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INTEGRATED CONSERVATION SOLUTIONS FOR THE ENDANGERED LOESS PLATEAU OF NORTHWEST CHINA

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Abstract

Since Sørensen first proposed the definition of ecotope in 1936, the stratified feature and distinct management of ecosystems has received extensive consideration worldwide. We chose the Loess Plateau of China as a case study to quantitatively establish a potential model system entitled the Stratified Strategies for Ecosystem Management (SSEM). The Loess Plateau is geographically dominated by hilly and gully topography. Intense rainfall during summer erodes the bare topsoil from the hill tops to the valleys, which leads to serious soil and water loss, land degradation and social poverty. Since the 1980s, four big national programs have been initiated and implemented to reduce the erosion and improve livelihoods, including the Grain for Green Program (GFGP), the Natural Forest Conservation Program (NFCP), the Terraced Field Construction Program (TFCP), and the Integrated Rain-harvesting Agriculture (IRHA). Our statistical analysis shows that these strategies have played positive roles in harmonizing ecosystem conservation with human development. Vegetation cover has been increased by 27.0% and total farmland area has been reduced by 23.6% at four typical sites. Soil organic carbon has increased by 1.59 g/kg, while annual topsoil loss has been reduced by 650 Kt. In addition, terracing has significantly improved soil water storage, sediment trapping and soil quality on the Loess Plateau. On the other hand, the IRHA system in the valley areas has brought about a significant increase in the productivity of summer crops. Based on the IRHA model, the grass-crop rotation system has led to considerable improvement in agricultural cropping patterns, and promoted modern agricultural and animal husbandry systems. The population of farmers growing crops has been reduced 20% but the regional GDP has increased 800%. Human productive activities have tended to transfer from the tops of the hills to the side of the hills and valleys. We therefore propose an integrated model of SSEM, which provides a novel strategy to conserve endangered ecosystems in semiarid and arid areas.

Introduction

The strategy for conservation of endangered ecosystems has been receiving extensive consideration worldwide. Due to the disturbance caused by human activity, the degradation of various ecosystems has become a serious problem, leading to a worldwide decline in ecosystem function and services (Costanza *et al*., 1997, Dobson *et al*., 1997, Assessment, 2005). An understanding of ecotope concept is critical for endangered ecosystem conservation. The first definition of an ecotope was made by Thorvald Sørensen in 1936 (Sørensen, 1936). Arthur Tansley defined an ecotope as the particular portion of the physical world that forms a home for the organisms which inhabit it (Tansley, 1939). Therefore, ecotopes actually represent relatively homogeneous, spatially-explicit functional units that are useful for stratifying landscapes into ecologically-distinct features for the measurement and mapping of landscape structure, function and change (Sørensen, 1936; Tansley, 1939; Huber-Sannwald *et al*., 2006). The theory of ecosystem stratification and management provides a fundamental platform for the conservation of endangered ecosystems, such as the severely degraded Loess Plateau of China.

The Loess Plateau of northwest China at 640,000 km^2 is the largest loess region in the world with a population of 34 million (Liu, 1985; Wang *et al*., 2010). Its major topographic characteristic is its hilly and gully terrain. Over recent decades, the Loess Plateau has suffered serious land degradation and soil/water erosion due to excessive use of the hilltops and hillsides for agriculture (Kang *et al*., 2005; Liu *et al*., 2006). Over recent decades, soil and water erosion has degraded 70% of the total area of the Loess Plateau (Liu *et al*., 2006). With 1.6 billion tonnes of soil lost by erosion annually, the Loess Plateau is regarded as one of the most severely eroded and severely eroding areas in the world with important ecological and socioeconomic consequences (Liu, 1985; Douglas, 1989; Wang, 1998; Saito *et al*., 2001; Peng *et al*., 2005; Wang *et al*., 2010). The Loess Plateau is an important dryland agricultural area providing food security and employment for a population greater than its 34 million residents. Of the total area of 64 million hectares, about 15 million hectares is cultivated and half of this cultivated area is on sloping land (Shangguan *et al*., 1999) that is very vulnerable to water and wind erosion as a consequence of deforestation and overgrazing (Turner *et al*., 2011).

