

Pattern of agricultural and pastoral development under water resource constraints in semi-arid areas: A case study of Tongliao, Inner Mongolia

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Abstract. In semi-arid areas (SAAs) of China, long-term excessive agricultural development has seriously damaged the original functional pattern of agricultural and pastoral development (APD), which gives rise to a series of ecological problems such as lowering of water table, vegetation degradation, and desertification. Converting farmland to pastures is an effective solution to the ecological problems associated with excessive agricultural activities. The purpose of this study was to provide a scientific basis for making a targeted policy on conversion of farmland. Through GIS spatial analysis, the study investigated the current functional pattern of APD in Tongliao and compared it with the pattern obtained under water resource constraints. The results show that excessive agricultural activities are currently taking place in 30 villages and towns in Tongliao, such as the town of Dalin Town. One suggestion is that these 30 villages and towns should be given priority when implementing the policy of converting farmland to pastures in future, in order to coordinate their APD. The findings of the study can offer theoretical support to help achieve coordinated APD in this city.

1. Introduction

Semi-arid areas are typically characterized by ecological vulnerability [1]. In China, SAAs are distributed mainly along the southern edge of the Inner Mongolia Plateau and the Great Wall. These areas range in annual precipitation from 200 to 400 mm and in aridity from 1 to 2. The long-term, large-scale agricultural activities there have disturbed the balance of regional aquatic ecosystems and caused the ecological environment to deteriorate, as indicated by the water scarcity, grassland degradation, desertification, etc. [2]. Over the past decades, the supply of crops and milk products from these SAAs has met the demand of over one hundred million people. However, after long-term extensive production and management, the productivity of farmland in these areas declined to a low level, at 1100 yuan per *mu*. In response, peasants arbitrarily convert grassland to cropland in an attempt to increase yield and income. Consequently, the unreasonable expansion of farmland disturbed the original mode of agro-pastoral development. In this context, in-depth research into the pattern of APD is expected to provide reliable theoretical support to help restore rational agricultural and pastoral production.



The continuous intrusion of farmland into natural grasslands due to imbalanced agricultural and pastoral production is a major cause of ecological damage in SAAs. So the pattern of APD becomes a hot topic for relevant research. Strong human disturbance has resulted in drastic changes in the spatial distribution of semi-arid environments. Both the overlay analysis by Jiang *et al* [3] and the land use/cover change (LUCC) analysis by Dong *et al* [4] reveal that China's SAAs are suffering from continuous deterioration of ecological environment. Land use change is often used as a basis for functional zoning of land. Gao *et al* [5] employed the CA-Markov model to analyze and predict the pattern of land use change in an agro-pastoral ecotone in northern China. Using multi-agent simulation, Gong *et al* [6] studied the driving mechanism behind land use change in an agro-pastoral region and their results can enrich the theory about functional zoning. Based on the theory about functional zoning, Xu *et al* [7] studied sustainable development under different agricultural and pastoral land patterns in a semi-arid region through system dynamic simulation. Their findings provide the governments of semi-arid regions with useful guidance on making development policies. Despite the fruitful research on the spatial pattern of agricultural and pastoral land, more thorough research is still needed into the pattern of APD in SAAs in order to theoretically support the efforts to recover reasonable pattern of agricultural and pastoral land and promote sustainable development there.

2. Overview of the study area

Semi-arid areas are widely distributed in China, spreading over 11 provinces or autonomous regions such as Inner Mongolia, Hebei, and Shaanxi [8]. For the study to be targeted, Tongliao City of Inner Mongolia, a typical semi-arid region, was selected as the object of the study [9].

