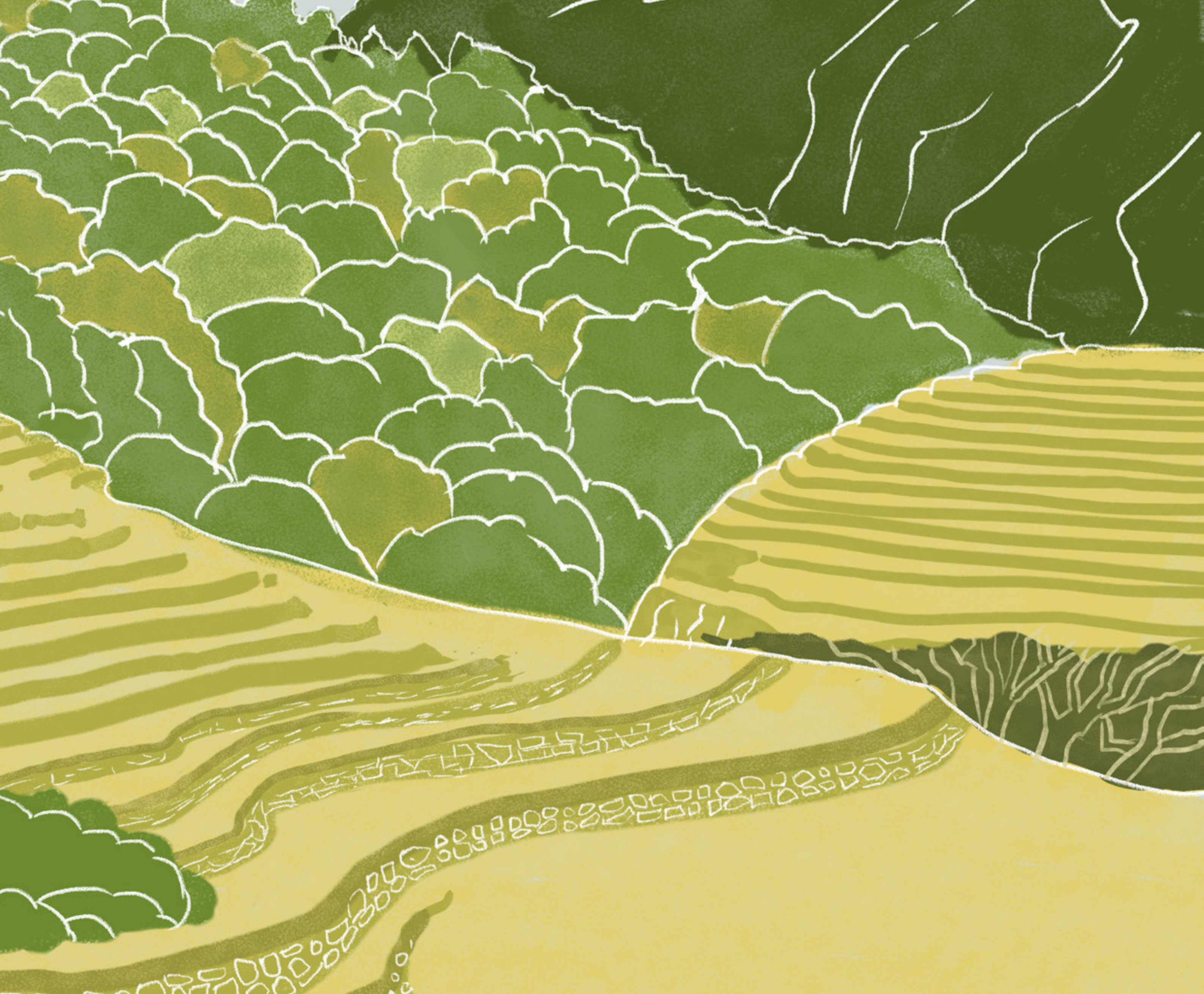


Case 8. Building stone dike terraces in rocky, mountainous areas for agriculture development

Brief Overview

For thousands of years, terracing has been one of the most important methods for preventing soil erosion, conserving water, and increasing agricultural production (Deng *et al.* 2021). China, Ethiopia, Indonesia, Italy, Japan, Nepal, Peru, the Philippines, Portugal and Switzerland, among others, have extensive terraced farmland areas (Baryla and Pierzgalski 2008). Here, we introduce an approach for building standard stone dike terraces in rocky, mountainous areas to enhance the sustainability of agricultural production. This protocol has been developed through extensive experiments in the Loess Plateau, China, over the past three decades. It is applicable to any rocky mountainous areas in the southern Gansu Province, China, and other rocky mountainous areas globally where the slope is less than 25 degrees. We recommend this protocol for sectors related to agriculture, environmental conservation and economic growth.

Figure 8.1. Slope farmland in Longnan City before comprehensive management.

Photo source: RCEES, CAS

Figure 8.2. Views of standard stone dike terraces after comprehensive management in Longnan City

Photo source: RCEES, CAS

1. Background

Terraces provide many ecosystem services, including the reduction of run-off and sediment by over 41.9 % and 52 %, respectively, the improvement of grain yields and soil moisture content by 44.8 % and 12.9 %, respectively, and the conservation of plant biodiversity on a local scale (Deng *et al.* 2021). Although terraces are considered an advisable and effective measure for soil and water conservation, poorly designed terraces can have negative effects. Wei *et al.* (2016) found that improperly designed terraced systems are even worse than no terracing at all, and terracing failures mainly result from agricultural abandonment, inappropriate design, environmental legislation and insufficient knowledge regarding design, construction and maintenance alternatives. In this context, it is important to share knowledge of and designs for building standard terrace systems for large-scale engineering projects.

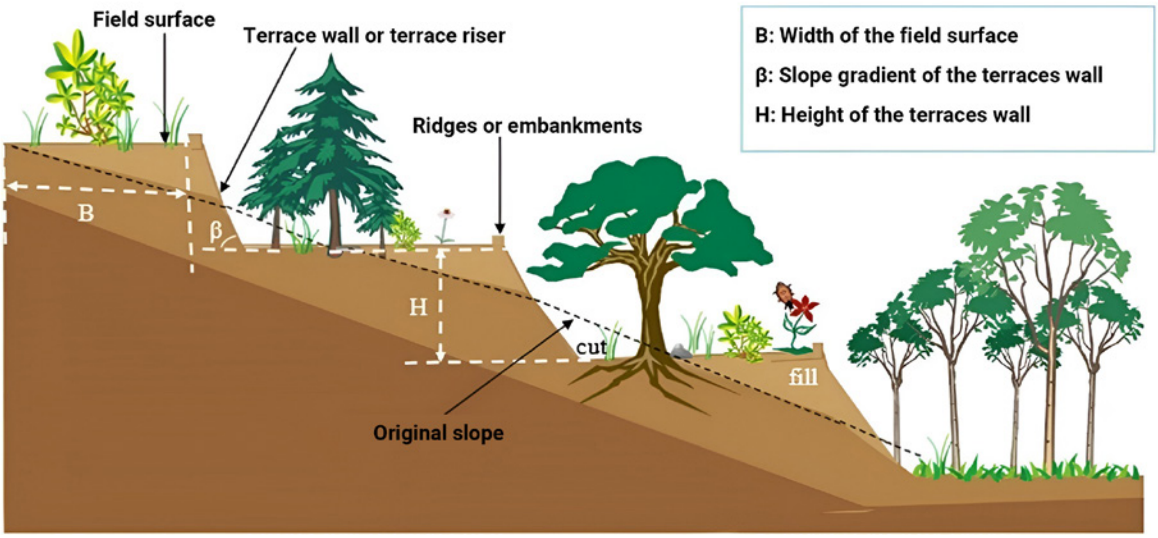
The rocky, mountainous Longnan City is in the south-western Gansu Province on the north-eastern edge of the Qinghai-Tibet Plateau, China. This area is part of the warm temperate and northern subtropical zone and exhibits an alpine and semi-arid climate with an average temperature of 6–15 °C, and 440–800 mm precipitation. Farmers are challenged by harsh natural conditions in this rocky, mountainous landscape, including frequent natural hazards (such as flooding and drought), thin and poor soil, limited productivity and sparse land connectivity. Soil erosion has been a serious issue. Terraced fields are essential for agricultural production to promote the economic and social development of the Province. Here, we built stone dike terraces using sand and gravel in local trenches accompanied by prefabricated concrete.