The vegetation cover has experienced significant changes since the 1980s. From 1981 to 1989, the vegetation cover tended to increase, and then remained relatively stable from 1990 to 1998. However, the vegetation cover declined sharply from 1999 to 2001 due to local extensive farming in the hilly and gully areas (Xin *et al*., 2007). Since the 1980s, four big national recovery programs have been implemented in this region, including the Grain for Green Program (GFGP, returning farmland to forest or grassland), the Natural Forest Conservation Program (NFCP), the Terraced Field Construction Program (TFCP), and Integrated Rain-harvesting Agriculture (IRHA). Among these programs, the GFGP, NFCP and TFCP were designed to increase vegetation cover and prevent land degradation (Kang *et al*., 2005), and the IRHA and TFCP mainly aimed to improve farmers' income and livelihoods (Jiao *et al*., 1999; Wu *et al*., 2003; Kang *et al*., 2005). The implementation of these programs has to a large extent inhibited soil and water erosion and improved farmers' livelihoods. Human productive activities have been largely transferred from the hilltops to less steeply-sloping areas and the valleys. The story of the Loess Plateau can be explained and analyzed using the theory of ecosystem stratification and management. In this study, a vertically stratified method is developed for the Loess Plateau based on the concept of stratified features and distinct management of these features. The objectives of the study were to summarize the technical approaches to the conservation and maintenance of the severely-degraded Loess Plateau ecosystem from existing studies conducted over the past few decades. Critically, we attempted to develop an integrated model of "Stratified Strategies for Ecosystem Management (SSEM)" for conservation of endangered ecosystems.

Materials and Methods

The Loess Plateau is located in northwest China (34°N, 103°E to 40°N, 114°E) and covers seven provinces - Gansu, Henan, Inner Mongolia, Ningxia, Qinghai, Shanxi and Shaanxi (Fig. 1). The area in Inner Mongolia is contiguous with the Mongolian Plateau and is sometimes referred to as the Inner Mongolian Plateau (Zhang *et al*., 2011). The average height of the Loess Plateau is 1200 m above sea level and has a monsoonal continental climate with cold dry winters and warm wet summers (Turner *et al*., 2011). The soil type is a wind-blown silt (loess) and the depth varies from 50 to 80 m.

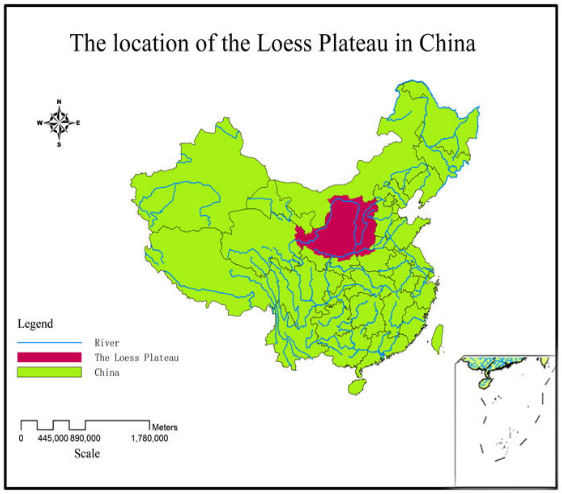

Fig. 1. Geographic location of the Loess Plateau in China.

The loess is very vulnerable to water erosion, which results in a fragile highly-dissected landscape. The majority of the Loess Plateau has a mean temperature of about 10°C, but the range of mean air temperature is significant, from just below 0°C in the higher west of the Plateau to just above 20°C in the south and east. Annual rainfall varies from about 600 mm in the south to between 100 and 200 mm in the north-west (Turner *et al*., 2011). The climate changes from semihumid in the southeast, to semiarid in the centre to arid in the northwest. As mentioned above, four national programs were implemented on the Loess Plateau, yet their goals varied from each other. The GFGP, NFCP and TFCP were designed to increase vegetation cover and prevent land degradation, while the IRHA and TFCP were mainly established to improve farmers' income and livelihoods. In this study, we assess the effectiveness of the four programs and attempt to construct an integrated model of SSEM.