Tongliao is located in the eastern part of Inner Mongolia Autonomous Region, at latitudes 42°15'~45°41'N and longitudes 119°15'~123°43' E. It stretches about 418 km from north to south and 370 km from east to west, covering an area of 59,535 km². This city has a temperate continental climate, with an average annual temperature of 0-6°C and average annual precipitation of 350-400 mm, and an average annual evaporation about five times the amount of precipitation. In 2014, its total population is 3.126 million, 62.04% of which depend on agriculture for their livelihoods. As for industrial structure, the primary, secondary, and tertiary sectors account for 15%, 51%, and 34%, respectively, of the city's economy. According to Chenery's theory of standard industrial structure and stages of industrialization, Tongliao remains in the initial stage of socio-economic development. The primary sector consists predominantly of agricultural and pastoral production (90%). Agricultural production requires a huge amount of water because the majority of farmland is irrigated land. Xiliao River system is the main river system of Tongliao. Due to global warming, approximately 90% of the city's rivers and over 70 small- and medium-sized water reservoirs have dried up, leading to a shortage of surface water resources. To ensure water supply for industrial and agricultural use, groundwater is extracted on a large scale. Statistics show that some 85% of the groundwater withdrawal is used for agricultural irrigation. The years of extraction result in a significant drop in the water table, and the ensuing ecological problems such as grassland degradation and desertification have a serious impact on the sustainability of local economic growth. It has been found that excessive agricultural production on land unsuitable for farming is the root cause of high water consumption for irrigation and associated ecological issues. This study investigated the pattern of APD under water resource constraints, with an aim to offer useful theoretical guidance on appropriate development of agricultural land in SAAs.

3. Data sources and methods

3.1. Data sources

Five categories of data were used in this study. Category 1 is the data on pattern of ecosystems across China and released by Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. It mainly includes a dataset of ecosystem structures extracted from Landsat TM images by full digital interactive interpretation and the ecosystems involved include grassland, farmland, forests,

deserts, wetlands and waters, human settlements, etc. Category 2 is statistical data, mainly including Statistical Yearbook of Tongliao (2000-2015), statistics about the banners and counties in Tongliao (2000-2015), Tongliao Water Resources Bulletin (2000-2015), and Tongliao Water Conservance Bulletin (2000-2015). Category 3 is observational data, including water table observations from 80 observation wells in Tongliao for the past 30 years. Category 4 is the auxiliary GIS data supplied by National Administration of Surveying, Mapping and Geoinformation, mainly including administrative boundaries of the city and counties within it. Category 5 is nighttime light images (spatial resolution $100\text{ m} \times 100\text{ m}$) made available by the National Oceanic and Atmospheric Administration (NOAA).

3.2. Methods

This study involved the use of analytic hierarchy process (AHP) and GIS spatial analysis.

3.2.1. AHP. AHP is a systematic approach to organizing a complex multi-objective decision problem into a hierarchical system. This can be achieved by decomposing the goal to multiple objectives or criteria and determining the priorities of elements on each level and overall priorities for each criteria through fuzzy quantification of qualitative indicators. In this study, an index system was created for assessing the pattern of APD in Tongliao under water resource constraints. It consists of 12 indicators across the following four categories: natural conditions, socio-economic conditions, land use, and water resource constraints. The first three categories of indicators can well reflect the situation regarding APD in a general region. But for SAAs suffering from water scarcity, it is necessary to consider the constraints imposed on APD by water resources. Then AHP was employed to comprehensively evaluate the index system and determine the weights to be given to the indicators. The results are presented in table 1.

Table 1. The division index system of agriculture and animal husbandry function under the restriction of water resources.

Target layer	Criteria layer			Indicator layer		
	Code	Indicator	Weights	Code	Indicator	Weights
Agricultural and pastoral development Index (APDI) A ₁	B ₁	Natural condition	0.1841	C ₁	Topographic relief(TR)	0.0553
				C ₂	Precipitation(PCP)	0.0924
				C ₃	Total water resources(TWR)	0.0818
				C ₄	Ecological background conditions(EBC)	0.0483
				C ₅	Geological hazard conditions(GHC)	0.0291
	B ₂	Social and economic condition	0.1228	C ₆	Public finance income(PFI)	0.0845
				C ₇	Population density(PD)	0.0579
				C ₈	Traffic dominance(TD)	0.0339
				C ₉	Night light index(NLI)	0.0283
	B ₃	Land use	0.2931	C ₁₀	Proportion of cultivated land(PCL)	0.4885
	B ₄	Water resources Restrictions	0.4	C ₁₁	Groundwater rate(GWR)	0.2016
				C ₁₂	Available water resources(AWR)	0.1984

3.2.2. GIS spatial analysis. The agricultural and pastoral development index (APDI) was calculated by GIS spatial analysis for the 78 villages and towns within Tongliao.

