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Green-depressing cropping system: A referential land use practice for fallow to ensure a harmonious human-land relationship in the farming-pastoral ecotone of northern China

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ABSTRACT

The farming-pastoral ecotone of northern China (FPENC) is a fragile ecosystem that severely suffers from the acute contradiction between population growth and limited land resources. The Chinese government emphasized that rehabilitated agriculture, such as current government-led fallow, should be developed in the FPENC. However, what kind of farmland needs to lay fallow, how to manage the fields during fallow periods, and the duration of fallow periods are unclear. Fortunately, the green-depressing cropping system (GDCS) (Yaqing in Chinese Pinyin) that has existed for approximately 300 years also as a farmland use practice to reduce farmland use intensity and to recover soil property has something in common with fallow in the field selection and field management, and can serve as the reference for specific fallow policy. Therefore, we aimed to improve our limited understanding of the GDCS and provide recommendations for future fallow policies. Given this, an approach using satellite data to map the GDCS fields was explored, and this information can be combined with a questionnaire survey to help understand the current state of the GDCS in the FPENC. Then, the factors influencing farmers' willingness to adopt the GDCS in the FPENC were evaluated using a binary logistic regression model (BLR). The results indicated that the GDCS was still a widely distributed and common land use practice in the FPENC, and approximately 3.34 % and 2.31 % of the total arable land of Shangdu experienced the GDCS in 2019 and 2018, respectively. Furthermore, farmers in the Houshan area had a higher willingness to adopt the GDCS than farmers in the Qianshan area. More specifically, passive GDCS predominated as a suboptimal choice due to severe drought, while older farmers and agro-pastoral households had a higher willingness to adopt an active GDCS. Ultimately, the GDCS plays an important role in improving soil fertility and conserving soil water, leading to an increase of at least 50 % in crop yields in the year immediately following implementation. Finally, according to the current state of the GDCS and factor analysis, we concluded that the future fallow program in FPENC should be first performed in regions with high proportions of dryland and sloping fields, a small resident population, high levels of mechanization and high farmland transfer rates. Additionally, fallow by omitting a year of cropping is enough for farmland to recover, and different fallow subsidies are required to encourage farmers to implement this practice.

1. Introduction

In recent decades, the farming-pastoral ecotone of northern China (FPENC) has experienced continuous population growth (Nan et al., 2018), and the center of grain production has shifted northward to northern China, including the FPENC (Li et al., 2017; Wang et al., 2018a,b). This shift has led to increasing pressure on grain production. However, low productivity due to a prolonged drought, as well as a shortage of water resources in the FPENC, necessitated investments in large additional inputs of water and modern technologies, such as center pivot irrigation and drip irrigation. The serious mismatch between water resources and agricultural production should not be ignored. Previous studies have indicated that intensive farming land use has led to severe land degradation in the past half-century in this region

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(Yang et al., 2015). Inevitably, the environmental burden of food production will continue to increase without sustainable agriculture (Davis et al., 2017). Furthermore, under rapid urbanization and industrialization, massive rural labor shifts to non-agricultural sectors in the FPENC (Li et al., 2015) have resulted in ongoing agricultural labor scarcity and acute tensions between human activities and land resources.

Recently, concerns regarding these unprecedented land use challenges have prompted the Chinese government to publish relevant policies (Wang et al., 2019). In November 2016, the Ministry of Agriculture and Rural Affairs of the People's Republic of China (PRC) promulgated a regulatory policy emphasizing that rehabilitated agriculture should be developed in the FPENC (Shi et al., 2019). Fallow pilot programs are an effective way to improve the process of cultivated land recuperation (Lu et al., 2019). In fact, since the 1930s, the United States (Conservation Reserve Program, 1985) (Spencer et al., 2017; Malone and Foster, 2019), the European Union (Macsharry Reform, 1992) (Weyerbrock, 1998; Winter, 2000), and China Taiwan (Agricultural Land Conversion Scheme, 1995) (Ferng, 2009) sequentially issued systematic policies to encourage farmers to adopt fallow practices to reduce the ecological damage of agricultural production, reestablish soil properties, and regulate the balance of food supply and demand. Nonetheless, the fallow practices of mainland China are currently still in the pilot stage and mainly focus on the groundwater funnel areas in the Heilonggang region of Hebei Province (Xie et al., 2018a,b), the heavy-metal-polluted areas in the Chang-Zhu-Tan area of Hunan Province (Xie et al., 2018a,b; Yu et al., 2019), the karst rocky desertification areas of southwestern China (including Guizhou and Yunnan Province) (Shi et al., 2019), and the ecologically degraded areas in Gansu Province (Yang and Gong, 2018). However, fallow guidance is missing in the FPENC. In this context, we aimed to explore what kind of farmland needs to lay fallow, how to manage the fields during fallow periods, and the duration of fallow periods. Fortunately, we can explore the answers and draw lessons from a long history of many land use practices, which are the result of the interactions between human activities and natural ecosystems.

Collectively, low precipitation, poor soils, and overly intensive land use in the FPENC all pose threats to stable grain production. To maintain the stability of agricultural production, local farmers have formed a cropland use practice called the green-depressing cropping system (GDCS) (Yaqing in Chinese Pinyin), which considers both cropland use and cropland conservation (Huang et al., 1979; Gong, 2006). The GDCS leaves farmlands uncultivated for a year after continuous planting for several years, turning over and mixing the aboveground biomass into the soil with a plow at specific times during the uncultivated period to preserve soil moisture and soil nutrients; then, crops are grown as normal the following year (Huang et al., 1979). An old proverb says, "*GDCS is the guarantee of grain production increase*," which reflects the local farmers' approval of the benefits of the GDCS (Jiang, 1989). Meanwhile, the benefits of the old conservation tillage practice have been approved by many scholars. For rain-fed agriculture constantly beset by droughts, the GDCS is conducive to rainwater accumulation in the rainy season that solves the water requirements of crop growth in the coming year (Wu, 1955). Thus, the GDCS can help realize the sustainable use of soil moisture and prevent soil drought (Liu and Shao, 2016). On the other hand, there is now evidence that the GDCS prevents the continuous depletion of soil nutrients due to the need to use less fertilizer and consecutive planting in the dryland. Huang (1987) compared the soil nutrients under different planting patterns; the results illustrated that the contents of available N and P were higher in soils in the GDCS; that is, the GDCS has favorable soil nutrient recovery (Huang et al., 1987). It is possible that this form of conservation tillage is a key determinant of cultivated land recuperation in ecologically damaged areas.

Given the potential benefits, the current implementation of the GDCS in the FPENC is far from optimal. Prior to the 1950s, the proportion of land cultivated using the GDCS accounted for approximately 30 % of the area in the northern foot of the Yinshan Mountains, and stable yields could be ensured despite the drought. By the end of the 1970s, this value declined to 15 %, and crop yields declined (The Inner Mongolia Autonomous Region Agriculture and Animal Husbandry Hall, 1979). With the recent increasing human demand for crop production, farmers' awareness of the GDCS has weakened, and higher harvest frequencies have been adopted. Consequently, crop rotations have become the major cropping system (Gong et al., 2007), and the proportion of the fields that use GDCS has continued to decline (Huang et al., 1984) despite a large amount of dryland experiencing broad planting but low harvests. The extensive expansion of irrigated agriculture led to rates of aquifer extraction that far exceeded the recharge, causing a decline in the groundwater table (Chen et al., 2019) and a deterioration in production conditions of the surrounding dry farming areas. Although the proportion of areas adopting the GDCS declined in the FPENC, this traditional land use practice still exists. Niu et al. (1979) suggested that the traditional GDCS should be quickly restored to help realize the sustainable use of farmland (Niu and Wang, 1979). However, only limited studies have paid attention to the GDCS, and most of them have focused on the effects on crop yield (Li and Yang, 1980; Yu, 1988) and soil properties (Jiang, 1989; Qin et al., 2007). Additionally, the relevant research was mainly conducted between the 1950s and the 1990s, so there is an urgent need for a clear understanding of the current adoption and specific characteristics of the GDCS in the FPENC. Currently, the abundance of satellite datasets provides a feasible source of data to monitor the spatio-temporal variation in the GDCS fields and access their characteristics.