Existing studies indicated that representative sites with the most serious soil erosion and land degradation in the Loess Plateau were found to lie in the semiarid and semihumid areas of the Plateau, such as the semiarid region of Mizhi, the semihumid area of Ansai, and the humid and semiarid area of Pengyang and Ansai (Fig. 2). Therefore, we chose these four locations as case studies to evaluate the effects of GFGP and NFCP programs on local ecosystem quality and socioeconomic progress. The TFCP program data were obtained from the whole Loess Plateau to assess their ecological effectiveness and field productivity. The IRHA program data were obtained from our previous experimental studies and related published papers. The period of data utilised in the study mainly ranged from the 1980s to 2010. The impact of the four programs on ecosystem quality and socioeconomic progress was evaluated. Data analysis follows the method of Analysis of Variance.

Results

The conservation solutions of Grain For Green Program (GFGP) and the Natural Forest Conservation Program (NFCP): The implementation of the GFGP and NFCP as strategies of ecological conservation or rehabilitation have played a critical role in the Loess Plateau over last three decades. The GFGP program aimed to return farmland to forest or grassland. Currently, over the whole Loess Plateau, 21%, (2.4 million ha) of sloping land (>25° gradient) has been converted from farmland, while over 1.3 million ha of natural forest has been effectively conserved by the NFCP program. The GFGP and NFCP programs have led to significant improvement in vegetation cover, soil and water conservation, and socioeconomic development. In the study, the four representative sites chosen in the core region of the Loess Plateau, Mizhi (semiarid area), Ansai (semihumid area) and Wuqi and Pengyang (transitional area from semiarid to semihumid area), had serious soil erosion and ecological degradation. The average farmland area converted to forest or grassland was 24% at the four sites. Average vegetation cover and soil organic carbon increased by 27% and 1.59 g/kg, respectively, while the average soil and water loss decreased by 650 kt/ha. The average annual runoff volume was lowered by 1.82 million m3/ha in Ansai (Fig. 2 and Table 1). Importantly, the percentage of farmers growing crops was reduced by 20% and regional GDP was 800% higher. In particular, the GFGP and NFCP programs fostered the ecological reconstitution in the hilltop and higher hillside areas.