- Calculation of the indicators. Based on interpretation of remote sensing images, spatial interpolation was performed with ArcGIS 10.2 to assess the 78 villages and towns in terms of the 12 indicators. The assessment method is illustrated with the example of Relief Degree of Land Surface (RDLS). RDLS is a composite indicator for characterization of elevation and relative height of a terrain. It can be calculated from digital elevation model (DEM) data using the following equation:

$$RDLS = ALT/1000 + \{[Max(H) - Min(H)] \times [1 - P(A)/A]\} / 500 \quad (1)$$

where RDLS represents the relief of a terrain; ALT denotes the average elevation of a given area centered on a certain grid cell (m); Max (H) and Min (H) are the maximum and minimum elevations within this area, respectively (m); P (A) is the area of land with a slope no higher than 5° (referred to as flat ground) in this area (km²); and A is the total area of this area, which is derived from DEM data. A DEM was constructed using a combination of TIN algorithm and linear and bilinear interpolation. A rectangular grid measuring 30 m × 30 m was the basic unit for assessment and thus A = 0.9 km².

- APDI. The weights of the 12 indicators were calculated for each village or town to derive its APDI. The method is described by the equation below:

$$APDI = TR \times 0.0553 + PCP \times 0.0924 + TWR \times 0.0818 + EBC \times 0.0483 + GHC \times 0.0291 + PFI \times 0.0845 + PD \times 0.0579 + TD \times 0.0339 + NLI \times 0.0283 + PCL \times 0.4885 + GWR \times 0.2016 + AWR \times 0.1984 \quad (2)$$

- Standardization of APDI. The APDI values derived for the 78 villages and towns were then standardized using the following standardization formula:

$$X'_{ij} = \frac{X_{ij} - \min\{X_{ij}\}}{\max\{X_j\} - \min\{X_j\}} \quad (3)$$

- APDI rating. Based on their standardized APDI values, the 78 villages and towns can be rated as agricultural ($1 \geq APDI \geq 0.8$), agro-pastoral ($0.8 > APDI \geq 0.2$), or pastoral ($0.2 \geq APDI \geq 0$).
- Then the functional pattern of APD under water resource constraints in Tongliao was obtained by plotting the results of APDI rating on a map of the city with ArcGIS 10.2.

4. Functional patterns of APD

4.1. Current functional pattern of APD

The current rapid growth in Tongliao's agriculture is driven by three major factors. First, from the perspective of natural conditions, the city's flat terrain is suitable for large-area mechanized farming, thus facilitating agricultural development. In terms of policy, the government regulation of grain prices can protect the rights of peasants and ensure supply in the grain market, which greatly motivates local peasants to engage in farming. In technological terms, the practice of mechanized farming substantially cuts the labor cost of farming, thereby making rural people more determined to participate in agricultural production. So local rural residents actively reclaim farmland from uncultivated land, especially pastures and land of ecological significance, breaking the original balance of agro-pastoral ecosystem. Moreover, as Tongliao's precipitation is too low to meet crops' water demand, irrigation has become the first choice to ensure steady yield. The high water consumption for irrigation, together with the warming climate and reduction in water from higher land, has led to disappearance of nearly 90% of local surface water. In response, groundwater becomes a primary water source for industrial and agricultural production. The groundwater overdraft during the past 20 years has lowered the water table in most parts of Tongliao, with Khorchin District showing the most rapid lowering of water table. This trend has caused irreversible changes in the ecological environment, such as grassland degradation, desertification, and biodiversity decline. In particular, local aquatic ecosystems are deteriorating apparently. Therefore, proper measures must be implemented to control agricultural growth. Investigation into the current functional pattern of APD

can provide important guidance on how to make proper policies for this purpose.

