Land use dynamics and landscape change pattern in Hetao irrigation district, Inner Mongolia, China

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ABSTRACT

This study analyzed spatial and temporal changes in land use in an irrigation district covering an area of 1.7 million ha in Northern China by GIS analyses and also investigated changes in landscape pattern using the landscape structure analysis program FRAGSTATS over the study period from 1986 to 2000. The decreases in farmland and the increases in grassland area mainly resulted from the policy of grain for green and converting slope farmland into pasture from China government. In spite of the efforts to conserve the fragile ecosystem, the land degradation, including soil salinization and grassland degradation, was spreading rapidly. The area of alkali-saline land increased by 22493 ha and about 50555 ha of dense grassland degraded into mid-density grassland. In terms of landscape fragmentation, both farmland and dense grassland showed the tendency of increased fragmentation. Both adverse natural conditions and human activities are responsible for the land degradation expansion in Hetao irrigation district, but the root causes are increasing population pressure and irrational human activities, such as flooding irrigation method and over-grazing. To prevent land degradation from spreading, population control and improvement of the management are prerequisite approaches.

Keywords: FRAGSTATS, GIS, land use change, landscape metrics, Irrigation District

1. INTRODUCTION

Irrigation district management has become an increasingly important issue in many countries including China, as nearly 80% of China's grain harvest are from irrigated land[1]. It is generally agreed that sustainable development and management of irrigated land for the welfare of local populations should be the key objective of irrigation district management. Effective management of irrigated land and other land resources in turn requires the understanding of the variability in time and the space of these resources.

In addition to area coverage, landscape pattern is an important characteristic for evaluating the processes and the effects of land use changes at class or landscape level. The concept is related to temporal and spatial heterogeneity and is emerging as an important field in the management and conversation of fragmented ecosystems at the local as well as the regional level [2].

There are various methods that can be used in the collection, analysis and presentation of resource data, but the use of remote sensing and geographic information system (RS/GIS) technologies can greatly facilitate the process [3,4]. Repeated satellite images are useful for both visual assessments of natural resources dynamics occurring at a particular time and space as well as quantitative evaluation of land use/land cover changes over time [5]. Analysis and presentation of such data, on the other hand, can be greatly facilitated through the use of GIS technology. A combined use of RS/GIS technology, therefore, can be invaluable to address a wide variety of resource management problems including land use and landscape change.

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In this paper, the land use and landscape change in Hetao irrigation district (HID), Inner Mongolia, China during the last 15 years was investigated. The objective of this study was to quantify changes in spatial and temporal pattern of land use and landscape and to create a basis for conducting land planning or setting up a sustainable development strategy in HID. Our particular objectives were: (i) to detect and document changes in major land use; (ii) to analyze patterns of changes in the landscape; and (iii) to trace the forces that have caused the changes of the study area during the period examined. The study used RS/GIS with substantial input from the field to achieve the stated objectives.

2. MATERIALS AND METHODS

2.1 Study area

Hetao irrigation district, covering an area of approximately 1.7 million ha, the third largest large-scale irrigation district in China and the largest irrigation system with one river mouth in Asia, is located between 106°20′~109°19′E and 40°15′~ 41°18′N, and it is 250 km in width from east to west and 50 km in length from north to south (Figure 1).

The history of HID could be dated back to the 2nd Century before Christ and a full-scale irrigation product was started about 100 years ago [4][6]. The whole irrigation-drainage system is mainly controlled by 13 main canals and 10 drainage ditches and has the Wuliangsu Lake as the drainage receiver (Figure 1). The area has become an important commodity grain base and holds an increasingly important social and economic position in Northern China.