2. The intervention approach and implementation plan

2.1 Design of standard stone dike terraces

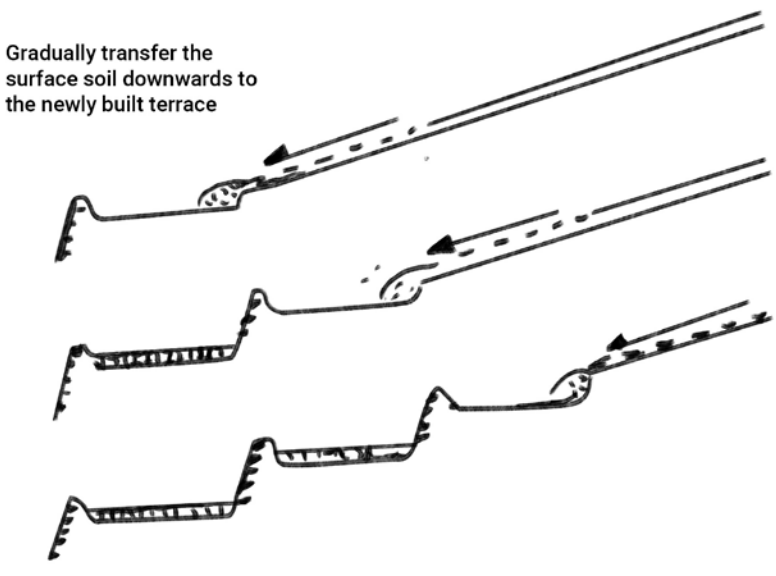
Cut-and-fill terraces are formed (see Figure 8.3). By filling areas, the arable land can be expanded, thus making it possible to grow crops on a large scale in hilly areas. The ridges or embankments play an important role in intercepting run-off and field water. But terraces are also at risk of collapse; the higher the terrace wall, the greater the risk of collapse (Deng *et al.* 2021). Note the surface soil is rolled downward to the newly built terrace, as indicated by Figure 8.4.

Figure 8.3. Sectional drawing of a terrace



Source: Deng et al. 2021

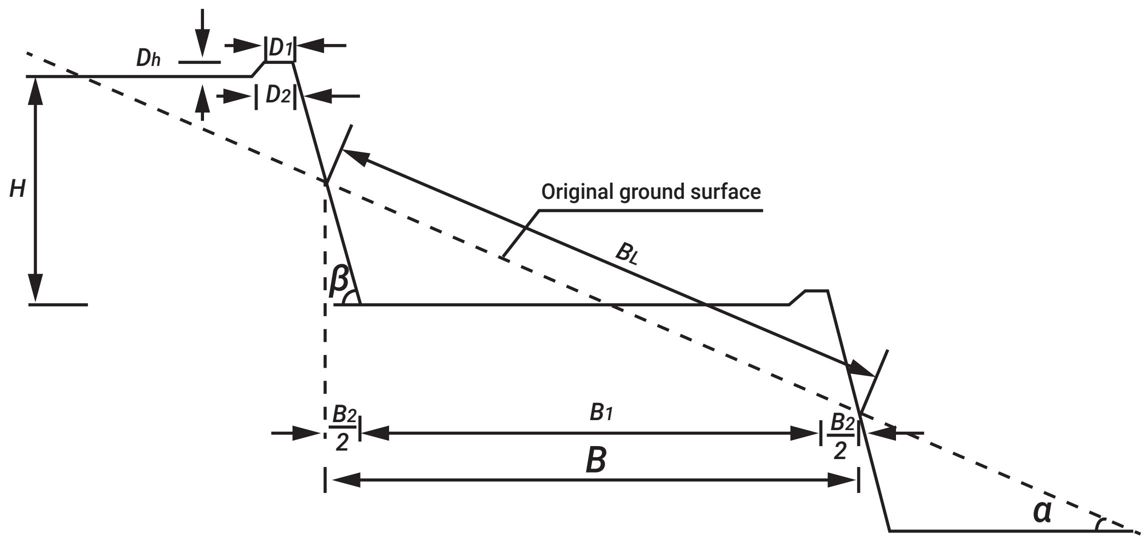
Figure 8.4. Sectional drawing of a terrace for the management of surface soil



In our demonstration site in Longnan City of Zhouqu County, we used the following design parameter standards where the mountainous field slope is no more than 25 degrees. The terraced fields are a minimum of 8 m wide and 1 mu in total area. As shown in the sectional drawing in Figure 8.5, the terrace wall height (H) is less than 3.5 m to avoid the risk of collapse, the embankment height (Dh) is 50 cm, and the embankment width (D1) is 40 cm. The outer slope of the field ridge is 65°. The terrace and embankment are built by rolling compaction, with the embankment biologically fixed.

The access road is designed to be 3 m wide, with an arch-shaped surface. After being tamped, the structure should be elevated by 0.2 m compared to the adjacent ground. The longitudinal slope of the path depends on the natural slope of the tableland surface and is generally around 1–3 %. The longitudinal road slope in mountainous regions is generally ~10 % and a maximum of 15 %. The minimum plane curve radius of the main road at the transition section should be 15 m and no less than 8 m for the internal path. The road is flanked by water ditches 0.5 m wide at the top, 0.2 m deep and 0.3 m wide at the bottom.

Figure 8.5 . Sectional drawing of the stone dike terrace design used in the demonstration site in Longnan City, Zhouqu County, China



Here α represents the original slope gradient (°); β represents the slope gradient (°) of the newly built terrace wall; H represents the height of the terrace wall (m); BL represents width of the original ground surface (m); B represents the gross width of the field surface (m); B1 represents the net width of the field surface (m); D2 represents the bottom width of the embankment (m); D1 represents the top width of the embankment (m); Dh represents the height of the embankment (m). Here $H = B_L Sin\alpha$, $B = B_L cos\alpha$, $B_2 = Hctg\beta$, $B_1 = B - B_2 = H(ctg\alpha - ctg\beta)$.