Farmers choose whether to adopt the GDCS based entirely on their awareness of farmland protection, which is rooted in their own decision-making behavior. Decision-making is a complex process influenced by both internal factors (inherent characteristics of rural households) and external factors (characteristics of farmland use, management conditions of farmland and natural environment) (Mehdi et al., 2018). To make the GDCS a solid agricultural production practice in the harsh natural conditions of the FPENC, we first need to clarify the current situation of the GDCS and the mechanism(s) influencing farmers' willingness to adopt the GDCS. Questionnaire surveys are an effective research method for data acquisition on land use behavior, with farmers as the behavior subject. Various statistical methods have been developed to distinguish the factors influencing farmers' decision-making in agricultural production (Zhang et al., 2015; Yamanaka et al., 2017; Zhang et al., 2018). Among them, the binary logistic regression model, a kind of discrete-choice model (Zeng et al., 2019), has been demonstrated as a preferable approach to the study of binary classification problems (Guo et al., 2014; Vu et al., 2014; Su et al., 2018; Xiao et al., 2018; Zhang and Han, 2018).

Here, we chose to conduct our research using Ulanqab, which is located in the central part of FPENC, as a case study. Combined with a questionnaire survey and semi-structured interviews, we used multi-source satellite data and a binary logistic regression model to (1) analyze the current situation of the GDCS in the FPENC, including the distribution of the GDCS fields in recent years, characteristics of the GDCS fields, farmers' willingness to adopt the GDCS, and its impacts on crop yield; (2) explore the main factors affecting farmers' willingness to adopt the GDCS; and (3) propose policy recommendations for reasonable and regional fallow policies referencing the GDCS.

2. Development of the GDCS in the FPENC

Throughout the history of the FPENC, the status of the GDCS has evolved as it was influenced by varying degrees of disturbances caused by changes in the human population's core needs, cognitive ability, and attitudes towards nature. Therefore, based on our previous study (Gong et al., 2007) and historical annals (Wuchuan Annals Editing, 1998), we reviewed the development of the GDCS and the performance of

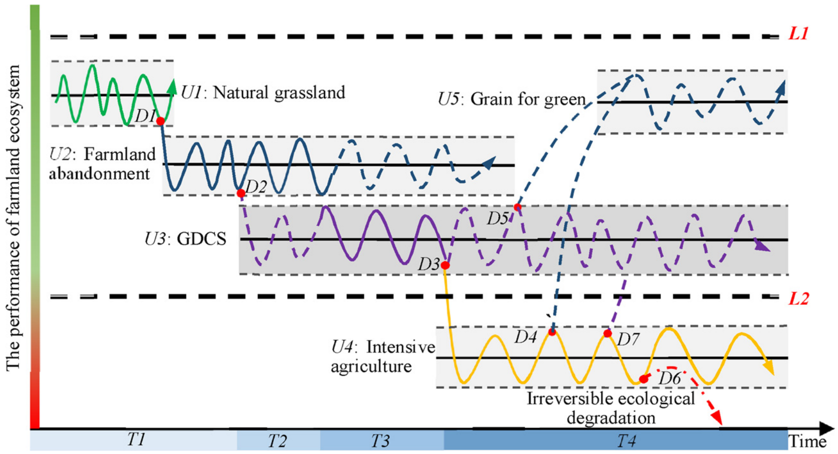

Fig. 1. The development of the performance of farmland ecosystems in the FPENC. *Un* represents different land use practices; *Dn* represents disturbances; *L1* and *L2* represent the ecological upper and lower limits, respectively. The climatic conditions in FPENC determine that *L1* and *L2* are natural grassland ecosystems and rain-fed agriculture. The solid wave line means this land use practice dominates the land use in this region, while the dotted line means the land use practice is auxiliary.

farmland ecosystems in the FPENC (Fig. 1) as follows.

First, there was the embryonic stage (T1). Before the Northern Wei Dynasty (386 AD), nomadism and hunting economies were the main production modes in the FPENC, and land cover was in a natural grassland state. The natural grassland ecosystem is the native ecosystem in the research area, which has a high resistance to disturbances such as climate changes and human activities. Given this, Zhang (2006) defines the natural grassland ecosystem as the ecological upper limit (Zhang, 2006). To meet the food demands of the garrisons during the Northern Wei Dynasty, the government issued policies to reward farming (D1). At that time, agricultural practices were extremely primitive and relied entirely on the natural fertility of the soil for production. Farmland was claimed randomly and temporarily and abandoned when the soil fertility was exhausted. During this agricultural era, a kind of slash-and-burn agriculture named farmland abandonment was born, resulting in the transformation of natural ecosystems to artificial ecosystems with lower ecosystem performance. Due to war and population migrations, farmland increased and decreased repeatedly over time. The dominant practice of farmland abandonment continued until the end of the Qing Dynasty.

Then, there was the generation stage (T2), which started with the reign of Emperor Qianlong (1711–1799 AD) when agricultural reclamation technologies from the Hetao region were introduced into the Yinshan area, and people in Shanxi Province and other places gradually immigrated to Yanmen Pass to engage in farming, leading to a marked increase in the amount of farmland. The farmland area in Wuchuan County, which was once subordinate to Ulanqab, reached 9465 ha in 1741 (Wuchuan Annals Editing, 1998). Farmland abandonment could not fully adapt to the contradiction between man and land due to the increasing population of the time; thus, some of the abandoned farmlands were forced into re-cultivation, and farmers began to stop farming for one year every few years. Thus, the GDCS was formed.

The leading stage (T3) came next when in 1902, the Qing government began an immigration policy that resulted in a large number of surplus human laborers being transported from the Yanmen Pass to the Yinshan area to engage in agricultural reclamation. This influx of workers caused an improvement in land use intensity to accommodate higher agricultural production. Obviously, farmland abandonment could not provide sufficient outputs, and continuous planting would threaten the soil fertility and ecosystem health, all of which supported the necessity of the GDCS. Thus, the GDCS was the dominant cropping system from then until 1949.

Finally, the recession stage (T4) was the period after 1949, when both the growing population in the FPENC and the strategies centered on economic development in China required the adoption of intensive agriculture practices such as crop rotations, causing a decrease in the prominence of the GDCS. The crop rotation system replaced the GDCS as the dominant cropping system in the FPENC. Especially in the 21 st century, with the introduction of drip irrigation and sprinkler irrigation, a large amount of dryland was transformed into irrigated agricultural land. However, the climatic conditions in the FPENC determines that rain-fed agriculture is at its ecological lower limit in this region (L2) (Zhang, 2006). It means that higher farmland intensity than rain-fed agriculture, such as the overdevelopment of intensive agriculture (D6), may disturb the ecological balance and cause irreversible ecological degradation.

In summary, with the increased intensity of human disturbance, the performance of farmland ecosystems shows a downward trend or even a collapse. Contemporarily, the GDCS is a peripheral farming system compared with intensive agriculture practices and systems. To determine the potential impact and use of the GDCS in modern agriculture on the FPENC, we carried out a study on the current role it plays and what can we learn from it.

3. Materials and methods

3.1. Study area

Ulanqab lies between 109°16′–114°49′E and 39°37′–43°28′N in the central part of the FPENC and includes a total of 11 counties or banners (Fig. 2). The Yinshan Mountains divide Ulanqab into the Qianshan area (comprised of the Jining District, Fengzhen City, Zhuozi County, Xinghe County, Chahar Right Front Banner, and Liangcheng County) and the Houshan area (comprised of Siziwang Banner, Shangdu County, Huade County, Chahar Right Back Banner, and Chahar Right Middle Banner). The study area is characterized by a semiarid temperate continental monsoon climate, with a mean annual precipitation ranging from 150 to 450 mm, which varies greatly from the Qianshan area (300 – 450 mm) to the Houshan area (150 – 400 mm). The mean annual temperature is 0–18 °C, and the frost-free period is 95–145 days.