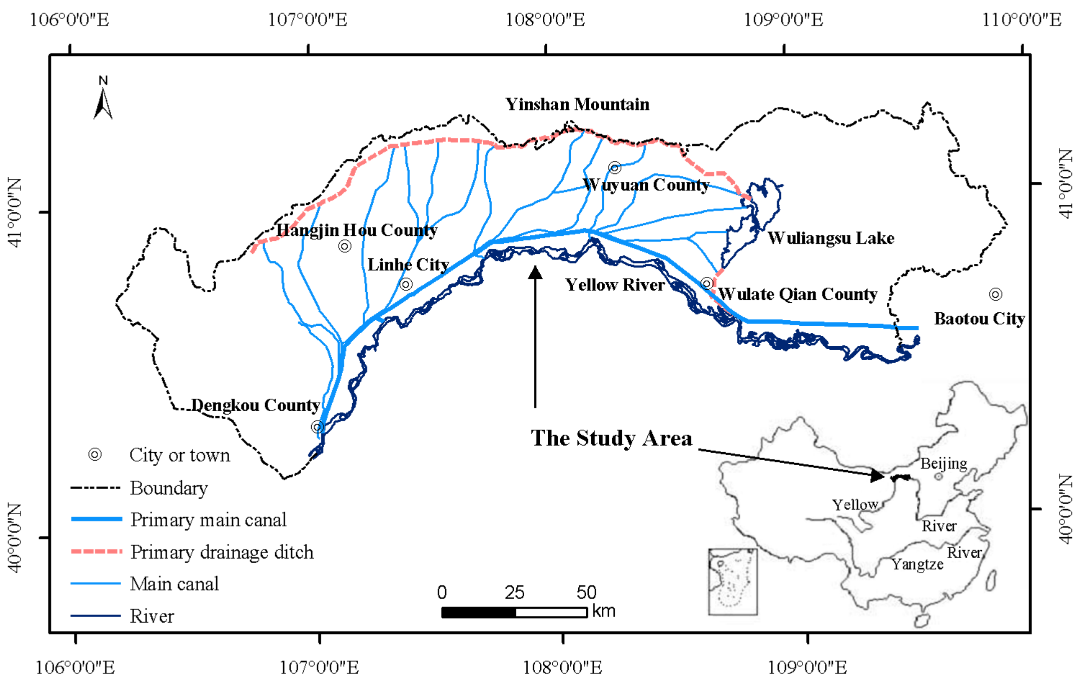

Fig. 1. Study area, location and irrigation and drainage system in Hetao irrigation district, Inner Mongolia, China

The climate of HID is continental with a dry season normally spanning from October to May and a rainy season from June to September. The annual precipitation is 165.6 mm and the annual evapotranspiration is 2177.3 mm (average for 1985-2000), which is over ten times of annual precipitation. This kind of natural condition determines that agriculture is impossible with no irrigation water from the Yellow River. The mean annual temperature is 6~8℃ and the relative humidity is 40~50%. The period of below-zero temperatures is 5 to 6 months, beginning from the middle ten days of November to the last ten days of April, and the largest soil depth it freezes to is 1.0~1.3 m. The frost-free period totals about 135~150 days. The wind is strong and frequent, with an annual wind speed of 2.8-2.9 m/s and the maximum wind speed of 23 m/s.

Soil in the study area has been developed from alluvial deposits from the Yellow River. Based on the soil map of the world, the soils in HID are mainly classified as mollic gleysols, eutric gleysols and calcic xerosols, and the phases of all these three soil units are saline [7]. Agricultural lands, including farmland and grassland, in the district are mostly irrigated. Spring wheat, maize, sunflower and sugar beet are major crops cultivated in the area. The main natural vegetation type is meadow.

There are one city and four counties in the study area, named Linhe City, Dengkou County, Hangjin Hou County, Wuyan County and Wulate Qian County (Figure 1). Linhe city is the administrative government of Bayannur League, of which other four counties also locate within. Dengkou county is a part of Mongolia Plateau, composed of mountainous region, desert land and plain and the altitude varies between 1030 and 2046 m. Linhe city, Hangjin Hou County and Wuyuan County all originated from alluvial plain of the Yellow River, and the altitude varies between 1045 and 1209 m. Wulate Qian County is composed of three parts, hill grassland, hill farmland and irrigated area from the Yellow River.

2.2 Data sources

Data used in this study were mainly obtained from two land-use maps dating 1986 and 2000. Both maps at scale of 1:100000, classified into 6 first levels and 25 second levels of land-use categories in total, are drawn based on the Landsat TM (Thematic Mapper) data through human-machine interactive interpretation to guarantee classification consistency and accuracy and stored in the National Resources and Environments Database of China. After images being geometrically corrected and geo-referenced, the average location errors are less than 50 m (about 2 pixels). The field survey and random sample check testified that the average interpretation accuracy for land use is 92.9% [8] [9].

The land use maps in HID are compiled based on the above database with the support of the GIS software - ArcGIS. The procedures can be described as follows:

(1) Formulate a classification system of the land use types in HID. A total of 10 types were identified (Table 1);

(2) Re-classify the 25 land-use types into 10 types in accordance with their properties such as physico-geographical conditions, soil type, utilization variance and covering degree of vegetation.

(3) Give a new attribute to each polygon in the land use maps, dissolving the polygons with the same type.