Based on the results of field surveys of the villages and towns involved, farmland and pastures in Tongliao were delineated on remote sensing images with ArcGIS10. The spatial distribution of the two land use types in these villages and towns was then obtained based on the images and the city's administrative map. If a town's farmland ratio was greater than 70%, the town was considered an agricultural zone. If the farmland ratio was between 30% and 70%, the town should be an agro-pastoral zone. A farmland ratio lower than 30% indicates a pastoral zone. Then the functional types corresponding to the farmland ratios of the villages and towns were marked on the city's map to obtain the current functional pattern of APD (figure 1). As shown in the figure, 51, or 65.38%, of the 78 villages and towns were agricultural zones, representing 45.89% of the city's total area. 21 or 26.92% of the villages and towns were agro-pastoral zones, representing 34.17% of the city's total area. Only 6 or 7.69% of these villages and towns were pastoral, and their area ratio was 19.94%.

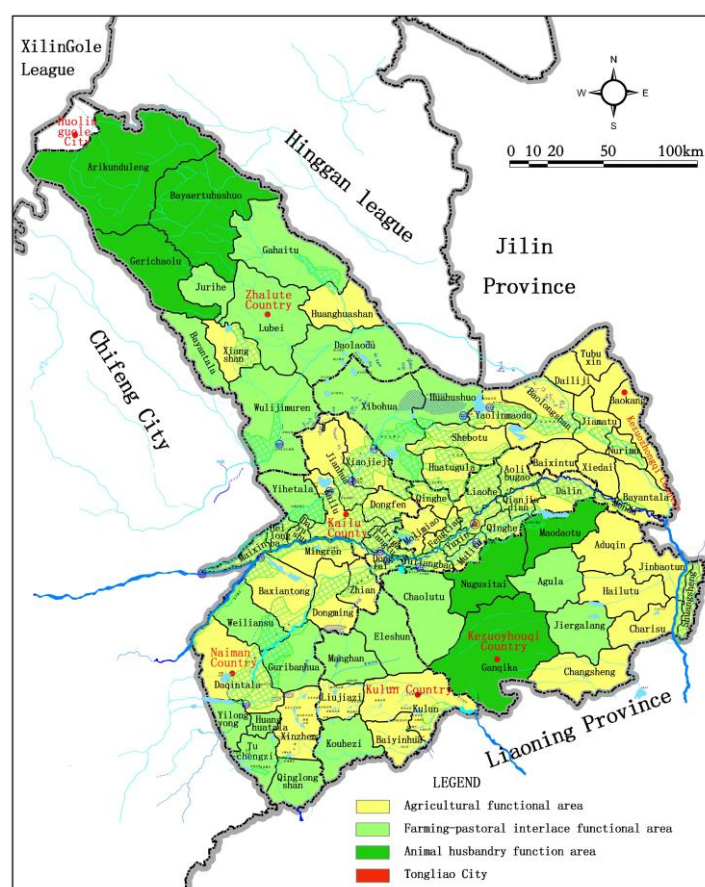


Figure 1. Current functional pattern of agricultural and pastoral development.

4.2. Functional pattern of APD under water resource constraints

It is clear that the long-term excessive development of agriculture have seriously disturbed the original pattern of APD in Tongliao, which has attracted high attention from the government and academia. It is widely accepted that only by restricting the expansion of agricultural land and converting farmland to pastures can the situation be solved. However, as excessive agricultural activities do not occur in all parts of Tongliao, it is necessary to identify the regions suffering from excessive farming and then develop a targeted development policy. Therefore, further analysis of APD pattern under water resource constraints can offer a scientific support for the government to formulate targeted policies on conversion of farmland to pastures.

4.2.1. Results of indicator calculations. The 12 assessment indicators were calculated for the 78 villages and towns using GIS spatial analysis. The results were plotted on Tongliao's map with the help of ArcGIS10.2 (figure 2).