2.2 Build support systems for terraces

The support system for these dike terraces should mainly include water-intercepting ditches, drainage ditches and reservoirs. The water-intercepting ditches should mostly have a trapezoidal cross section, while the water drainage ditches and diversion canals should have rectangular cross sections. The reservoir can be closed or opened, equipped with water inlets and discharge pipes, terraced ridges etc. and is usually round or rectangular in shape. The reservoir should also have a sedimentation tank to block silt, which may be rectangular or circular depending on the terrain. The width of the reservoir should be 1.5–2.0 times the width of the ditch connected to it and at least 50 cm deeper than the ditch depth.

2.3 Transformation of low-quality terraces into standard terraces

The main issues encountered with the existing low-quality terraces were 1) narrow and uneven fields; 2) weak ridges and low utilization rates; 3) limited, poor-quality roads; and 4) improper planning of drainage ditches, reservoirs and other water storage and drainage facilities. All these issues resulted in poor resilience, reduced crop production and poor soil water control. A study by Deng *et al.* (2021) showed that as terraces age, disadvantages gradually emerge, including interference with water circulation and serious environmental problems caused by poorly designed or mismanaged terraces, where the average run-off and soil loss can be 1–5 times that of well-managed terraces. However, these low-quality terraces can be transformed by incorporating small patches into large patches, restoring field surfaces and strengthening ridges to make full use of growing areas. This transformative process provides flat fields, producing more stable ridges and simplifying operations.

Implementing this approach in the semi-arid area of the Loess Plateau supports the Grain for Green programme's objective of improving overall ecosystem health by reducing agricultural land and expanding forest and grasslands in slopes. In this context, transforming these low-quality terraces into more standard terraces maximizes yield per land unit and therefore has great value for the implementation of the Grain for Green programme.

This process also helps minimize production loss and supports stable grain production. The "dual-cropping system" approach is recommended for new terraces, in which key economic crops are planted in undisturbed topsoil, and adaptive, resilient plants are planted in the newly restructured deep soils to improve soil composition and fertility. As dual cropping is not yet common practice in this region, proper instruction and technical assistance are required to mitigate problems for local practitioners during the transition phase. These methods should also be integrated with local industries, rural area revitalization programmes and land-use transitions.

3. Restoration outcomes

3.1 Water and soil conservation

After slope farmland had been transformed into standard terraces, the run-off speed was reduced by up to 60 % under the same rainfall intensity, intercepted rainfall was 70–100 mm, 70–95 % surface run-off was intercepted, and run-off sediment content was reduced by 90–100 %. The conversion of slope farmland into terraces conserved water, reduced soil erosion and increased grain production. These effects also helped to meet national arable land red-line[2] requirements while promoting slope farmland reclamation and preventing soil erosion.

3.2 Strengthened resilience against drought and other natural disasters

Standard stone dike terraces have increased soil moisture, providing substantial protective benefits against drought and natural disasters. This is due to improved soil structure and organic matter content, which reduces surface run-off velocity, thereby alleviating flood pressure downstream. Additionally, terraces enable the redistribution of water resources to improve utilization efficiency and thus build better resilience to drought.

3.3 Enhanced regional ecosystem services

The ecological benefits of agricultural terrace construction are fourfold. From a hydrosphere perspective, the construction of terraces greatly reduces surface run-off during heavy rainfall and improves surface run-off utilization efficiency. From a pedosphere perspective, sediment loss is reduced while drought resistance, soil moisture, fertility and soil structure and health are enhanced. From an aerosphere perspective, changes in the regional temperature, humidity and light absorption help moderate the microclimate and prevent other agrometeorological hazards. From a biosphere perspective, these physical parameter improvements allow plants to grow faster and thus increase forest and grass coverage in a shorter period.

3.4 Economic benefits

The economic benefits of dike terraces include the improvement of infrastructure and support for rural agriculture development. According to the production data provided by the Wuwei Municipal Soil and Water Conservation Station and the statistics from agricultural and statistical authorities, the benefit of terraces is calculated per 1 ha terrace and other crop values are converted to wheat. Slope farmland wheat yield was 2,370 kg/ha, and terrace farmland yield was 3,300 kg/ha. The yield improvement was therefore 930 kg per hectare. Annually, terraced fields increased yield by 320.85 tons in total, improving gross output

[2] The Chinese government has a national policy where the country must retain a "red line", or minimum, of 121.2 million hectares of arable land.

value by 1,395 CNY per hectare and net output value by 1,350 CNY per hectare.

Over the course of the study, the annual net output value across the entire Liangzhou District increased by 465,800 CNY. The construction of terraces has accelerated the regional economy, helping 256 households (or about 768 people) get out of poverty.

4. Demonstration and scaling

The implementation of this project has brought considerable improvements to the infrastructure of the agricultural sector and the regional environment. We also saw increases in food production and reductions in poverty. The continued construction of terraces will help increase farmers' economic income, promote sustainable production and help people live more prosperous lives. Additionally, women are also involved in related agriculture activities and provided with favourable working conditions, promoting progress towards overall sustainability. At present, the cost-to-benefit ratio of these stone dike terraces is low due to development difficulties and high up-front investment. The time taken to recoup this investment is substantial. These terraces, however, are very promising in the rocky, mountainous areas of Longnan City.

5. Estimation of investment and investment payback period

Building terraced fields in mountainous areas using machinery requires an investment of 3750 CNY/mu, or $8395 /ha (based on the current rate of 6.7 CNY=$1).

It is estimated that it will take 40 years to get the initial investment back without government subsides.

6. Prospects for commercial transformation and promotion of findings

Arable land in Longnan rocky mountainous areas in Gansu Province is represented by 6 % standard terrace, 6 % low standard terrace, and 52 % slope or other farmland. There is still great potential for upscaling standard stone dike terraces.

Due to ample light, heat and lucrative local industries, there are local examples of planting potatoes, fully mulched corn, forests with fruit production, crops for Chinese herbal medicine and pasture on standard terraces, which could provide even greater income to local farmers.

When Wei *et al.* (2016) reviewed global terrace practices, they made a few recommendations to better manage terracing practices. First, the scientific criteria for terracing designs should be developed and followed, including the associated environmental legislations. Second, terraces need to be built in conjunction with other water recycling techniques and field treatments, such as vegetation cover and riser protection, to ensure the security of terraces, the efficiency of rainwater harvesting and land productivity. Lastly, there is an urgent need to transfer knowledge on terracing and sustainable land management from academia and policymakers to local farmers. The potential damage and risks of agricultural terraces should be better evaluated to protect the interests of both farmers and the greater watershed. Special funds and economic subsidies for terracing should be considered so farmers will manage them better, which may help with the goals of environmental protection and land sustainability.

Further information	
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Case 9. Planting desert ginseng as a new livelihood along the desert highway

Brief Overview

This case introduces our ecological restoration efforts in the second largest shifting desert in the world – the Taklamakan Desert. When we built a protective highway green belt along the Taklamakan Desert, we also brought a new livelihood through desert ginseng, a Chinese herbal medicine. These efforts and achievements are based upon the long-term applied research of the Xinjiang Institute of Ecology and Geography (XIEG), CAS, over the last few decades. Desert ginseng (*Cistanche deserticola* and *Cistanche tubulosa,* Fig. 9.1) are root parasites that live off planted shrubs (*Haloxylon ammodendron* and *Tamarix spp*.) along the highway green belt, which can provide a win-win solution with ecological and economic benefits through sustainable production and harvesting practices. This approach can be used by desertification control and desert economy development sectors and practitioners.