Table 1. Land use types in Hetao Irrigation District and their description

No.	Land use types	Description
1	Farmland	Lands covered with temporary crops followed by harvest and a bare soil period (main crops: spring wheat and maize)
2	Forested land	Lands with seasonal broadleaf trees, shrub or apples
3	Dense grassland	Lands with herbaceous types. The canopy cover is over 60%
4	Mid-density grassland	Lands with herbaceous types. The canopy cover is 20- 60%
5	Sparse grassland	Lands with herbaceous types. The canopy cover is 5-20 %
6	Water area	Rivers, lakes, reservoirs, wandering river bed, irrigation and drainage canals
7	Residential area	Land covered by buildings and other man-made structures
8	Sandy desert	Lands expose sand and never have more than 5% vegetated cover
9	Alkali-saline land	Lands covered with salt or alkali and little or even no vegetation
10	Swampland	Land of swampy consistency or having many swamps on it

2.3 Methods

As Lambin *et al.* pointed out that the key themes in land use change include patterns of land use change, processes of land use change, development of databases on land surface, biophysical processes and their drivers [10]. A transition probability matrix was established with the help of ArcGIS to define the mutual transition regimes of various land use types for process analysis of land use change[11][12]. The land use data for 1986 and 2000 were overlaid in ArcGIS and the area converted from each of the classes to any of the other classes was computed.

The change of landscape pattern was analyzed using the landscape structure analysis program FRAGSTATS, developed by the Forest Science Department, Oregon State University, U.S.A. [12][13]. FRAGSTATS can calculate more than 60 landscape indices. For the analysis of landscape pattern at class level, six indices were selected, including number of patches (NP), mean patch size (MPS), area-weighted mean shape index (AWMSI), coefficient of variation of patch area

(PSCV), mean proximity index (MPI), and interspersion and juxtaposition index (IJI). The definition and description of these indices in FRAGSTATS are given by the FRAGSTATS user's guide or FRAGSTATS' website [14]. The raster version of FRAGSTATS was used in this study to ensure that a great number of indices could be calculated. Several important considerations in the calculations are that the grid resolution is 50 m, all the boundary weight values are equal to one (i.e. the landscape boundaries are treated as maximum-contrast patch edges), and the search distance used in the calculation of proximity index is 2500 m.

3. RESULTS

3.1 Changes in land use

The change in different cover types is one of the major indicators to show general changes of the landscape. The area under the ten land use types during the two periods is shown in Table 2. Results show that the areas of farmland, dense grassland, sandy desert and swampland decreased while all the other land use types increased. A detail of losses and gains among the ten land use types over the study period is included in Table 3. The transition replacement rates of farmland, dense grassland and swampland were very high at 11.7%, 27.9% and 20.7%, respectively. Residential area had the lowest transition rates of nearly zero.

Table 2. Changes in area for different land uses between 1986 and 2000 in HID (ha)

Land use types	1986		2000		Changes	
	ha	%	ha	%	ha	%
Farmland	613684	35.1	556413	31.8	-57271	-3.3
Forested land	47288	2.7	48026	2.7	738	0.0
Dense grassland	187935	10.8	139919	8.0	-48016	-2.7
Mid-density grassland	294351	16.8	367107	21.0	72756	4.2
Sparse grassland	91849	5.3	106209	6.1	14360	0.8
Water area	59017	3.4	60226	3.4	1209	0.1
Residential area	118932	6.8	121537	7.0	2605	0.1
Sandy desert	269233	15.4	264679	15.1	-4554	-0.3
Alkali-saline land	41792	2.4	64285	3.7	22493	1.3
Swampland	23210	1.3	18889	1.1	-4321	-0.2

Table 3. The transition matrix of land use types in HID from 1986 to 2000 (%)