The study area belongs to an area of single cropping systems. However, in the past 30 years, climate change and profit chasing have combined to change the standard cropping system, which has witnessed a decrease in the cultivation area of wheat crops (such as wheat and naked oats) and a sharp increase in the cultivation area of crops with high economic benefits (such as potatoes, maize, sugar beet, and sunflower). The local government began introducing the center pivot irrigation system to improve agricultural production in the early 21 st century. Previous work by our group indicated that the number of center pivot irrigation systems increased from 8 in 2002 to 845 in 2017 (Chen et al., 2019). The total population of Ulanqab increased from 2615 thousand persons in 1985–2721 thousand persons in 2017, growing continuously at an average annual rate of 0.13 %. In contrast, over the same period, the number of agricultural employees in Ulanqab dropped by 27.28 %, from 880 thousand persons to 640 thousand persons (Ulanqab Bureau of Statistics, 2018). Nowadays, about 80 % of

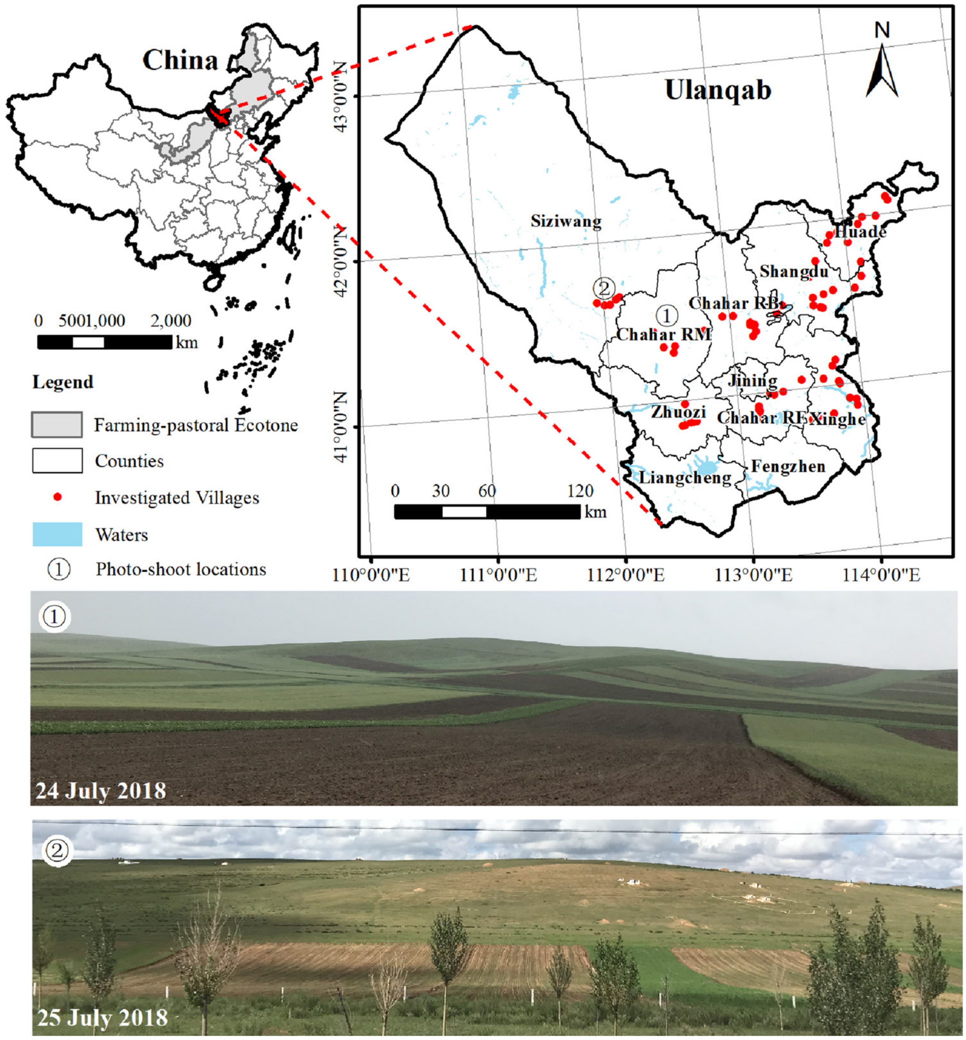

Fig. 2. The location of Ulanqab. Bare fields (brown parcels) in selected locations 1 and 2 represent the GDCS in late July 2018.

the local farmers are between 50 and 70 years old (Lan, 2013). It can be seen that the continuous growth of the total population, agricultural labor losses, and agricultural labor aging have brought great challenges to sustainable agricultural production in this area. Besides, Ulanqab is characterized as a mosaic of a transition zone between traditional farming and pastoral regions. 72.79 % and 8.07 % of the rural population are engaged in agricultural and animal husbandry activities in Ulanqab, respectively. The share of the primary industry (including agriculture and animal husbandry) in GDP in Ulanqab declined from 54.58 % to 17.90 % during 1990–2017 (Inner Mongolia Autonomous Region Statistics Bureau, 2018).

3.2. Data and processing

3.2.1. Questionnaire data

We conducted a semi-structured interview and a questionnaire survey with farmers in Ulanqab from July 14 to July 28, 2018. A total of 328 questionnaires were collected, of which 304 were valid. Specifically, 37.83 % and 62.17 % of the questionnaires were obtained in Qianshan area and Houshan area respectively (Table 1). The research area covered 9 banners or counties and 66 villages in the Qianshan and Houshan areas. The questionnaire data involved the characteristics of rural households, characteristics of farmland use, and rural households' current opinions and use of the GDCS.

3.2.2. Satellite data

Remote sensing images with a spatial resolution between 10 and 30 m allow for the identification of single agricultural fields in most landscapes (Carfagna and Gallego, 2005; Pan et al., 2012). The crop phenology and the household survey illustrated that the GDCS fields were normally plowed for the first time in mid-July, while the crops were unharvested until early September (Table S1). That is, it is very easy to distinguish the GDCS fields from other farmlands using the satellite images from late-July to late-August. However, heavily influenced by cloud contamination and instrument malfunctions, several Landsat images are unsatisfactory for monitoring the distribution of the GDCS fields. Here, the Sentinel-2A/B images were used as supplementary remote sensing data. Also, we need to map its distribution in 2018 and 2019 to analyze the alternate features of this land use practice. The Landsat ETM+/OLI scenes and Sentinel-2 scenes for the period of late July to late August were downloaded from the United States Geological Survey (https://glovis.usgs.gov/). The satellite images used in this study are shown in Table 2. Then, these data were calibrated and atmospherically corrected through the corresponding modules provided in the ENVI software.

3.2.3. Ground truth data

Mapping the GDCS fields is highly expert knowledge-driven and often relies on external data such as reference ground truth data. Therefore, during early August 2019, a ground truth database was compiled from 50 samples for the GDCS fields and 84 samples for other

Table 1
Areas and villages included in the questionnaire survey data collection.