Figure 9.1 Irrigation of *Cistanche* – the desert ginseng – along the *Haloxylon ammodendron*

Photo source: UNEP-IEMP

1. Background

Xinjiang Uygur Autonomous Region, located in north-western China, is home to the second largest shifting desert in the world – the Taklamakan Desert. The Tarim Basin, covering the Taklamakan Desert, has a temperate desert climate with less than 50 mm of average annual precipitation. In 1995, the Tarim Desert Highway, world longest desert highway (522 km), was built throughout the Taklimakan Desert, running from north to south to transport oil and gas from its centre. This highway has also brought local communities back to the desert, who live along the highway. Protecting the highway and sustainable livelihoods in the desert have been key issues in the region.

To cost-effectively protect the highway from sand-dune encroachment, the XIEG tested 273 species of plants in a desert climate with saline water irrigation with the aim of building a green belt within the Taklimakan Desert over a few decades. *Haloxylon ammodendron*, *Tamarix spp.* and *Calligonum* were found to be the best species, surviving well in extreme environmental conditions, playing a vital role in sand fixation, controlling desertification and providing a green buffer for the highway. As a result, a green belt (Fig. 9.2) stretching for 436 km through the heart of the Taklamakan Desert was constructed over a period of 16 years from 1991 to 2006 to protect the Tarim Desert Highway (Mills *et al.* 2015).

Another issue to be addressed by the project is local sustainable livelihoods within the desert. Since 1986, the XIEG has undertaken and completed numerous long-term applied research projects with multiple stakeholders on the production of a medicinal plant, the desert ginseng (*Cistanche deserticola* and *Cistanche tubulosa*). These plants are root parasites that live off the shrubs (*Haloxylon ammodendron* and *Tamarix* spp.) along the highway green belt, which can provide a win-win solution with ecological and economic benefits if appropriately promoted. However, due to high demand for *Cistanche* and increasing prices in the early days, excessive digging resulted in a sharp decrease in the wild *Cistanche* species, their host plants *Haloxylon ammodendron* and *Tamarix* chinensis and their habitat. This long-term research is expected to be backed up by the high-yield and sustainable planting of *Cistanche deserticola* and *Cistanche tubulosa* in southern and northern Xinjiang while conserving the desert vegetation.

Meanwhile *Cistanche*, known as Rou Cong-Rong in Chinese or desert ginseng, are an endangered wild species mainly distributed in the arid lands and warm deserts of north-western China (Xu, 2009). The species has been traditionally used in China and Japan as a medicinal plant for a long time and has a huge market regionally. Research showed that the total suitable production area of *C. deserticola* in China was 675,354.9 km^2 and distributed mainly in the Alashan League of Inner Mongolia, the north-eastern Xinjiang, northern Gansu and the middle of Ningxia (Chen *et al.* 2007).

Figure 9.2 The green belt along the Tarim Desert Highway

Photo source: XIEG, CAS

2. Intervention approach and implementation plan

2.1 *Cistanche* host plantation

Both *Tamarix* and *Haloxylon* are important hosts for *Cistanche* and native species for controlling sand movement. Planting *Tamarix* and *Haloxylon* in the desert provides an opportunity to develop a *Cistanche* industry. These host shrubs should be planted in a way that facilitates *Cistanche* intercropping.

Haloxylon ammodendron, a protected species in China, is a xerophytic perennial shrub or small tree of high ecological value in anti-desertification strategies due to its high tolerance to drought and salt stress. It dominates many sandy and saline areas of Asian deserts (Huang *et al.* 2003). It plays an important role in the maintenance of the structure and function of the desert ecosystem via sand fixation, wind control and microclimate amelioration (Ma *et al.* 2021). Through numerous experiments, *Haloxylon ammodendron* was introduced successfully to the Taklimakan Desert hinterland and became the major tree species for desert highway shelter belt construction in 1992, laying the foundation for *Cistanche deserticola* inoculation and expanding the planting range of *Cistanche deserticola* to southern Xinjiang.

Planting *Tamarix* is recommended for the highway green belt along the road and in planned areas. Sandy lands with relatively low salinity, and strong water permeability are recommended areas for planting *Tamarix*. The shifting desert land in the Hotan area is also the right habitat for *Tamarix*.

2.2 *Cistanche* planting technologies for high yield

2.2.1 *Cistanche* seed selection

Seeds with full and glossy grains and high maturity should be chosen. In the 1990s, there were very few *Cistanche* seeds in the market, and the price could be as high as 120,000/kg. Nowadays, with the high yield of *Cistanche*, the cost of its seeds in Xinjiang is only a few hundred CNY/ kg.

2.2.2 *Cistanche* planting methods

Table 9.1 Recommended Cistanche planting methods

Ditching	First, build a furrow next to the host vegetation (*Tamarix or Haloxylon*) at a distance determined by the height of the host plant. Generally, the height of the host plant should be more than 50 cm to ensure good survival. It is recommended that the furrow is 20 cm away from the host plant and parallel to it, and about 50–80 cm deep.
Sowing *Cistanche*w	The *Cistanche* seeds and sandy soil is mixed and then sprinkled into the furrow in the proportion of 1 kg of seeds to 10 mu of land. In this way, the seeds are three-dimensionally distributed in the sand since *Tamarix* roots extend in all directions. Three-dimensional sowing can improve opportunities for contact between seeds and roots, increasing the inoculation rate. To avoid damage caused by the low temperature, the inoculation depth should not be less than 70 cm. Most farmers in the Hotan area now use machines to sow seeds, which significantly saves labour cost.
Irrigation	Drip irrigation technology is used twice a year to make the plant roots shallower, usually in June and August.
Harvest	The best time to harvest is spring and autumn when it is easier to spot the cracks on the ground caused by the growing *Cistanche*. The harvest period in the Hotan region is November, since summer is the dormancy period, and the low winter temperatures will cause plant damage. To ensure a sustainable harvest for 5 years for one planted *Cistanche,* it is recommended to only harvest the top part in the spring and leave at least 5 cm of growth for the next seasons.

Figure 9.3 Planting and harvesting Cistanche with related capacity-building by XIEG, CAS

Photo source: XIEG, CAS

2.2.3 Field management

Because of the strong wind and sandy soil in the desert, the roots of *Haloxylon ammodendron* and *Tamarix* are very likely to be exposed to the wind. Attention should be given to wind control and keeping the soil moist.

Diseases and insect management should be considered. *Haloxylon ammodendron* and *Tamarix* can be affected by powdery mildew. Farmers usually will choose organic fertilizer or medicine to solve this problem, though this will undoubtedly increase their costs. It is not recommended to use fertilizer or chemicals if there is no sign of diseases or insects.