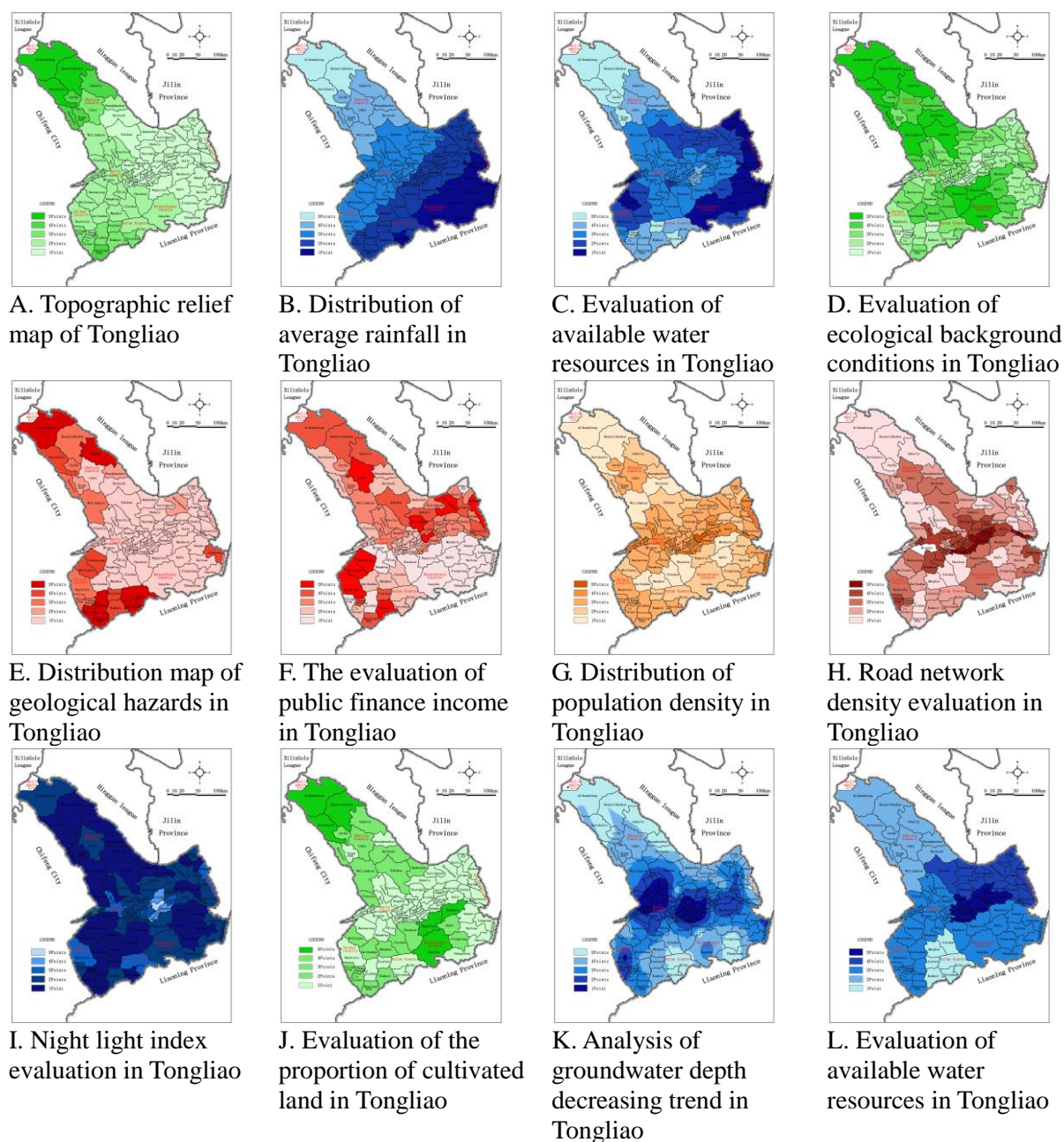


Figure 2. Calculation results of 12 indicators.