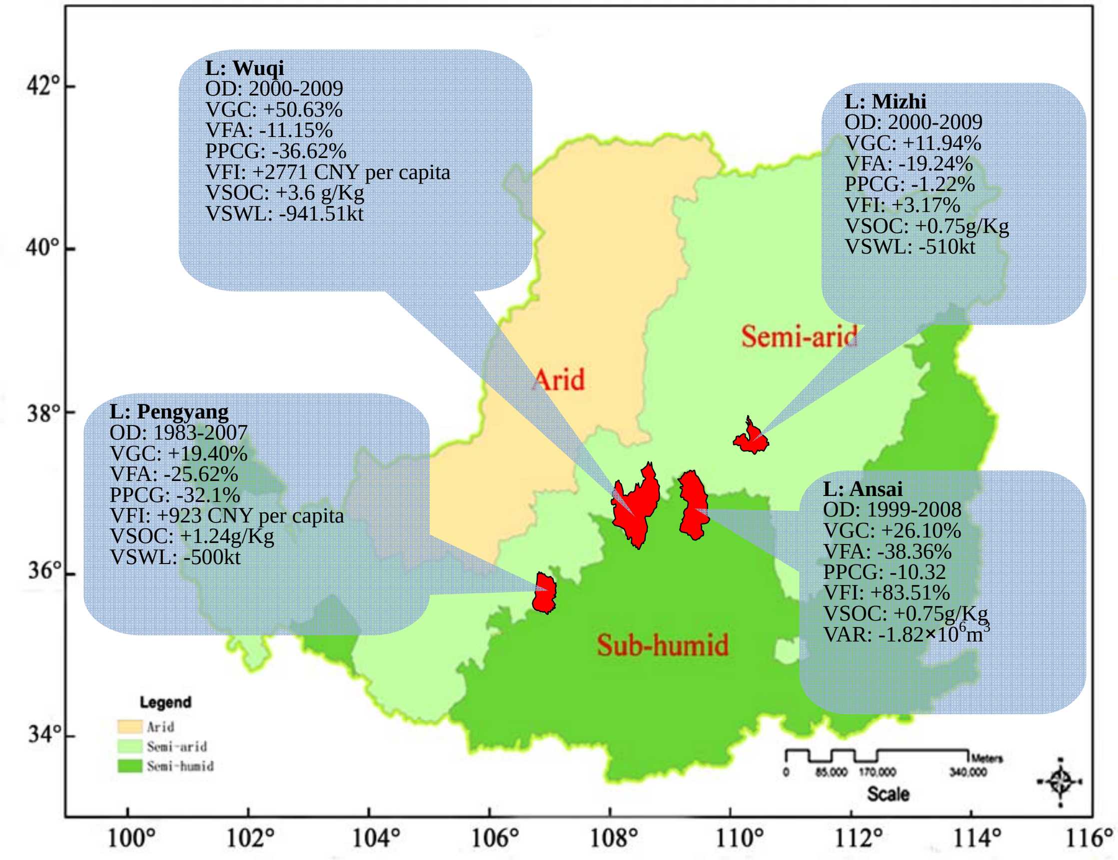

Fig. 2. Climate type classification and ecological and socioeconomic indicators of GFGP and NFCP in four representative endangered sites in the Loess Plateau.

Notes: the symbol of "+" refers to increase and the symbol of "–" refers to decrease

L: Location; OD: Operation duration of Grain for Green Program (GFGP) and the Natural Forest Conservation Program (NFCP); VGC: Variation in vegetation cover (reconstructed forest / grassland) (%); VFA: Variation in farmland area (%); PPCG: Percentage in the population of crop growers (%); VFI: Variation in farmers' income (CNY or percentage); VSOC: Variation in soil organic carbon in GFG lands (g/kg); VSWL: Variation in soil and water loss (kt); VAR: Variation in annual average runoff volume (m^3)

Table 1. Ecological and socioeconomic performances of GFGP on the Loess Plateau.

Ecological indicators	**Average**	**SD**	**Returned cropland area (ha)**
Variation in vegetation cover (%)	+27.02	16.77	2.365 million ha consists of **20.79%** of total cropland area on the Loess Plateau
Variation in farmland area (%)	-23.68	11.36	
Crop grower population (%)	-20.07	17.02	
Soil organic carbon (g/kg)	+1.59	1.36	
Soil and water loss (kt)	-650.5	252.1	

The Terraced Field Construction Program (TFCP) as strategy of ecological & productive co-evolution: Over the last few decades, the terracing of the hillsides has experienced rapid expansion due to its productive and ecological effectiveness on the Loess Plateau. The terraces are generally located on hillsides with less than 25° slope in the lower hillside areas, accounting for almost 40% of the total cropland area. Previous studies have shown that the terraces are effective in terms of terrace function. Data collected over 40 years have shown that soil water storage and sediment trapping in terraced fields were up to 237 m3/ha and 112 t/ha, respectively, i.e. 82% of the runoff and 84% of the sediment from the sloping land was preserved and trapped (Table 2). Soil quality of level terraced fields was observed to be better than that of sloping fields. Average soil organic matter and total nitrogen were 13.0 g/kg and 79.6 mg/kg, significantly higher that of the sloping land (Table 2). Additionally, the bulk density of the soil on the terraces was 1.12 g/cm^3, considerably lower than that of the sloping fields. Terracing increased the total phosphorus and available potassium. The changes in soil physical and chemical properties were presumably made after some time for the redistribution of nutrients and topsoil development. Critically, the data indicated that alfalfa gave a higher economic output than that of wheat crops (Table 2). In this case, it can be argued that terrace construction in conjunction with a pasture legume has great potential on lower slopes of the Loess Plateau.

Table 2. Ecological and economic performances of the TFCP on the Loess Plateau.