2.3 Sustainable production of *Cistanche*

Cistanche deserticola inoculation takes 1–2 years after sowing, and it can be harvested with good yield for 4 years. Two sustainable management models for *Cistanche deserticola* were tested to ensure a yearly harvest and income for local communities.

The first model involved rotational cropping for each side of *Haloxylon ammodendron* every two years. Namely, sowing *Cistanche* seeds on one side of the *Haloxylon ammodendron* plantation rotationally every two years. This can support a continuous harvest for 4 years after each sowing year. From the fifth year on, the average yield reached 520 kg/mu. This model is suitable to establish a high-yield *Cistanche* farm.

The second model involved rotationally cropping at two *Haloxylon ammodendron* forests. When the harvest starts in the third year after sowing in one forest, start sowing in the other forest. This rotation will support continuous harvesting with reasonable labour inputs. From the fifth year on, the yield reached 236-283 kg/mu stably and average yield could reach 260 kg/mu. This ensures both ecological and economic benefits and can be operated at the household level.

3. Restoration outcomes

The inoculation rate and yield of *Cistanche* were significantly increased by three-dimensional sowing technology. The two sustainable planting models can recover expenses after five years and bring 3,942 CNY/mu and 2,330 CNY/mu net incomes in the sixth year respectively. In the Hotan area, farmers planting *Cistanche deserticola* have an annual income of 100,000–300,000 CNY.

Developing a *Cistanche deserticola* industry can bring more income to the people in the desert area, thus alleviating poverty and promoting the development of related industries. For example, the ditching machine for planting *Cistanche* is fully developed. The efficiency of a ditching machine can be equivalent to a workforce of 30 people, while the cost is about 20%, which significantly reduces the planting cost and improves work efficiency.

Through this win-win ecological plantation practice, the green belt protected the desert highway, avoided wind and sand hazards, reduced wind intensity, increased relative humidity and improved microclimate. Regional biodiversity has improved, with small and medium-sized rodents, insects and birds returning to the desert.

4. Demonstration and upscaling

Up to 2012, the planting of *Tamarix* in Hotan area of Xinjiang had reached 20,000 hm^2, and the inoculation of *Cistanche tubulosa* had reached 10,000 hm^2, accumulating to 130,000 hm^2, with the significant benefit of establishing a *Cistanche* industry at an annual value of 150 million CNY.

From the perspective of science and technology development, the team developed two new technologies, three new products, compiled five technical regulations and obtained 13 national patents. More than 400,000 people received training on these technologies and practices. The capacity of local men and women was strengthened by sharing knowledge and technology.

5. Estimation of investment and investment payback period

Our pilot shows that with the first sustainable planting model, the initial investment can be covered in the fifth year, and produce 3,924 RMB/mu net income from the sixth year on. With the second planting model, the initial investment can be covered in the sixth year, and generate 2,330 RMB/mu after the seventh year.

6. Challenges and potential issues

Although the *Cistanche* industry has brought positive environment changes and significantly increased incomes for the local people in the desert areas, there are still many potential issues that cannot be ignored.

Farmers do not plant according to the recommended planting norms. Some farmers plant too many *Cistanche* seeds for one *Tamarix* to get a higher yield, causing the host plant to die, which then decreases the soil quality and ecosystem services. Thus, it is important to give training to farmers about the correct planting method and effective supervision. However, enforcing these methods is always challenging.

Secondly, the market price of *Cistanche* fluctuates a lot. It mainly depends on a few leading domestic enterprises, which can greatly influence the market price. *Cistanche tubulosa* is mainly used for medicine extraction rather than food because of its bitter taste. At present, due to insufficient publicity and awareness, *Cistanche tubulosa* is only popular in Jiangsu, Zhejiang, Hubei and Guangdong, and does not yet cover the other provinces' markets. In such a fluctuating market, farmers would find it difficult to make profits and sustain their conservation and production.

7. Prospects for commercial transformation and promotion of findings

Cistanche cultivation is one of the most profitable desert industries. Creating a high-yield *Cistanche deserticola* plantation can have win-win results with both ecological and economic benefits and promote the benign cycle of ecological construction.

According to the Up Market Research report, the global *Cistanche deserticola* market is projected to grow at a compound annual growth rate of 3 % between 2017 and 2028. Key factors driving this growth are the rise in demand for natural remedies for chronic diseases, increased adoption by new consumers and growing interest among health-care professionals in herbal supplements. *Cistanche* is also a global genus of a holoparasitic desert plant, which is primarily endemic to North African, Arabic, and Asian countries (Nan *et al.* 2013). There are equal opportunities for other desert regions to cultivate *Cistanche* as a desert livelihood and develop its industry.

It is believed that *Cistanche* market can be improved through the following actions, 1) accelerating the progress of the homologous certification of medicine and food and providing more training and supervision for quality production; 2) attracting more leading enterprises to enter the *Cistanche* industry; research and preferential policies are required to support enterprise development; and 3) strengthening exchanges and cooperation with domestic and foreign countries and financial support for professional teams to develop *Cistanche* cultivation.

Further information	
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Case 10. Ecological restoration of Yongding River in China

Brief Overview

Here we describe our ecological restoration experiences in the Yongding River, the “mother river” of Beijing. We introduced the stepwise ecological restoration theory (STERE) and its three restoration modes based on level of degradation to help restore the Yongding River. A series of supporting technology was developed to assist with the theory implementation, including a river restoration multi-objective optimization and decision-making system. Our interventions enabled the Yongding River to be fully flowing by 2020, which ended the 25-year history of river cut-off. The theory and technology of river restoration have been successfully applied in 27 projects on 24 rivers in nine provinces in China through collaborations among universities, enterprises and the Government. This is an important reference for river-basin-restoration decision makers and practitioners.

1. Background

The Yongding River is the "mother river" of Beijing, and it is highly significant to the social and economic development of the riverside areas and the sustainable development of the capital region of China, i.e. the Beijing-Tianjin-Hebei urban agglomeration. The Yongding River is 747 km long with a drainage area of 47,016 km^2. The Yongding River starts in Shanxi Province, flows through Inner Mongolia, Shanxi, Hebei, Beijing and Tianjin and terminates at the Bohai Bay. It is the largest river in Beijing, running over 170 km through the southwest of the capital city. In the past few decades, the river has experienced several environmental and ecological problems due to factors such as overexploitation of water resources and water pollution. Since the 1970s, incoming water from upstream has decreased, and the current inflows are about 1/10 of the original discharge. Many environmental problems emerged, such as cut-off at many sections, groundwater decline in the river basin, severe water pollution and river ecosystem degradation. The dry riverbed became the source of a sandstorm in Beijing and the surrounding regions.