Area	County/Banner	Village	Number	Ratio (%)
Qianshan	Xinghe	(11): Qiaolonggou, Ertaizi, Sanruili, Shiwuhao, Halagou, Fujiayao, Gelengying, Shibahao, Huangtu, Fugou, Shafangwa	57	18.75
	Chahar Right Front Banner	(6): Chengjia, Nan, Houguoyaodi, Gulinaobao, Shidagu, Wengjia	26	8.55
	Zhuozi	(6): Jiaochangtan, Lanqi, Beiliantai, Yintangzi, Sisumu, Xipo	23	7.57
	Jining	(2): Hanjialiang, Erhao	9	2.96
	Total	**25**	**115**	**37.83**
Houshan	Shangdu	(11): Youfang, Luojia, Ningyuan, Fangjia, Habeiga, Dawa, Bajia, Xishidagu, Gangfang, Xiaowotu, Tianjiabu	59	19.41
	Huade	(10): Tuchengzi, Luyi, Debaotu, Fengman, Hemu, Erdaogou, Jiefang, Daolahudong, Doujiadi, Desheng	52	17.11
	Chahar Right Back Banner	(10): Dadonggou, Gaojiadi, Sanyi, Houlujia, Siwangzhu, Qianshuangjing, Houshuangjing, Dongshuangjing, Hongshuifang, Hangainao	43	14.14
	Chahar Right Middle Banner	(5): Heinaobao, Xujia, Yixingquan, Milaingjv, Huangyangcheng	18	5.92
	Siziwang Banner	(5): Donghao, Sanyuanjing, Xianghuangdi, Liudaogou, Xigou	17	5.59
	Total	**41**	**189**	**62.17**

farmlands collected in Shangdu County. The ground dataset also helped to determine how the optical profiles of the GDCS fields and other farmlands differed, which in turn helped to expand our training dataset into regions and other years (Estel et al., 2015). Through the questionnaire survey and crop phenology records, we learn that in Ulanqab crops begin to enter the harvest period in early-September (Table S1), but the GDCS fields are normally plowed for the first time in mid-July. This pattern means that from late-July to late-August, except for GDCS fields, the surfaces of other farmlands are covered with vegetation. Consequently, we can easily obtain the prior knowledge of the optical feature that GDCS fields and other farmlands are characterized by bright yellow strip parcels and green strip parcels in true-color Landsat images, respectively. Thus, to solve the problem of the paucity of ground data in 2018, the sample points that year were attained according to prior knowledge.

3.2.4. Auxiliary data

The crop phenology data are a critical proxy to determine the time gap between the time points of the GDCS and crop harvest activities, and this information was obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn). We also downloaded the precipitation data at county level from this website. Furthermore, the slope data derived from the Terra ASTER-GDEM at a 30 m spatial resolution were used to analyze the characteristics of the GDCS fields. The dataset was provided by the Geospatial Data Cloud site (http://www.gscloud.cn). Our existing cropland mask was carried out to eliminate non-agricultural classes, and this method has been shown to generally improve the classification accuracy (Nagy et al., 2018).

3.3. Methods

3.3.1. Mapping the GDCS fields with multi-source satellite data

The flow chart of mapping the GDCS fields with multi-source satellite data is shown in Fig. 3. First, we determined the time gap between the time points of the GDCS and crop harvest activities in light of the questionnaire data and crop phenology. As mentioned in section 3.2, there are no vegetation covers on the GDCS fields, while other farmlands are covered with vegetation during the time gap (from late-July to late-August). As a result, GDCS fields and other farmlands are characterized by bright yellow strip parcels and green strip parcels in true-color Landsat images, respectively. Given this difference in the optical feature, we collected the ground truth data and downloaded the satellite data during the time gap. Also, we expanded our sample point dataset into 2018 based on prior knowledge of the optical feature. Then the cropland mask was performed to eliminate non-agricultural classes. Next, the distributions of the GDCS fields in 2019 and 2018 were extracted through a random forest classifier, which is both computationally efficient and optimal in performance (Gong et al., 2019). In addition, the visual interpretation method, a post-classification process, was conducted directly to optimize the classification results, such as filling missing GDCS pixels and eliminating noise. Finally, the overall accuracy, Kappa coefficient, producer's accuracy and user's accuracy were calculated to assess the accuracy of the classification.

3.3.2. Modeling of the willingness to participate in the GDCS

(1) Binary logistic regression model (BLR)

Considering that the dependent variable is binary, we applied a BLR probability estimation model (Zeng et al., 2019) to estimate the effects of the internal and external factors on farmers' willingness to adopt the GDCS. The model can be expressed using the following equation:

$$Ln\left(\frac{p(T_i = 1)}{1 - p(T_i = 1)}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{1}$$

where $p(T_i = 1)$ denotes the probability of the i_{th} farmers' willingness to adopt the GDCS; x_1, x_2..., x_n are the explanatory variables; n is the number of explanatory variables; β_1, β_2..., β_n are the estimated coefficients (a positive β_n indicates the bigger the x_n, the more likely people are to adopt the GDCS, while a negative β_n indicates the bigger the x_n, the less likely people are to adopt the GDCS); and β_0 is the regression intercept.

We found that not all farmers proactively and intentionally left their farmland uncultivated for a year. Additionally, quite a few farmers were forced to bury aboveground biomass, including growing crops and weeds, due to poor crop growth. Thus, we also built a BLR to explore the mechanisms influencing the activeness and passivity of the GDCS, that is, which factors determined farmers' willingness to arrange part of their cropland to be uncultivated regardless of climate conditions, while other farmers participated in the GDCS passively. According to different binary dependent variables, the following two BLRs were proposed:

Model I: Determine whether farmers adopted the GDCS. $T = 1$ if

Table 2
The Landsat OLI/ETM + and Sentinel-2A/B images used in this study.

Sensor	Landsat OLI/ETM+		Sentinel-2A/B			
Tiles No.	Path 126, Row 31	Path 125, Row 31	T49TFG	T49TFF	T49TGG/T50TKM	T49TGF/T50TKL
Acquisition Time	20,190,806 (OLI)	20,190,730 (OLI)	20,190,814	20,190,814	20,190,730	20,190,730
	20,180,819 (OLI)	20,180,820 (ETM+)	–	–	20,180,819	20,180,730

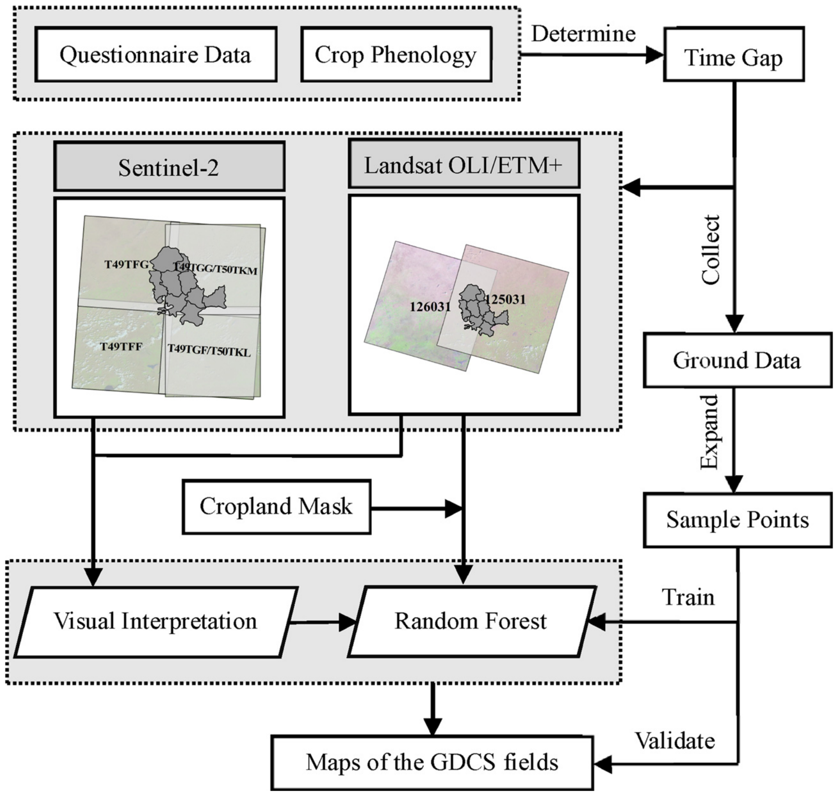

Fig. 3. Flow chart of mapping the CDCS fields.

the investigated farmer was involved in the GDCS, and $T = 0$ otherwise.