Soil and water conservation capability of terraced croplands					
Sloping land		**Terraced cropland**			
Runoff amount (m^3/ha)	**Sediment amount (t/ha)**	**Water storage (m^3/ha)**	**Water storage efficiency (%)**	**Sediment trapping (t/ha)**	**Sediment trapping efficiency (%)**
290.2 ± 94.5	133 ± 49.6	237 ± 77.2	81.66	112.2 ± 41.8	84.34

Soil quality and field productivity of terraced croplands and sloping land						
	SOM (g/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**AK (mg/kg)**	**BD (g/cm^3)**	**Crop economic output (CNY)**
Level terrace	12.97 ± 1.4	79.62 ± 7.9	138.1 ± 18.5	71.2 ± 4.4	1.12 ± 0.01	740.02 wheat
Sloping land	10.69	70.06	131.38	68.87	1.32	1442.93 alfalfa

Notes: SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; AK, available potassium; BD, bulk density.
The data are cited from the documents by Wang, 1998; Jiao *et al*., 1999; Wu *et al*., 2003; Kang *et al*., 2005.

Integrated Rain-harvesting Agriculture (IRHA) as a strategy for intensive sustainable production: Over the past three decades, the IRHA program has been gradually developed on the lower hillsides and the valleys. The core technique of this program is to harvest and conserve the rainfall to mitigate the differences between water supply and demand (Gan *et al*., 2012), and improve the agricultural productivity and ecosystem sustainability in rainfed agricultural areas. The most noticeable progress was achieved using a system of double ridge-furrow plastic-mulch. This system functions as an on-site rainfall conservation system and soil-warming system in the cold spring and has been widely used for maize, potato, wheat, soybean and other rainfed crop production on the Loess Plateau. Taking maize as an example, previous studies have shown that the average grain yield was significantly increased from 170 to 1150 kg/ha in the dry year of 2006 and from 536 to 6130 kg/ha in the wet year of 2007 (Table 3). Grain yield with the ridge-furrow plastic mulch technique in 2007 was 10-times higher than that of traditional flat-planting technique. More critically, rainwater use efficiency was 3.1 kg/ha/mm in 2006 and 16.6 kg/ha/mm in 2007, being 8 times and 13 times those of the conventional technique (Table 3). In conclusion, the benefit of double ridge-furrow plastic-mulch system is partially that the plastic helps to warm the soil and enable maize growth in the cold spring so that it has time to set a cob and mature before the winter. Other benefits of this system are to prevent the evaporation of available water in topsoil and harvest rainwater to store in the soil. Since 2008, this tillage technique had been extended to the whole of the Loess Plateau, with the area of adoption now over 2 million hectares (Table 3). As a result of the IRHA program, straw production has substantially increased, resulting in the rapid development of a livestock industry. This has resulted in intensification of agricultural production in the lower hillsides and valleys, such as the use of greenhouses and increased animal production. Furthermore, to ensure the sustainability of the lowland agricultural ecosystems, conservation techniques including zero or minimum tillage, straw retention, crop-legume rotation and others have been rapidly adopted.

As for other dryland crops, the IRHA system was also found to improve and stabilize agricultural production such as potato and wheat. Wang and others (2005) conducted a typical field experiment to evaluate the effects of this system on potato production in semiarid Loess Plateau of China. They found that this system promoted potato growth during the early period and diminished water stress at the later stages of potato growth. Potato yield and water use efficiency in the system was significantly higher than those of other systems. The best ridge width was between 40 and 45 cm (Wang *et al*., 2005). Li and others (2001 and 2002) conducted similar field experiments using winter wheat and millet. Plastic-covered ridges served as rainfall harvesting zones and stone-, straw- and film-mulched furrows as planting zones in their experiments. The results indicated that the IRHA system significantly increased crop yield and yield components and the ridge to furrow ratios had a significant effect on them. For winter wheat, optimum ridge to furrow ratio was 1:1 in the semiarid areas with about 300 mm rainfall, 1:2 in the areas with 400 mm rainfall and 1:4 in the areas with 500 mm rainfall. For millet, the best ratio was 1:3 in the areas with 300 mm rainfall. The combination of the IRHA system with supplemental irrigation practice will make the IRHA system more attractive (Li *et al*., 2001; Li and Gong, 2002).