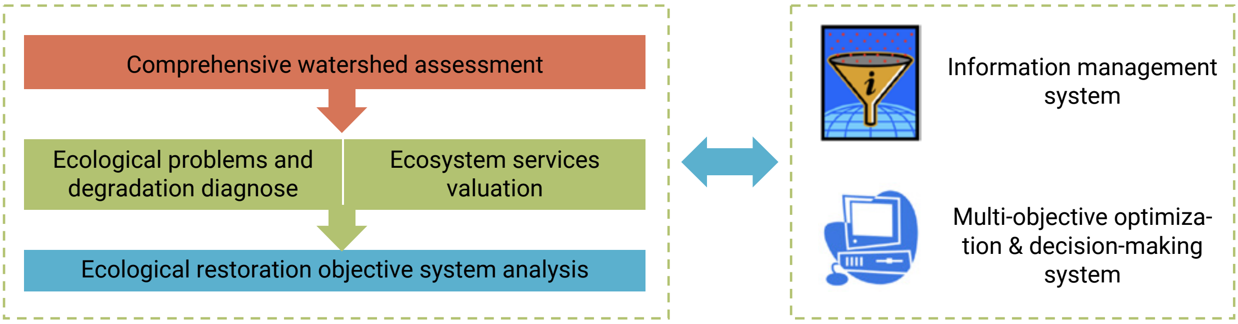
Previous interventions were mainly based on flood control projects. Although ecological function zoning had been initially established, there were no clear ecological restoration goals and objectives. With the improvement of living standards, people have a higher demand for the ecological functions of the Yongding River. There was an urgent need for river restoration. Since 2009, the municipality of Beijing has taken several measures to restore the Yongding River. One important task is to set clear goals and objectives for river restoration.

How to restore a river remains a big challenge. Many theories in other developed countries set the objective of returning the river to its state prior to degradation. But after a rigorous assessment, we found such theories do not apply to the restoration of the Yongding River. First, it is difficult to restore it to a prior-degradation status. Built in 1954, the Guanting Reservoir is located upstream of the Beijing section, at the junction of Beijing and Hebei Province. The Guanting Reservoir was the first large-scale reservoir to be built after the founding of the People's Republic of China. It covers an area of 230 km^2 and has a total storage capacity of 2.2 billion m^3. This reservoir has completely changed the natural flows. In addition, the Yongding River suffered from different levels of degradation in different areas. Downstream, the river ran dry due to the terrible ecological situation. Second, the prior-degradation status is also not an ideal situation. Historically, there were many disastrous floods due to the riverbanks bursting, which was the main reason for building the Guanting Reservoir.

2. The intervention approach and implementation plan

We proposed the stepwise ecological restoration theory (STERE) to help the river restoration, thanks to support from the 'Strategic Priority Research Program of the Chinese Academy of Sciences (Grant ID:XDA20060402)'. The STERE integrates three restorative modes that can be used with different levels of ecosystem degradation: environmental remediation for seriously degraded ecosystems, ecological rehabilitation for moderately degraded ecosystems and ecological (even natural) restoration for slightly degraded ecosystems (Liu *et al.* 2020). The expected goal of the river restoration was to achieve a "flowing river, green river, clean river, and safe river" in order to solve the four big problems of river cut-off, ecological degradation, water pollution and flooding. A framework was established to set concrete restorative objectives, consisting of different steps such as diagnosing ecological problems, determining the levels of ecological degradation, valuing ecosystem services provided by the ecosystem and identifying restoration objectives (Fig. 10.1).

Figure 10.1 Framework to set restoration objectives for the Yongding River



The comprehensive watershed assessment was supported by a watershed remote sensing (RS) inversion model based on an RS-GPS (Global Position System)-Sample integration technology (Fig. 10.2). The 3S technology (geographic information system, RS and GPS) was used to comprehensively analyze the spatial-temporal evolution characteristics of hydrology, water quality, ecosystem and ecological functions in the Yongding river basin. Based on the social and economic development of the Yongding river basin, the driving factors of river ecosystem degradation were identified, and the mechanism of ecological degradation was explored.

Figure 10.2 Schematic diagram of the watershed RS inversion model based on RS-GPS-Sample integration

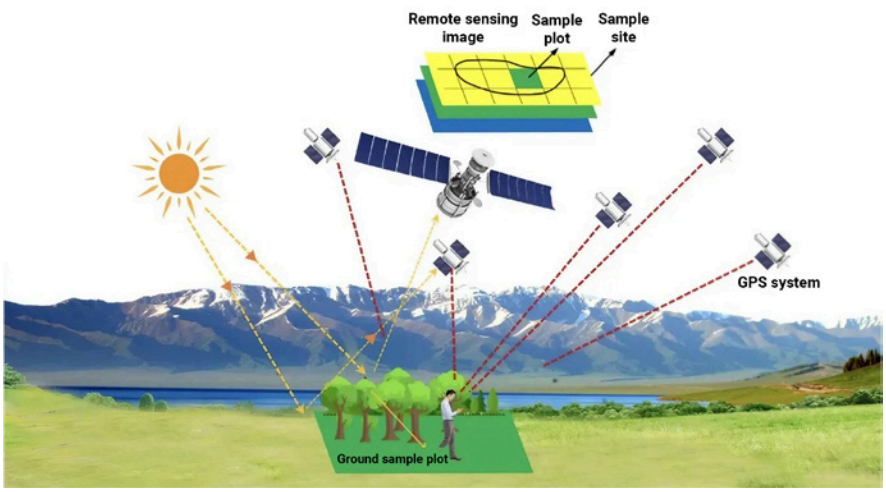
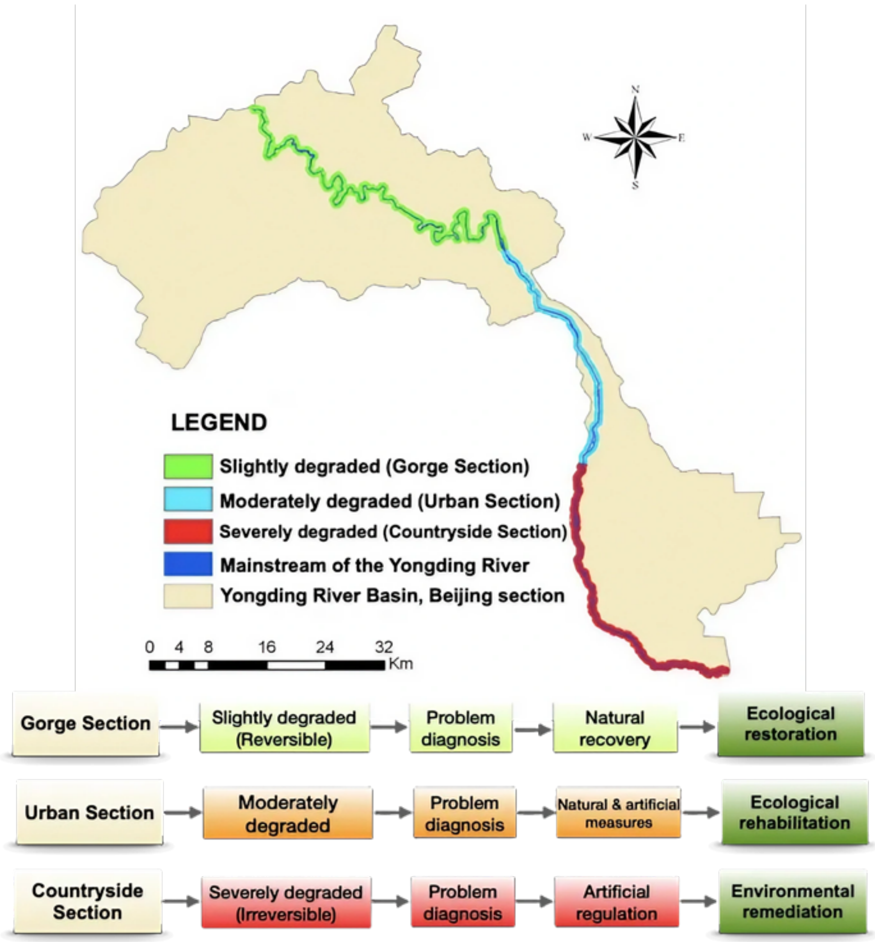
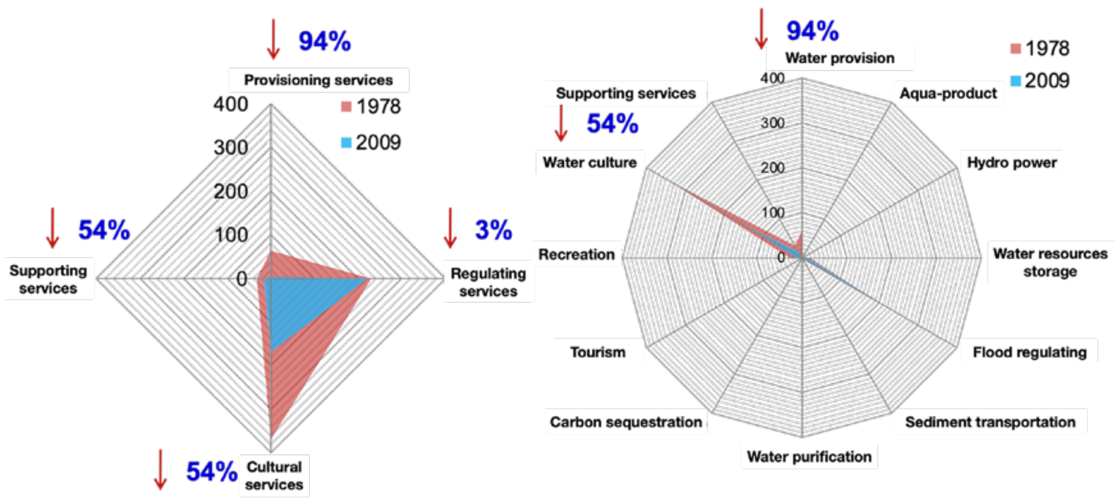