Model II: Among farmers who are involved in the GDCS, determine whether they are actively adopting the GDCS. $T = 1$ if the investigated farmer was involved in active GDCS, and $T = 0$ otherwise. Obviously, the dependent variable of model II was the reclassification of the farmers engaged with the GDCS.

(2) Explanatory variable selection

How farmers use farmland was jointly determined by the inherent characteristics of a rural household (*HOUVAR*), characteristics of farmland use (*LUVAR*), management conditions of the farmland (*MCVAR*), and natural environment (*NEVAR*). We selected the following 14 explanatory variables that affect whether farmers adopt the GDCS (Table 3). The *HOUVARs* included the gender of the respondent, number of workers, average age of the workers, and type of rural household as defined by the dominant income stream. The *LUVARs* included the per capita cultivated land, proportion of dryland, number of farmland parcels, whether the investigated farmer has contracted farmland from others, and whether the investigated farmer has subleased their farmland to others. The *MCVARs* included the ratio of the resident population to the registered population, distance from the village to the county, and the number of machines owned by the village. The *NEVARs* included annual precipitation and the landform type of the village.

We adopted the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test to examine the appropriateness of questionnaire data for factor analysis performance. To screen explanatory variables, the multicollinearity between them was discussed using variance inflation factor analysis (VIF).

4. Results

4.1. Current situation of the GDCS

4.1.1. Categories of the GDCS

The combination of different farmland conditions, labor force structures, and levels of mechanization results in different types of GDCSs adopted by farmers. However, the original categories of the GDCS in previous studies were based solely on the number of plows. In light of the rural household survey and existing studies, we enriched the category system of the GDCS in the FPENC. The original and improved categories are described as follows:

(1) According to the number of plows, the GDCS was classified into GDCS1, GDCS2, and GDCS3. GDCS1 refers to rural households that plow farmland only once a year around late August due to a lack of draft animal and labor. GDCS2, the most common practice (Fig. 4), denotes rural households that plow their farmland twice a year. Farmlands are plowed for the first time in mid-July when higher temperatures and heavy rainfalls mean that weeds will easily rot in the soil. The second plow was performed in late August to accelerate the decay rate and fertilize the soil. In GDCS3, rural households plow their farmland three times a year in early May, mid-July, and mid/late September, dependent on sufficient draft animals and labor.

(2) According to the farmers' initiative, we classified the GDCS into active GDCS (AGDCS) and passive GDCS (PGDCS). During the period of the AGDCS, no crops are planted. Left unchecked, weeds flourish and are then buried into the soil at specific points in time. Compared with the AGDCS, the PGDCS appears to be a helpless choice. Specifically, crops suffer from drought and are swallowed up by weeds, resulting in poor growth and no harvest. Hence, farmers have no alternative but to turn over growing crops and weeds together into the soil.

(3) According to farmers' field management methods, the GDCS was classified into natural GDCS (NGDCS) and manure crop-GDCS (MGDCS). To meet the demands of improving soil fertility and animal husbandry, very few farmers plant manure crops, including *Vicia cracca and Medicago sativa* L. Then, they bury green manure crops at the right time. We call this the MGDCS. However, when farmers adopt the NGDCS, they do not plant any crops and they let weeds grow totally free before turning them over into the soil.

Table 3
Variables in the BLR of farmers' willingness to adopt GDSC and active GDCS.

Variables	Abbreviation	Variable definitions
Whether farmers adopted the GDCS	*IFFALL*	Dummy variable: 1 = yes; 0 = no.
Among farmers who are involved in the GDCS, whether it is active	*IFAFALL*	Dummy variable: 1 = yes; 0 = no.
1) Inherent characteristics of a rural household	***HOUVAR***	
Gender of respondent	*RESGEN*	Dummy variable: 1 = male; 2 = female.
Number of workers	*LABNO*	Continuous variable
Average age of workers	*AVEAGE*	Continuous variable
The type of rural household	*HOUTYP*	Dummy variable: 1 = agriculture-led; 2 = animal-husbandry-led; 3 = agro-pastoral household; 4 = non-agriculture-led; 5 = self-sufficient household.
2) Characteristics of farmland use	***LUVAR***	
Per capita cultivated land	*AVELAN*	Continuous variable
Proportion of dryland	*RATDRY*	Continuous variable
Number of farmland parcels	*LANNO*	Continuous variable
Whether the investigated farmer has contracted farmland from others	*IFIN*	Dummy variable: 1 = yes; 0 = no.
Whether the investigated farmer has subleased their farmland to others	*IFOUT*	Dummy variable: 1 = yes; 0 = no.
3) Management conditions of farmland	***MCVAR***	
Ratio of the resident population to the registered population	*RATRES*	Continuous variable
Distance from the village to the county	*DISCOU*	Continuous variable
Number of machines owned by the village	*MACNO*	Continuous variable
4) Natural environment	***NEVAR***	
Annual precipitation	*ANNPRE*	Continuous variable
The landform type of the village	*GEOTYP*	Dummy variable: 1 = flat; 2 = sloping.

4.1.2. Distribution of the GDCS fields

First, we counted the number of interviewed farmers adopting the GDCS and summarized the information by county (Fig. 5). The results indicated that 134 of 304 (44.1 %) surveyed farmers in Ulanqab adopted the GDCS in 2018. It is thus clear that the GDCS is still a common land use practice in FPENC. The proportion of farmers adopting the GDCS (Gfarmers) in the Houshan area was higher, reaching 65.7 %, while in the Qianshan area, the value was only 18.95 %. Specifically, farmers in Chahar Right Middle Banner, Siziwang Banner, and Huade expressed a higher willingness to adopt the GDCS, and the proportions of Gfarmers accounted for 83.3 %, 82.3 %, and 80.8 %, respectively.

Furthermore, taking Shangdu County as an example, we mapped the GDCS fields in the last two years using Landsat OLI/ETM + and Sentinel-2 (Fig. 6) with an overall accuracy of 97.69 % and a kappa coefficient of 0.951 (Table 4). Approximately 3.34 % and 2.31 % of the total arable land of Shangdu used the GDCS in 2019 and 2018, respectively, which also indicated that the GDCS was still a widely distributed and common land use practice in this area. Moreover, a significant alternate feature was observed in the field management (Fig. 6h-j). This result means that farmers left part of their farmlands uncultivated in 2018 and in turn left another part of the farmlands uncultivated in 2019. In addition, it is obvious that the distributions of the GDCS fields are spatially heterogeneous at the town level, with comparably higher ratios of the GDCS field area to the total arable land area (Gratio) in Maodu, Dakulian, Bolihujing and Tunkendui. However, less than 2% of the farmland in the towns near the Qianshan area, such as Xiaohaizi, Shibaqing and Daheishatu, adopted the GDCS.

4.1.3. Nature of the GDCS fields

Then, the nature of the GDCS fields was explored by combining the basic geography data and questionnaire data. First, we extracted the average slope of each farmland parcel using the Zonal Statistics as Table tool in ArcGIS 10.2, which illustrated that the terrain of the GDCS fields was fairly poor, with an average slope of 3.870°, compared with the other farmlands that had an average slope of 3.667°. The regulation for gradation of agricultural land quality introduced by the Ministry of Land and Resources of the People's Republic of China (MLRPRC) divided the slope of farmland into six gradients: 0° ≤ slope < 2°, 2° ≤ slope < 5°, 5° ≤ slope < 8°, 8° ≤ slope < 15°, 15° ≤ slope < 25°, and slope ≥ 25° (Ministry of Land and Resources of the People's Republic of China, 2012). Furthermore, Peng et al. (2019) classified farmlands into flat farmland (0° ≤ slope < 5°), gentle slope farmland (5° ≤ slope < 15°) and steep slope farmland (slope ≥ 15°) (Peng et al., 2019). Given this, spatial overlay analysis was performed to explore the proportion of GDCS fields on different slope gradients in 2019 and 2018. More than one-quarter (25.15 %) of the GDCS fields were sloped farmlands; more specifically, 24.38 % and 0.77 % of the GDCS fields were gentle slope farmlands and steep slope farmlands, respectively. These fields, which suffered from serious soil and water loss, were sensitive to climate