Moreover, the methodology for design of water harvesting system for high rainfall areas had been also developed by Srivastava (2001). He proposed simulation model to design a system for determining catchment / command area ratio, size of tank, desirable command area of a single tank and the feasibility / economics of lining of tank. The model was able to design efficient water harvesting system in high rainfall areas with variable spatial and temporal distribution (Srivastava, 2001).

Table 3. Grain yield, WUE and extension area of integrated rainwater-harvesting techniques in the Loess Plateau.

Treatments	Size design	2006 (dry year)		2007 (wet year)		Extension areas in the Loess Plateau (ha)
		Grain yield (kg/ha)	WUE (kg/ha/mm)	Grain yield (kg/ha)	WUE (kg/ha/mm)	
CK	Flat planting	170	0.4	536	1.3	> 2 million
Ridge-furrow with plastic mulching	40-50 cm Optimum ridge width	1150	3.1	6130	16.6	

The data are cited from Jia *et al*., 2006; Liu *et al*., 2009; Jia *et al*., 2009 and Zhou *et al*., 2009.

Discussion

Ecotopes are the smallest ecologically-distinct landscape features in a landscape mapping and classification system. As such, they represent relatively homogeneous, spatially-explicit landscape functional units that are useful for stratifying landscapes into ecologically-distinct features for the measurement and mapping of landscape structure, function and change (Bastian *et al*., 2003). Like ecosystems, ecotopes are identified using flexible criteria, in the case of ecotopes, by criteria defined within a specific ecological mapping and classification system. Just as ecosystems are defined by the interaction of biotic and abiotic components, an ecotope classification should stratify landscapes based on a combination of both biotic and abiotic factors, including vegetation, soils, hydrology and other factors (Sørensen, 1936; Tansley, 1939; Costanza *et al*., 1997: Dobson *et al*., 1997: Assessment 2005).

The Loess Plateau is an example of a typical hilly and gully ecosystem. To develop an integrated management model on the basis of the ecotope theory proposed by Sørensen is crucial for its sustainability. In this paper, we bring together the methods, approaches and theories of arid agroecology which have been conducted over the last two decades on the Loess Plateau (Yang *et al*., 2005; He *et al*., 2007; Wang *et al*., 2009). Furthermore, we incorporate this previous work into the recent advances, and propose a new model of how to manage fragile arid agricultural ecosystem on the Loess Plateau (Li et al., 2003). The model aims to improve both vegetation cover and agricultural productivity to bring greater economic benefits to local farmers. Our study included a theoretical model and practical approaches to significantly improve the yields and water use efficiency of corn and alfalfa by developing double ridge-furrow and plastic-mulching, together with novel techniques of fallow and rotation tillage (Guo *et al*., 2010). Based on the rain-conservation agricultural model, the alfalfa-crop rotation has led to considerable improvement in agricultural cropping patterns, and promoted the update of agriculture and animal husbandry in the semiarid rainfed farming region of the Loess Plateau (Jia *et al*., 2006ab; Jiang *et al*., 2006; Liu *et al*., 2009; Jia *et al*., 2009; Zhou *et al*., 2009).