1986	2000									
	Farmland	Forested land	Dense grassland	Mid-density grassland	Sparse grassland	Water area	Residentia area	Sandy desert	Alkali-saline land	Swamp land
Farmland	**88.3**	0.2	0.4	6.0	2.2	0.3	0.2	0.1	2.2	0.0
Forested land	1.0	**96.6**	0.1	2.0	0.2	0.0	0.0	0.0	0.1	0.0
Dense grassland	0.4	0.1	**72.1**	26.9	0.1	0.2	0.0	0.3	0.0	0.0
Mid-density grassland	2.5	0.2	0.7	**93.9**	1.0	0.2	0.2	0.0	1.2	0.0
Sparse grassland	1.3	0.0	0.0	0.1	**93.1**	0.0	0.8	0.7	4.0	0.0
Water area	0.1	0.1	0.0	1.3	0.8	**96.7**	0.0	0.4	0.4	0.2
Residential area	0.0	0.0	0.0	0.0	0.0	0.0	**100.0**	0.0	0.0	0.0
Sandy desert	0.5	0.0	0.0	0.2	1.0	0.1	0.0	**97.5**	0.5	0.1
Alkali-saline land	1.8	0.0	0.0	1.9	1.1	0.0	0.0	0.0	**95.1**	0.0
Swampland	9.7	0.3	0.0	0.8	0.8	0.4	0.0	0.0	8.6	**79.3**

Although the transitions among different patch types were quite complex, farmland and mid-density grassland remained the most predominant types. Among the major land use types, around 88% of farmland and 72% of the dense grassland area remained unchanged until 2000. The very high losses from these two land use types were only partially compensated by gains from other types resulting high net losses to both of these land uses. Mid-density grassland lost 6.1% of its 1986 area to other types and gained 24.7% from other types resulting in a net gain of 72756 ha (10% of the farmland and 13.8% of the dense grassland area) during the period examined (Table 2 and Table 4). Sandy desert shrank by about 1.7% of 1986 area in between 1986 and 2000 (Table 4).

Table 4. Overview of changes in major land use types between 1986 and 2000 in HID (%)

Land use types	Percent of land use in 1986 Unchanged in 2000	Lost to other classes in 2000	Gained from other classes in 2000	Net gain/loss
Farmland	88.3	11.7	2.6	-9.1
Dense grassland	72.1	27.9	3.2	-24.7
Mid-density grassland	93.9	6.1	24.7	18.6
Sandy desert	97.5	2.5	0.8	-1.7

3.2 Changes in landscape pattern

Table 5 shows the dynamics of major landscape indices at class level. From the comprehensive analysis of the table, we have obtained the following results.

Table 5. Dynamics of major landscape indices at class level in Hetao Irrigation District

	TYPE	NP	MPS (ha)	AWMSI	PSCV	MPI	IJI
1986							
1	Farmland	1833	334.8	27.3	1057.8	16561.7	71.3
2	Forested land	702	67.4	2.5	190.3	53.1	69.0
3	Dense grassland	552	340.5	4.0	292.8	309.5	61.3
4	Mid-density grassland	2797	105.2	5.1	447.2	243.0	51.3
5	Sparse grassland	1002	91.7	3.4	211.3	36.1	64.2
6	Water area	395	149.4	2.7	311.2	51.1	80.3
7	Residential area	3367	35.3	2.2	192.0	21.0	36.8
8	Sandy desert	443	607.7	4.7	377.4	6294.7	72.2
9	Alkali-saline land	466	89.7	2.7	150.3	28.5	61.4
10	Swampland	300	77.4	2.4	170.3	6.0	73.6
2000							
1	Farmland	1829	304.2	26.4	1043.9	13835.8	71.1
2	Forested land	697	68.9	2.4	177.9	51.0	70.6
3	Dense grassland	535	261.5	3.2	229.5	90.2	64.1
4	Mid-density grassland	2594	141.5	6.6	599.8	693.1	55.3
5	Sparse grassland	1026	103.5	3.5	225.6	46.5	68.1
6	Water area	361	166.8	3.1	296.3	45.1	81.5
7	Residential area	3395	35.8	2.2	191.1	22.0	40.1
8	Sandy desert	445	594.8	4.7	383.3	6429.0	73.2
9	Alkali-saline land	543	118.4	3.9	187.7	70.3	57.5
10	Swampland	292	64.7	2.4	169.1	5.9	74.9

Mid-density grassland was the highest variable landscape patch type. Its area increased from 294351 ha in 1986 to 367107 ha (table 2), whereas its number of patches decreased from 2797 in 1986 to 2591 in 2000 and the mean patch size increased to 622 ha from 459 ha in 1986. The mean proximity index of patches was almost thrice the original value and the interspersion and juxtaposition index also increased (Table 5). These changes of landscape indices reflect that the distribution of mid-density grassland was less fragmentary and the discrete degree among patches became less discrete in 2000 than in 1986. During the 15 years period studied, mid-density grassland has expanded, which was mainly at the cost of the decline of dense grassland. The number of dense grassland patches decreased from 553 to 536, and mean patch size decreased by 156 ha. The interspersion and juxtaposition index increased, but mean proximity index decreased to one-third of the original value, meaning that dense grassland tended to be fragmented and the discrete degree among patches was much higher than before.