4.2.2. Results of APDI calculation. The APDI values of the 78 villages and towns were calculated from the values of the 12 assessment indicators and corresponding weights using equation (2). The index results were then standardized using equation (3). Based on the standardized index values, these villages and towns were classified into three types of functional zones: agricultural, agro-pastoral, and pastoral. By plotting the results on the city's map, the functional pattern of APD under water resource constraints was derived (figure 3). As can be seen in the figure, 27 villages and towns (sumu) (34.62% of the total number) were rated as agricultural, representing 22.62% of Tongliao's total area. 40

villages and towns (sumu), or 51.28% of the total number, were agro-pastoral, accounting for 49.33% of the city's total area. There were 11 pastoral villages and towns (sumu), representing 14.01% of the total number and 28.05% of the city's total area. This distribution pattern is a satisfactory APD pattern and is expected to be achieved after implementation of the policy of returning farmland to pastures.

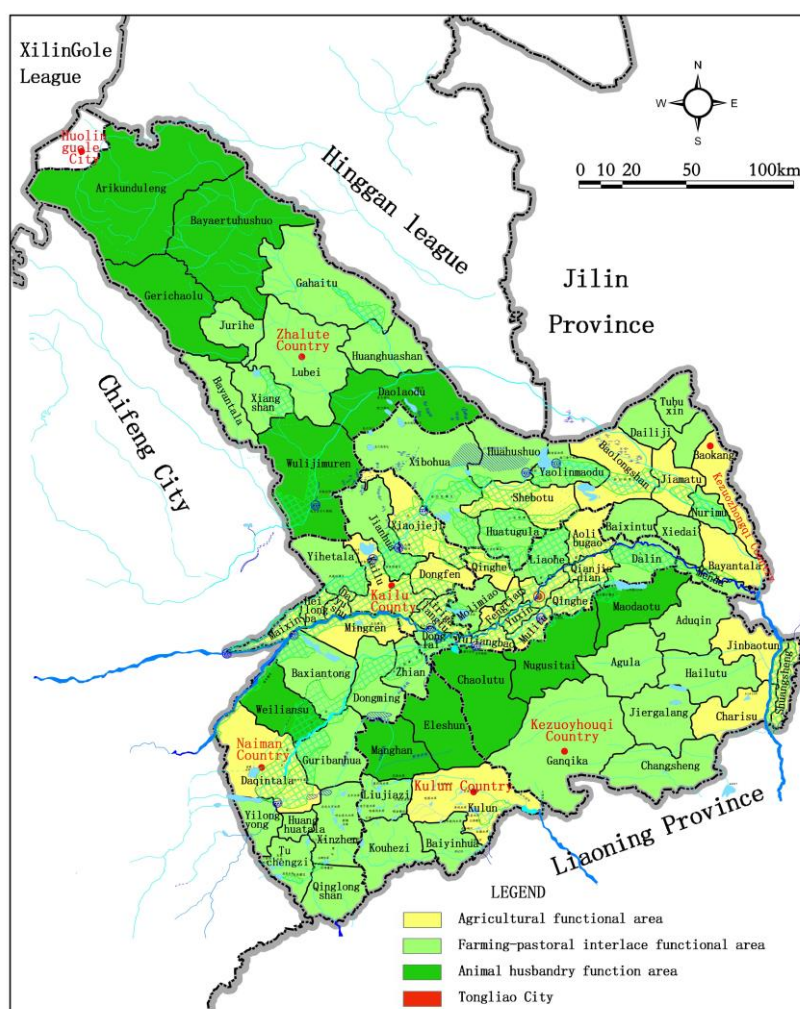


Figure 3. The functional pattern of agricultural and pastoral development under the constraints of water resources.