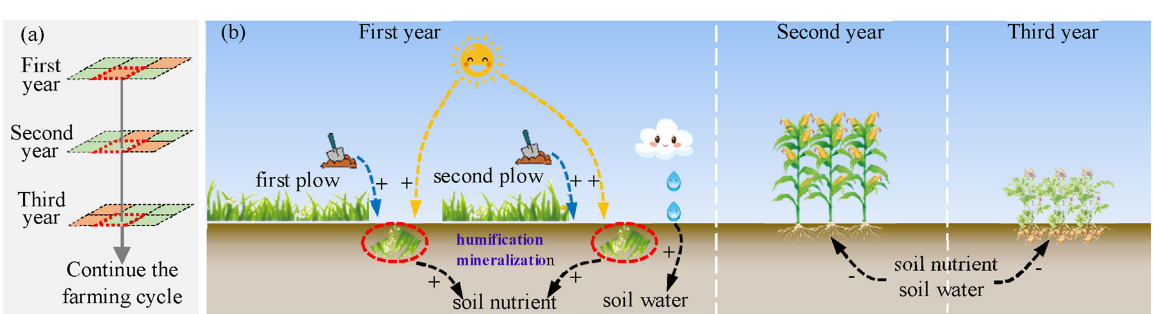

Fig. 4. A diagram of GDCS2. Green polygons and brown polygons in (a) represent the fields practicing and not practicing the GDCS that year, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

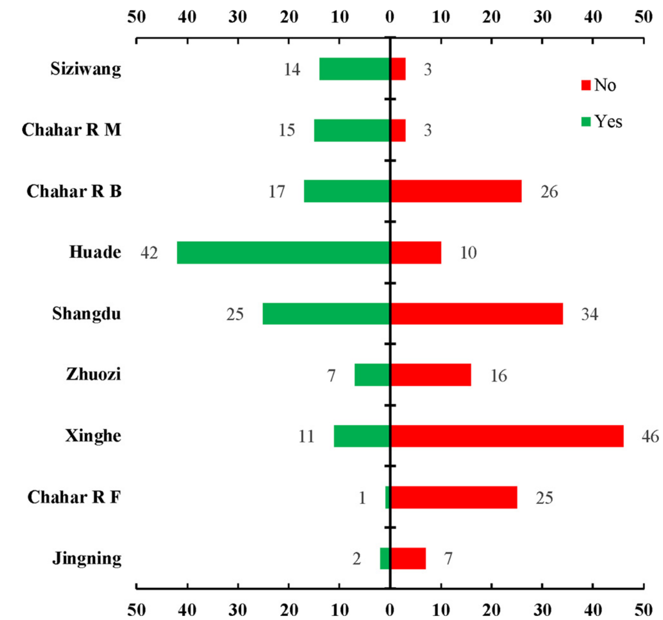

Fig. 5. The number of interviewed farmers adopting the GDCS (or not) by county. Green bars represent the number of farmers who adopted the GDCS, while red bars represent the number of farmers who did not adopt the GDCS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variability. Therefore, the GDCS is an essential measure for stabilizing and increasing the crop yield for sloped farmland. Further analysis showed that the proportions of sloped farmland were relatively larger in towns with high topographic relief, such as Daheishatu, Xijingzi, Maodu, and Dakulian (Fig. 7).

Then, the questionnaire data were used to analyze the irrigation condition and soil thickness of the GDCS fields (Table 5). Most of the GDCS fields were rain-fed farmlands with low fertilizer inputs and no irrigation. Due to the continuous overexploitation of groundwater, when the groundwater level falls below the wells, some of the irrigated lands are confronted with a lack of water supply. Consequently, 4% of irrigated lands still adopted the GDCS, and all of them were distributed in Chahar Right Front Banner. In addition, the average thickness of the plow layer of the GDCS fields was 31.2 cm in Ulanqab, and the value in the Qianshan area (32.59 cm) was larger than that in the Houshan area (30.41 cm).

Table 4
Accuracy assessment (confusion matrix) of the GDCS fields and other farmlands.

GDCS fields	Other farmlands	Producer's accuracy (%)
GDCS fields	47	3
Other farmlands	0	80
User's accuracy (%)	100.00	96.39
Overall accuracy (%)	97.69	
Kappa coefficient	0.951	

An overwhelming majority (85 %) of Gfarmers applied the GDCS2 during the study period. The lack of a labor force and/or the high cost of plowing forced 15 % of Gfarmers to apply the GDCS1 in 2018, while no Gfarmer showed any interest in the GDCS3. Although they are all GDCS2-oriented, differences in climate conditions and farmland quality make the number of plow events vary greatly from the Qianshan area to the Houshan area. The proportion of the GDCS2 in the Houshan area (88 %) was higher than that in the Qianshan area (67 %). The widely distributed weed species in the GDCS fields are *Agrophyllum squarrosum*, *Leymus chinensis*, and *Artemisia carvifolia.*

The analysis of farmers' initiative to use the GDCS indicated that in 2018, 53 % of the Gfarmers in Ulanqab adopted the AGDCS to prevent the loss of water and soil nutrients. In contrast, there were still many Gfarmers (47 %) who were particularly passive and practiced the PGDCS. Similarly, Gfarmers' awareness differed greatly by county. Farmers in the Houshan area, such as Huade, Siziwang Banner, and Chahar Right Back Banner, had a strong sense of farmland maintenance. A total of 57.5 % of Gfarmers the farmers chose to use the AGDCS, while most of the farmers (71.4 %) preferred the PGDCS in the

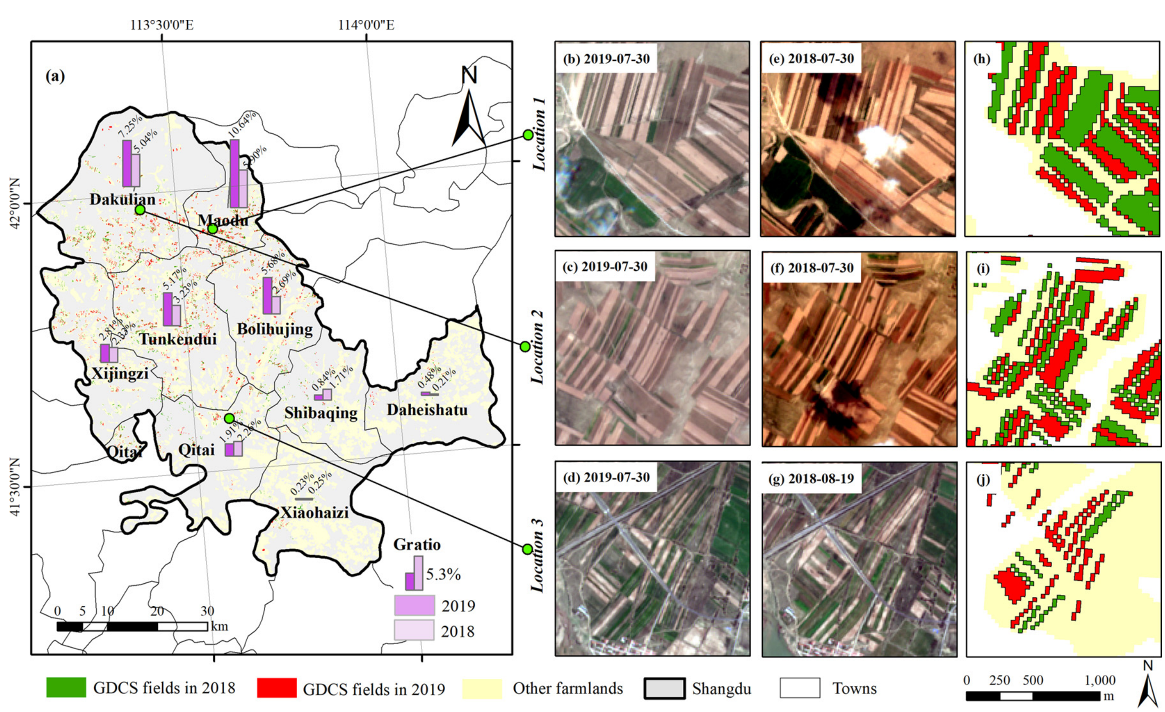

Fig. 6. Maps of the GDCS fields of Shangdu in 2019 and 2018. (b)-(d) and (e)-(g) are true color Sentinel-2 images of three selected locations in 2019 and 2018, respectively, and (h)-(j) show the successive arrangement of this land use practice.