Figure 10.3 Ecological restoration modes of the Yongding River (Beijing section)



We proposed an ecosystem services assessment indicator system for river restoration based on the approaches established by involving stakeholders (Zhang *et al.* 2011). Recommended stakeholders include rights-holders and especially under-represented groups, including local women and youth as well as various vulnerable groups that are often left furthest behind. Based on the basic analysis of the general ecological condition of the Yongding River (the Beijing section), the values of ecosystem services were assessed to help identify ecological problems. From 1978 to 2009, the value of provision, supporting and cultural services showed an obvious trend of decline, especially the values of water culture and water provision (Fig. 10.4). The sharp decline of these two services was the main reason for the decrease in the total value of ecosystem services provided by the Yongding River (Beijing section) (Zhang *et al.* 2011). Due to the interception of river discharge by the upstream reservoirs, in particular the Guanting Reservoir, it was very difficult to increase the water supply capacity. Therefore, the contribution of the increase of water provision to the total ecosystem services value provided by the Yongding River is limited. On the contrary, increasing the ability of water culture inheritance through ecological restoration was feasible and effective (Liu *et al.* 2015). This required an expansion of the area of water bodies and wetlands in or surrounding the river.

Figure 10.4 Values of ecosystem services provided by the Yongding River (the Beijing section) in 1978 and 2009



Source: Zhang et al. 2011

Meanwhile, a multi-objective optimization and decision-making system for ecological restoration was developed, which comprehensively considered the coordination of various ecosystem services, carried out the comprehensive optimization of multi-objective and multi-constraint conditions, determined the ecological construction and restoration objectives of the Yongding River (Beijing section) in different periods, and formed the ecological restoration objective system of the Yongding River. A watershed information management platform was built to monitor the restored ecosystems throughout the whole restoration process and provide practical and handy tools for river restoration and management (Fig. 10.5). The information management platform is based on the basic information of the Yongding river basin, ecological assessment, RS inversion and other models.

Figure 10.5 Interfaces of Yongding River watershed information management platform

This restorative practice provided theoretical and scientific support for the overall plan for the comprehensive management and ecological restoration of the Yongding River. In 2016, the Overall Plan for Comprehensive Management and Ecological Restoration of Yongding River was issued and implemented. The green and ecological corridor project was initiated in 2020. The scale (in terms of area and total volume of water) of these lakes, lines and wetlands was estimated by the multi-objective optimization and decision-making system. The results were used to determine the ecological water replenishment scheduling for river restoration to enhance river ecosystem services, in particular cultural services.

3. Restoration outcomes

The Yongding River ecological water replenishment started on 20 April 2020. A total volume of 166 million tons of water was released from the Guanting Reservoir to the lower reaches of the Yongding River. The 170-kilometre river in Beijing was full of water for the first time in 25 years, and the river flowed to the Wuqing District of Tianjin, resulting in a continuous waterway of 248 km from the outlet of the Guanting Reservoir. On the basis of this, in 2021, additional water was replenished by using reclaimed water and water from the South-to-North Water Diversion Project. The entire river was full of water from the source region to the sea for the first time in 26 years. The water flow in the river has provided significant ecological effects in Beijing and has improved the water ecological environment in the areas along the Beijing-Tianjin-Hebei urban agglomeration.

The proposed approach helped determine the ecological flow threshold of the Yongding River and recommended appropriate water replenishment required to achieve the goal of ecological restoration, which provides a theoretical basis for the rational allocation of water resources in the Yongding River. It will effectively guarantee the construction of ecological civilization in Beijing as well as in the Beijing-Tianjin-Hebei urban agglomeration.

In addition, the practice was very significant for the construction of the green ecological corridor of the Yongding River, which can effectively guide the ecological restoration and improve river ecological services. The construction of the Yongding River ecological corridor will not only significantly improve the ecological environment in the southwest of Beijing but also effectively implement the overall urban planning of Beijing and help improve the urban ecological environment quality and the construction of Beijing as an international first-class ecological harmonious and liveable city.

4. Demonstration and upscaling

By working closely with several enterprises and the Government, the proposed STERE and restorative technology have been successfully applied in 27 restoration projects on 24 rivers in 16 cities in nine provinces. The research team also helped formulate 17 relevant plans for comprehensive watershed management and river restoration in nine cities, including Shenzhen, Chongqing, Jinan and Hangzhou.

5. Estimate of investment

In 2010, the Government invested 17 billion CNY to start the green ecological corridor project on the Yongding River (Beijing section). This means that the average investment was about 100 million CNY per 1 km of river. In addition, a total of about 65 billion CNY was invested in improving the surrounding regional environment within the river basin to assist in the river restoration. It will take an estimated four to 10 years to restore the Yongding River according to the level of degradation. There are no detailed data to support our evaluation in terms of the payback period for such restoration investments.