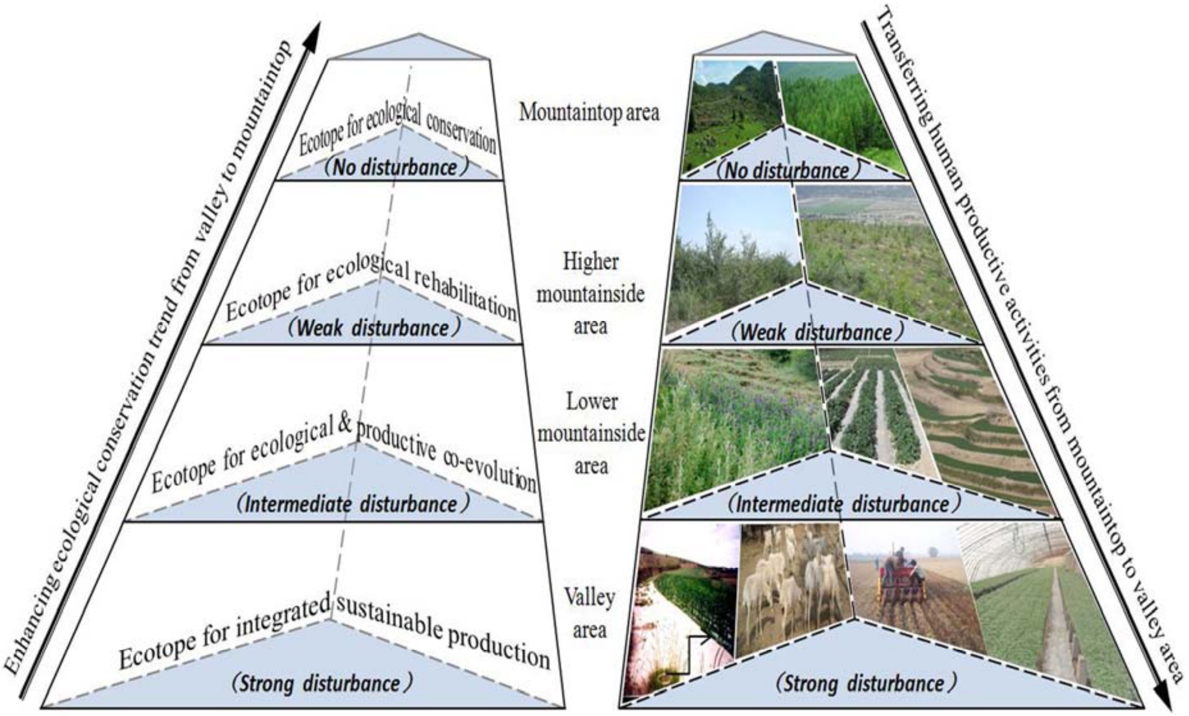

Fig. 3. Integrated Model of Stratified Strategies for Ecosystem Management (SSEM) in the Loess Plateau.
Note: There are four ecotopes according to vertical stratified principle due to hilly and gully terrain characteristics in the Loess Plateau.

Arid agro-ecosystem management has been developing at multiple scales from individual organisms to global ecosystems, and across the dimensions from natural to social ecosystems (Smith *et al*., 2003). The Stratified Strategies for Ecosystem Management (SSEM) is theoretically consistent with the perspectives of the 'drylands development paradigm (DDP)' proposed by Reynolds *et al*. (2007) and the 'coupled natural and human systems (CHANS)' of Liu *et al*. (2007). In this study, we summarized the ecological and socioeconomic performances of four big national recovery programs (GFGP, NFCP, TFCP and IRHA) conducted over last few decades on the Loess Plateau. The data quantitatively support the model, the Stratified Strategies for Ecosystem Management (SSEM) on the Loess Plateau (Fig. 3). At the top of the hills and higher slopes, the areas were placed in ecotopes for ecological conservation and ecological rehabilitation, respectively so that disturbance is zero and weak, respectively. We assigned an intermediate disturbance pattern and strong disturbance pattern on the lower hill slopes and valley areas, respectively, with ecotopes for ecological & productive co-evolution, and integrated sustainable production, respectively. Up the hillslope the ecological conservation gradually increases from the bottom to the top. Conversely, human productive activity is gradually transferred from the hilltops to the valleys (Fig. 3).

In conclusion, the approach to implement the 'coupled natural and human systems' requires ecological restoration to be boosted over large areas (mainly on fragile and infertile hilltops and steep slopes), and develop efficient agriculture in small but potentially productive areas (mainly on the lower slopes and flat valley bottoms). The proposed model may act as a paradigm to cope with the increasing challenges caused by global climate change and variability in arid agro-ecosystems in the coming decades.

Acknowledgements

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