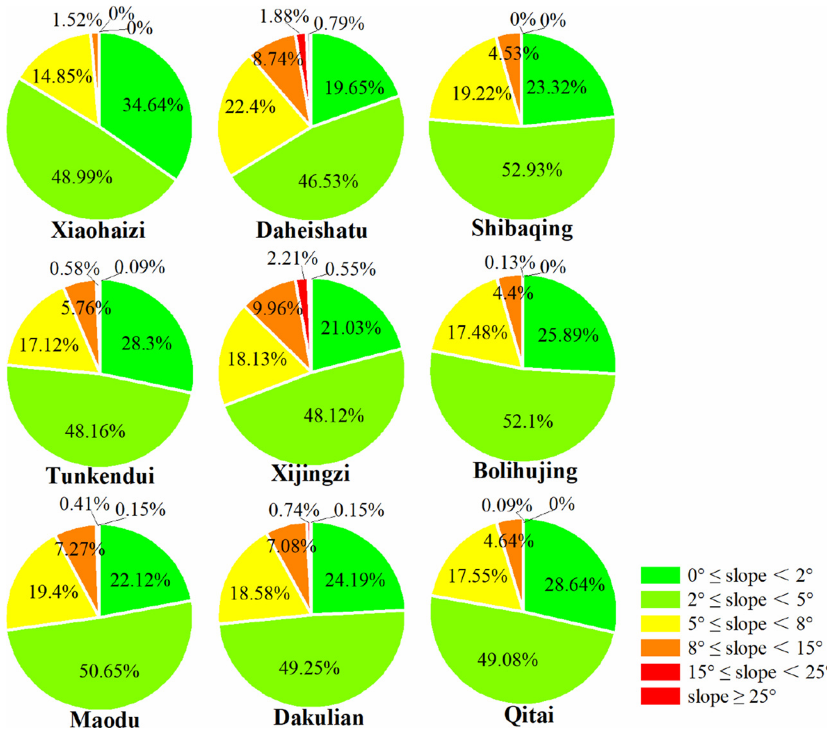

Fig. 7. The proportion of GDCS fields on land with different slope gradients at the town level.

Qianshan area.

4.1.4. Effects of the GDCS

We also conducted a survey on the effects of the GDCS. Comparisons of crop yields before and after adopting the GDCS showed that the yields of all kinds of crops increased by at least half or even doubled in the first year after implementing the GDCS (Table 6). More specifically, the per mu yield of wheat, naked oat, flax, potato, corn, and silage corn in Ulanqab increased by 101 %, 74 %, 84 %, 100 %, 48 %, and 150 %, respectively. Similar results were described in previous works. Jiang (1989) reported that the land use practice increased crop yields by 50%–80%, and some yields were even more than 100 % in the 1950s (Jiang, 1989). Niu and Wang (1979) found that in the Yinshan hilly area, the grain yields in the GDCS fields experienced an increase of at least 50 % in the subsequent year (Niu and Wang, 1979). The considerable increase was mainly attributed to the improvement in soil properties by the GDCS. A field experiment conducted by Zhao (1962) in FPENC showed that the GDCS increased the available nitrogen (N), phosphorus (P) and potassium (K) by 21.4 %, 33.3 % and 126.2 %, respectively (Zhao, 1962). Huang et al. (1979) found that the average soil moisture during the growing period in GDCS fields was 23.33 % higher than that in farmland not using the GDCS (Huang et al., 1979). Additionally, soil moisture was high in the first year after adopting the GDCS, and therefore, 66.1 % of Gfarmers chose to plant spring wheat, which needs more water in the early growing period. Additionally, 19.5 % of Gfarmers chose to plant naked oats. Crop rotation patterns in the coming years after adopting the GDCS were also key considerations of Gfarmers. A GDCS-spring wheat-naked oat or a GDCS-spring wheat (naked oat)-potato rotation was most vehemently recommended by local rural households. However, traditional rotation patterns are currently very rare because of the lack of labor, missed sowing dates, poor crop growth, and inadequate farmland (Huang et al., 1987).

4.2. Factors influencing farmers' willingness to adopt the GDCS in Ulanqab

KMO and Bartlett's tests were performed to examine the appropriateness of questionnaire data for factor analysis. This result indicated that the KMO value (0.581) was greater than 0.5 and the p-value (0.000) from Bartlett's test was less than 0.05, which suggested that factor analysis was feasible with the questionnaire data.

We then evaluated the multicollinearity between all the explanatory

Table 5
Descriptive statistics of the GDSC samples.

Indexes		Ulanqab	Houshan area	Qianshan area	Shangdu	Huande	Chahar R B	Chahar R M	Siziwang	Chahar R F	Xinghe	Zhuozi	Jining
1) The natures of farmland parcels													
Farmland types	Dryland	129	108	21	25	42	12	15	14	1	11	7	2
(sample size)	Irrigated land	5	5		–	–	5	–	–	–	–	–	–
Thickness of plow layer (cm)		31.02	30.41	32.59	26.84	28.33	28.33	35.36	33.17	10	32.5	47.86	40
2) Technology of GDCS													
The number of plows	GDCS1	20	13	7	9	2	2	–	–	–	–	6	1
(sample size)	GDCS2	114	100	14	16	40	15	15	14	1	11	1	1
Weed species			*Agriophyllum squarrosum, Leymus chinensis, Artemisia carvifolia* and so on.										
3) Farmers' initiative to GDCS													
(sample size)	AGDCS	71	65	6	7	23	16	9	10	–	–	6	–
	PGDCS	63	48	15	18	19	1	6	4	1	11	1	2

Table 6
Comparisons of crop yields before and after adopting the GDCS (kg/mu). The terms 'Before' and 'After' refer to a year before and after adopting the GDCS, respectively. A mu is a Chinese unit of area (1 mu = 1/15 of a hectare).

Crop	Times	Ulanqab	Houshan area	Qianshan area	Shangdu	Huande	Chahar R B	Chahar R M	Siziwang	Chahar R F	Xinghe	Zhuozi	Jining
Wheat	Before	54	54		35	51	66.5	58.5	58				
	After	108	108		94	107.5	120.5	113.5	105				
Naked oat	Before	60.5	58	63	31	43.5	82.5	75		75	57	70	50
	After	105.5	113	98.5	100	65.75	136.5	150		125	93		75
Flax	Before	45	56.5	41.5	56.25					24	50		50
	After	83	74	87.5	73.75					100	75		
Potato	Before	500		500							500		
	After	1000		1000							1000		
Corn	Before	187.5		187.5							200	175	
	After	278		278							293.5	262.5	
Silage corn	Before	1000	54				500				1500		
	After	2500	108				2500						

Table 7
Results of multicollinearity statistics.

Variables	Statistics	
	TOL	*VIF*
RESGEN	0.951	1.052
LABNO	0.921	1.085
AVEAGE	0.894	1.119
HOUTYP	0.936	1.069
AVELAN	0.882	1.134
RATDRY	0.706	1.416
LANNO	0.958	1.044
IFOUT	0.772	1.295
IFIN	0.845	1.183
RATPERP	0.673	1.486
DISCOU	0.737	1.357
MACNO	0.923	1.084
ANNPRE	0.793	1.261
GEOTYP	0.679	1.474

variables using a variance inflation factor (VIF) analysis (Table 7). The tolerance value was less than 1, and the mean VIF between our explanatory variables was 1.219, with a minimum of 1.044 and a maximum of 1.486. Given that our mean VIF value was well below 10 (Prendergast et al., 2019), no variables were excluded.