6. Challenges and potential issues

The STERE requires long-term monitoring to make sure the river ecosystem evolves in a way that follows the planned restorative aim. One challenge is the lack of long-term real-time monitoring systems. In future, there is a need for continuous monitoring of water, soil, benthos and biodiversity to track the restoration effect, and flexibly adjust the actions if necessary. In addition, although restoration targets were clear, reference ecosystems were not yet widely used in the restoration process in many countries. One reason for this is that many rivers have been altered greatly by human activities, and it is difficult to find a section or tributary without strong human interventions. However, there are many ways to select reference ecosystems (Liu *et al.* 2017). In future, reference ecosystems should play a more important role in river restoration, especially when natural recovery is applied.

7. Prospects for commercial transformation and promotion of findings

The STERE and river restoration technology have broad application potentials not only in China but also in other countries. Based on the research and practice, we wrote a book (Liu and Clewell 2017) to provide the conceptual foundation for addressing questions related to ecological restoration and rehabilitation. It answers many questions relevant to the administration and technical management of rehabilitation projects. This book become one of the foundation documents for the preparation of the International Standards for the Practice of Ecological Restoration of the Society for Ecological Restoration (Gann *et al.* 2019), the most recent version of which was released on 27 September 2019 at the eighth World Conference on Ecological Restoration. There is also potential for commercial transformation given the United Nations General Assembly declared 2021-2030 the Decade of Ecosystem Restoration, and many countries are establishing more and more restorative projects to achieve the targets established in this decadal programme.

Further information	
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Conclusion

Restoring degraded ecosystems is a complex issue that requires the integration of ecological, socioeconomic and cultural dimensions. The 10 principles of the UN Decade state that successful ecosystem restoration: 1) contributes to global policy frameworks; 2) promotes fair and inclusive engagement; 3) includes a continuum of restorative activities; 4) aims for the highest possible recovery for the benefit of nature and people; 5) addresses the causes of degradation; 6) integrates all types of knowledge; 7) sets measurable ecological, cultural and socioeconomic goals; 8) adapts activities to local and land/marine contexts; 9) measures results and adapts actions; and 10) integrates policies and measures for sustainable impacts. These principles provide a guiding tool for the implementation of the UN Decade and maximizing the sustainable production of goods and services.

Looking forward, the ongoing United Nations Convention on Biological Diversity COP-15 has been negotiating a new post-2020 global biodiversity framework with an ambitious initial goal of conserving 30% of land and sea areas globally, which will be integrated into wider landscape and seascape change. To maximize net gains to biodiversity, ecosystem health and integrity, and human health and well-being, an integrated approach to restoration is essential.

As the country with the largest population in the world, China has some of the most vulnerable ecosystems. Fifty-five per cent of the land area of China is vulnerable to degradation (National Development and Reform Commission of China 2015). Ecological restoration in China entered a new era when the Chinese Government made ‘ecological civilization’ a paramount objective, and in 2018, it became one of the constitutional principles of China (Cui *et al.* 2021). In 2020, Chinese Government approved the Master Plan for National Key Ecosystem Protection and Restoration Major Projects (2021–2035) with nine major projects involving 3 trillion CNY in investment and covering all seven key ecosystem areas in China (Sino-German Environmental Partnership II 2020). In September 2020, the Chinese Government launched the Guidelines for Ecological Restoration Projects of Mountain, River, Forest, Farmland, Lake and Grassland Ecosystems. These laid good foundations for ecosystem restoration in China for the UN Decade from a governance, policy, finance and technical perspective.

This report presented technologies, approaches and outcomes of integrated ecosystem restoration efforts in China over the past few decades, especially the significant progress made by the CERN in social-ecological management and accumulated experiences in environmental conservation, safeguarding public infrastructure and improving livelihoods. These 10 case studies presented the national policy context on restoration, inclusive multi-stakeholder participation, long-term monitoring and research-based adaptive management, local community empowerment by enhancing livelihoods, and how they addressed the root causes of degradation. These are ground-level practices that successfully fulfil the 10 principles proposed by the UN Decade.

A sustainable use of ecosystems implies a balance between protection and exploitation (Weißhuhn, Müller and Wiggering 2018). This report analyzed trade-offs between short-term and long-term benefits, ecological and socioeconomic benefits and upstream and downstream development. Local community buy-in and behaviour change to scale up pilot interventions usually takes time and adaptive management is used to best fit the local context and knowledge. In the Inter Mongolia grassland, Loess Plateau, Taklamakan Desert and Yongding river basin studies, long-term issue-based monitoring and applied research were carried out for over 10 years to develop tested standards and regulations to scale up the technology.

Such knowledge and technology sharing are expected to enhance the good practices knowledge hub and capacity-building in order to help implement the UN Decade. In many cases, vulnerable groups and communities rely on vulnerable ecosystems. As a result, they face heightened risks from natural and climate-induced hazards (United Nations Framework

Convention on Climate Change 2018), especially in the least developed countries. Since technical capacities and skill and knowledge gaps often constrain response options, there is a need to develop capacities for sustainable land management and associated information systems, particularly in developing countries that are prone to and most affected by land degradation (United Nations 2020). This may involve, for example, appropriate measures to enhance sharing of indigenous and local knowledge that has been effective in addressing land degradation problems in certain contexts (United Nations 2020). Such South-South knowledge exchange between areas with a similar vulnerability and socioeconomic development status allows more effective mutual learning.

From these shared experiences and lessons learned in different vulnerable ecosystems, a few issues are worth further attention with regards ecosystem restoration project implementation, especially for large-scale interventions.

1. Long-term monitoring and research on ecosystem restoration lays the foundations for effective restoration intervention. Having multiple stakeholders engaged in applied research greatly supports technology innovation, use of traditional knowledge, capacity-building and increased cost-effectiveness and local buy-in. This modality was clearly demonstrated in most of cases in the CERN. The Loss Plateau Grain for Green Programme started at a small pilot site in Zhifanggou at the CERN Ansai Ecological Station. The desert ginseng plantation is part of a range of solutions for building and maintaining the green belt along the desert highway after over 10 years of applied research. To apply these ecosystem restoration or management technologies elsewhere requires local testing and calibration.

2.An adaptive management approach by all stakeholders in restoration initiatives is critically important. Achieving sustainable development and balancing social-ecological trade-offs is fully dependent on the response and feedback of coupling nature and society ecosystem elements (Zhao 2020). Although the long-term sustainability of social-ecological systems is initially dependent on users or a government to establish rules, these rules may not be sufficient in the long run. The long-term sustainability of rules at local level depends on monitoring and enforcement and them not being overruled by larger government policies (Ostrom 2009). Emphasis should therefore be given to the interaction between policies and the wisdom of local stakeholders in the response and feedback between ecosystems and social systems.

3. The short- and long-term regional water resource balance should be thoroughly evaluated during ecosystem restoration, considering the socioeconomic benefits. Carbon-water coupling cycles are regulated by multiple factors, e.g., precipitation, land use, land-use change and management strategies. The continuous ecological restoration project in the dryland regions in China has resulted in an increase in forests and shrublands, which has reduced annual stream flow and sediment load (Zhao 2020). The water consumption of revegetation and its outputs have to be evaluated as well in terms of the sustainable livelihoods of the local community.

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