4. DISCUSSION

Spatial and temporal databases have been used to assess the changes in land use and landscape patterns over a 15-year period using land use transition and landscape indices as process indicators in Hetao irrigation district.

4.1 Land use change from 1986 to 2000

The observed trends of continuously decreasing farmland areas could be explained by the following three main reasons. Firstly, a substantial proportion of farmlands in Wulate Qian County are in inclinations above 25° where slop stability and soil erosion is of critical concern. Those steep farmlands suffer from rapid soil erosion and nutrient depletion, which forces farmers to turn their agricultural plots into grassland after a few seasons of cultivation. Recent studies on the farmland in China have found that many farmlands in Inner Mongolia have been converted to grassland in recent years in order to prevent soil erosion and land degradation under the policy of grain for green and converting slope farmland into forest or pasture from China government [15][16]. There is evidence also from Inner Mongolia [17] that many households support the policy of grain for green for a sustainable ecological environment. In addition to local user groups, the local governments have also been involved in environment protection and have been providing financial and moral supports to the local farmers for the conversion of farmland into grassland[18].

Secondly, low yield and poor land quality force farmers to abandon this kind of unproductive farmlands. As shown in Table 2 and Table 3, farmland lost about 13501 ha of its 1986 area to sparse grassland in 2000. This kind of land transition mainly happed in Dengkou County, where the area of desert land account for over 60% of the whole county and the formidable natural conditions in addition with declining soil productivity and limited water resource constrain the cultivation of farmland.

Thirdly, seriously salt-affected agricultural plots were abandoned with more and more salt accumulated on the ground surface. In the process of soil salinization, natural conditions such as enclosed topography and evaporation in great excess of precipitation play the decisive role, but the role of human activity is also an assignable cause. In the long history of irrigation, inappropriate water and land use practice like flooding irrigation, irrigation with no timely drainage, extensive cultivation in agriculture and monoculture of growing crops are all reasons leading to soil salinization [19].

The process of soil salinization, however, was not alone in farmland. As Table 3 indicated, except dense grassland and residential area, there is transition to alkali-saline land from all the other land use types. Resulty, the area of alkali-saline land got a net gain of 22493 ha in spite of improvement of some alkali-saline land into farmland and grassland. As mentioned above, all the phases of three soil units in HID are saline, which means that the soil in HID is prone to salinization that is significant to the use or the management of land. However, many drainage ditches were out of order because of no regular maintenance and less attention was paid to discharge outlet. Thus the groundwater table was elevated under the long-term flooding irrigation and the groundwater then took part in evaporation. Under the condition of large evaporation, more and more salt were accumulated on the land surface, resulting in increased alkali-saline land.

Although there was a net increase in mid-density grassland area, it was mostly at the expense of dense grassland besides farmland with about 36821 ha conversion from farmland and 50555 ha from dense grassland respectively during the study period (Table 2 and Table 3). Some earlier studies in Bayannur League have found that grassland degradation is increasingly serious[20][21]. From conversions with local farmers it was revealed that the degradation area of grassland increased continuously over the study period. Many factors may have contributed to the grassland degradation in HID, including overgrazing and climatic fluctuations. Although it may still be debatable, the results of numerous studies since the 1950s have strongly suggested that anthropogenic factors (especially overgrazing) are primarily responsible for the grassland degradation [22][23][24]25]. This has much to do with rapidly growing human population and livestock number over the past 15 years. For example, the county of Hangjin, which is located within HID (see Figure 1), experienced a rapid growth in human population from 269,500 in 1986 to 298,300 in 2000 and an even faster increase in the number of livestock from 429,200 to 1.102 millions for the same time period [26][27]. Because of the low investment in grassland construction and the relatively low output of natural grassland, farmers try to increase the amount of livestock in order to increase their income without consideration to the potential impacts resulting from the increase of livestock. Consequently, not only in HID but also in the whole Northern China over-grazing has been prevailing and resulted in wide grassland degradation [20]. Owing to the selection for prey by livestock the grasses become low and sparse, edible herbs of high quality decreased while toxic herbs increased. Viewed from the point of social institution, Erdenzhab suggests that variations in stockbreeding price system, the limitation in the system of land property right and the 30-year land contract system should also be the important reasons leading to predatory management and grassland degradation[21].