4.3. Comparison of the two functional patterns

The current functional pattern of APD is a product of agricultural and pastoral development over the past years in the study area. The functional pattern of APD under water resource constraints represents the desired functional pattern adaptable to water resource constraints and the goal of the policy to convert farmland to pastures. It can be used by Tongliao's government as a basis for making specific policies. A comparison of the two functional patterns shows that excessive agricultural activities occur in about 30 villages and towns, which account for 38.46% of the total number of villages and towns and 35.54% of Tongliao's total area. Currently, there are 24 villages and towns suffering from excessive agricultural development: Dalin, Liaohe, Molimiao, Dailiji, Tubuxin, Xiedai, Yaolinmaodu, Menda, Huatugula, Nurimu, Baixingtu, Hailutu, Changsheng, Aduqin, Liujiaz, Baiyinhua, Dongming, Zhi'an, Baxiantong, Xin, Jianhua, Donglai, Xiangshan, and Huanghuashan (Molimiao, Tubuxin, Xiedaisu, Baixingtu, and Aduqin are sumu while the rest are towns). These areas represent 30.77% of

the total number of the villages and towns studied and 23.26% of the total area. The excessive use of pastures was found in Chaolutu Town, Eleshun Town, Manghan Sumu, Weiliansu Village, Daolaodu Sumu, and Wulijimuren Sumu. Under water resource constraints, 7.69% of the villages and towns experienced a shift from pastoral production to agro-pastoral production and these agro-pastoral zones make up 12.28% of the total area. It follows that the 30 villages and towns with excessive agricultural development should be given priority when making and implementing the policy of returning farmland to pastures. A targeted policy will help curb agricultural development more effectively and achieve optimal outcomes.

5. Discussion

- Long-term excessive agricultural activities are a serious threat to sustainable development. The current functional pattern of APD is the spatial representation of man-land relationship resulting from agricultural and pastoral production. As agricultural production has higher economic output than pastoral production, many rural residents choose to practice farming on uncultivated land. This has led to rapid expansion of farmland and shrinkage of pastures. Meanwhile, the high water consumption for irrigation can far exceed the water storage capacity of an ecologically vulnerable semi-arid area, thereby causing deterioration of the ecological environment [7].
- Raising the overall ecological awareness among peasants is essential in order to achieve the pattern of APD under water resource constraints. The interview survey carried out in 62 villages and towns found that about 72% of the farmers and herdsmen interviewed did not have ecological awareness. These people believed that the current changes in ecological environment had no connection to agricultural activities and did not worry about the environmental degradation. About 20% had some ecological awareness. They recognized the direct relationship between the continued lowering of water table and overdraft, but would not make any change because no irrigation water means no income. 8% of the people interviewed were aware of the seriousness of ecological degradation and suggested that the government should take regulation measures to change the situation. Most of them have a post-secondary educational degree. A comprehensive investigation indicates that the farmers and pastoral and herdsmen in Tongliao have relatively weak ecological awareness overall, which is the basic contributor to the irrational pattern of APD. Therefore, it is necessary to enhance their ecological awareness in order to achieve a more reasonable pattern of APD under water resource constraints.
- A shift to the functional pattern of APD under water resource constraints requires a change of current concept of development. The proportions of the primary, secondary, and tertiary sectors in Tongliao's economy are 15%, 51%, and 34%, respectively, indicating that the city remains in the initial stage of socio-economic development. This industrial structure, characterized by predominance and importance of agriculture, is typical of Chinese SAAs. We need to change the current concept of development while maintaining the important status of agriculture. Emphasis should be put on promoting precision farming guided by the concept of circular economy, further modernization of agricultural production, use of more agricultural techniques, and improving use efficiency of resources, especially water resources. Protecting the environment while enhancing economic results is totally beneficial to local development.

6. Conclusions

- The study comprehensively examined the functional pattern of APD in Tongliao from different perspectives. The current functional pattern of APD in Tongliao and the functional pattern obtained under water resource constraints were obtained. An APD index system was developed for functional zoning based on a single or multiple criteria. This study offers a new approach to research into the sustainability of APD in semi-arid regions as well as theoretical innovation.

- The functional pattern of APD under water resource constraints is a desired pattern for future APD. Compared to the current pattern, this functional pattern exhibits higher level of sustainability and is able to mitigate the huge pressure from ecological degradation. It not only represents the goal of APD in the future, but also provides a valuable example for adjustments to the functional pattern to APD in semi-arid areas.

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