4.2 Changes in landscape metrics

Under the disturbance of natural and human forces, the landscape will be changed from simply to complexly and this process is called landscape fragmentation [28]. Of the landscape indices chosen in this study, MPI (mean proximity index) and MPS (mean patch size) could show the process of fragmentation.

As for farmland, not only its mean patch size but also its mean proximity declined, which means the fragmentation increased. Through field survey it was revealed that alkali-saline land converted from seriously salt-affected farmland scatted in the farmland landscape, adding to the fragmentation of farmland. In addition, expansion of settlements, other constructions, and infrastructural developments were mostly at the cost of farmland in Linhe City and increased fragmentation.

There are also two possible reasons for increased fragmentation of dense grassland. Firstly, about 2455 ha of grassland in 1986 was reclaimed into farmland for the sake of economic benefit (see Table 2 and Table 3). Secondly, overgrazing and soil erosion led to the degradation of slope grassland into sandy desert mainly in Wulate Qian County.

Although mid-density grassland showed no tendency of fragmentation, its low productivity would impede further development of livestock breeding, let alone sparse grassland.

Forested land showed no trend of fragmentation in addition to its increased area. However, it mainly resulted from the increased orchard area according to detail land use data. There was little change in the area of protection forest. Ci showed that constructing protection forest in form of a net, patch or belt is the most effective way to improve agricultural conditions, maintain ecological balance, and protect the development of agriculture and grazing in a fragile ecosystem like HID[29]. For the economical benefit, farmers chose to plant more fruit trees and ignored the fact that the fragile ecosystem needs more protection forest to refrain from further deterioration.

5. CONCLUSION

The quantitative evidences of land use change and landscape pattern presented here, which were delivered by GIS and FRAGSTAST analyses, corroborate the findings of some earlier studies that a number of factors, both natural and induced by human activity, act on the fragile ecosystems and agricultural land (farmland and grassland) to cause increasing problems with soil salinization and progressive degradation of grassland[17][18][19][20][21].

In terms of total area, it is obvious that the main cause for decreasing farmland and increasing grassland was the policy of grain for green and converting slope farmland into forest or pasture from China government. This kind of conversion has been growing year-by-year since 1989 [30]. The data may be indicative of China's attempts to put sustainable development, one of the country's basic national policies, into practice. The aim is to strengthen the protection and rational use of ecosystems and the environment. However, in spite of efforts to protect and improvement of some alkali-saline and swampland, land resources in HID has been severely threatened by land degradation and the major types of land degradation in HID are soil salinization, grassland degradation, and soil nutrient depletion. Both adverse natural conditions and human activities are responsible for the land degradation expansion. In HID, the earth's surface consists of sandy sediments, the saline phase of all the soil units is prone to salinize, the strong wind is concentrated in dry seasons from winter to spring with little rain and no vegetation cover and the evaporation is large year round. Undoubtedly, the fragility of ecosystems and the saline phase of soil are the prerequisite for the occurrence and development of land degradation. But the natural factors are not the root cause of degradation development in this area. It was reported that irrigation water from the Yellow River washed off the salt in soil so that the seeds of crop could germinate. However, inappropriate water and land use practice like flooding irrigation, irrigation with no timely drainage, extensive cultivation in agriculture led to secondary salinization [7][19]. Due to livestock development, severe over-grazing is the main cause of the spread of degradation in grassland.

As a consequence of some combination of these factors, land resources are more prone to land degradation. It is worth mentioning that salinization of farmland can cause a significant drop in land productivity long before land is officially classified as "salinized" [31]. In addition, grassland degradation has impeded further development of livestock breeding which is another main economic activity in this area.

The root causes of degradation in the study area seem to be large and increasing population pressure and mis-management. According to the statistics by local government, the population has increased by 20% from 1986 to 2000 [23] [24]. The people rely only on the land for their income, as agriculture and livestock breeding are the main economic activities in this area. On the other hand, management and some of the traditional techniques like flooding irrigation are very extensive. But little attention has been paid to the potential impetus of large population and the poor management to land degradation at present. Much money has been invested in the improvement of irrigation and drainage canal system; simultaneously, however, land resources in HID have continued to degrade in wider areas.

To prevent the land degradation from spreading, population control and improvement of the management are prerequisite approaches. Special consideration should be given to seek both economic and environmental benefits in accordance with local conditions. Land management decision should be made based on the unity of social benefit, economic revenue and ecological effectiveness. If just the economic revenue is focused on, it is impossible to keep sustainable development in such a fragile ecosystem.

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