The impact of the explanatory variables on farmers' willingness to adopt the GDSC (Model I) and active GDCS (Model II) were analyzed using BLR, and the results are given in Table 8. The Hosmer-Lemeshow (H–L) test for the two BLRs resulted in p-values of 0.613 and 0.209 (p-value > 0.05), respectively, that showed no statistically significant differences between the predicted data and the observed data, indicating a good fit of the models to the data.

The estimation results of Model I suggested that *HOUTYP(2)*, *HOUTYP(3)*, *RATDRY*, *IFOUT(1)*, *RATRES*, *DISCOU*, *MACNO*, *ANNPRE* and *GEOTYP* had significant impacts on rural households' willingness to adopt the GDCS (Table 8).

Among them, *RATDRY*, *IFOUT(1)*, and *MACNO* were positive indicators affecting farmers' willingness to adopt the GDCS, with partial correlation coefficients of 1.195, 0.764, and 0.002, respectively. It was easy to understand that farmers with a higher proportion of dryland had a higher willingness to participate in the GDCS. A possible reason for this was that the growth of rainfed crops was largely determined by uncertain rainfall, resulting in unstable yields due to drought (Yuan et al., 2013). We found that 80.6 % of Gfarmers' farmlands were dryland. Therefore, compared with farmers with mostly irrigated farmland, farmers with mostly dryland had a greater motivation to use traditional methods to preserve soil water. It was clear that the GDCS was of great significance to the enhanced resilience of dry farming to external disturbances in the FPENC. For farmers who subleased part or all of their

Table 8
Logistic regression results of the impact of explanatory variables on farmers' willingness to adopt the GDSC and active GDCS.

Model summary		Model I		Model II	
Model performance (H–L test)	Chi-Square	6.302		10.881	
	p-value	0.613		0.209	
	Overall corrected prediction	71.6 %		77.8 %	
Variables		**Coefficients**	**Wals**	**Coefficients**	**Wals**
RESGEN(1)		−0.071	0.027	−0.182	0.079
LABNO		0.250	0.699	−0.545	1.061
AVEAGE		0.010	0.399	0.061**	4.719
HOUTYP(1)		−0.609	1.926	0.121	0.043
HOUTYP(2)		−2.315***	8.086	1.185	0.667
HOUTYP(3)		−1.124**	4.717	1.814**	5.227
HOUTYP(4)		−0.694	0.872	−0.005	0.000
AVELAN		0.001	0.077	−0.004	0.166
RATDRY		1.195***	8.383	−2.073**	5.509
LANNO		0.012	0.137	−0.176*	3.487
IFIN(1)		−0.181	0.254	0.056	0.009
IFOUT(1)		0.764**	4.606	−0.213	0.114
RATRES		−0.865*	5.209	−0.763	1.071
DISCOU		−0.017*	2.918	0.014	0.509
MACNO		0.002***	5.696	0.000	0.203
ANNPRE		−0.031***	38.867	0.008	0.726
GEOTYP(1)		−0.742**	4.900	−0.827*	2.942
Constant		10.528	19.164	−2.353	4.094

Note. N = 304. *Significance at 10 % ($p < 0.1$). ** Significance at 5% ($p < 0.05$). *** Significance at 1% ($p < 0.01$). The number in brackets after the variable is the value of the dummy variable.

farmlands to others, their main income was from the land rental fees or non-agricultural incomes. Hence, they had a lower willingness to engage in farming. Moreover, most of the farmlands rented out were high quality, so the farmers were willing to adopt the GDCS in the remaining poor farmlands without large losses and heavy farming burdens. The GDCS requires a relatively high cost for plowing, ranging from 30 to 40 yuan per mu at a time, according to the rural household survey. For farmers owning plowing machinery, this cost was reduced, so they might prefer to adopt the GDCS. Therefore, the number of machines owned by the village had a positive effect on the farmers' willingness to adopt the GDCS.

Conversely, *HOUTYP(2)*, *HOUTYP(3)*, *RATRES*, *DISCOU*, *ANNPRE* and *GEOTYP(1)* had negative effects on farmers' willingness to adopt the GDCS, with partial correlation coefficients of -2.315, -1.124, -0.865, -0.017, -0.031 and -0.742, respectively. We assume the principal reason for this is that the income from raising cattle, sheep, and other livestock accounted for a large proportion of the income of animal-husbandry-led farmers (*HOUTYP(2)*) and agro-pastoral households (*HOUTYP(3)*). These farmers usually need to grow forage crops such as silage corn to feed their livestock and grow food crops to meet their demand for the grain ration. This type of farmer mostly adopts rotations of silage maize-other crops. Furthermore, because of the high pressure of fodder grain and the insufficient amount of rotational farmland, many animal-husbandry-led farmers and agro-pastoral households still chose the continuous cropping practice of silage corn-silage corn, and they were less likely to participate in the GDCS. In general, villages with higher *RATRES* had a sufficient labor force but fewer farmlands, which were mostly located in areas with good soil and water. These villages usually had a large proportion of irrigated land. Consequently, farmers in these villages showed less willingness to change their cropping system. In addition, lower *RATRES* means more population outflows and serious aging problems. From this point of view, the GDCS was an effective method to relieve rural labor shortages and avoid farmland abandonment. The loss of the young labor force is more common in villages relatively close to the county, so the old labor forces in these villages are more likely to take the GDCS. A negative correlation coefficient of *ANNPRE* proves again that the GDCS is a typical dry farming practice, which is more common in regions with less rainfall. In addition, the topographical conditions of the GDCS fields are generally poor, so the farmers living in the flat villages are less likely to take this practice.

4.3. Factors influencing Gfarmers'farmers' willingness to adopt the AGDCS in Ulanqab

We conducted analysis to identify the determinants of a farmer's willingness to adopt the AGDCS in Ulanqab. The results of Model II are given in Table 8. It was clear that *AVEAGE*, *HOUTYP(3)*, *RATDRY*, *LANNO*, and *GEOTYP(1)* had significant impacts on rural households' willingness to adopt the AGDCS.

Among them, *AVEAGE* and *HOUTYP(3)* played positive roles in Gfarmers' willingness to adopt the AGDCS, with partial correlation coefficients of 0.061 and 1.814, respectively. Some farmers were too old to manage a large amount of farmland, and they normally maintained the tradition of adopting the GDCS. Older farmers tended to readily, proactively, and designedly leave part of their farmlands uncultivated for a year. *HOUTYP(3)* farmers kept fewer livestock, and they liked to arrange it so a part of their farmland could grow manure crops to satisfy their livestock; then, they turned over the biomass of the manure crops in the rainy season.

In contrast, *RATDRY*, *LANNO*, and *GEOTYP(1)* played negative roles in Gfarmers' willingness to adopt the AGDCS, with partial correlation coefficients of -2.073, -0.176, and -0.827, respectively. The larger the proportion of a Gfarmers' dryland was, the more sensitive the crop growth was to the impact of less precipitation, and the greater the probability of adopting the PGDCS was. Considerable numbers of farmland parcels will cause a high cost of plowing and a long working distance, resulting in a decreased willingness to adopt the AGDCS. Only when there were poor growth and no harvest suffering from drought would farmers resort to the PGDCS. A negative partial correlation coefficient for *GEOTYP(1)* illustrated that adopting the GDCS in flat fields was mostly due to decreased precipitation, while adopting the GDCS on sloped fields was a necessary measure to assure regular production.

5. Discussion

5.1. The role of the GDCS in human-land interactions of the FPENC

The human-land interaction in the FPENC (Fig. 8) is complex and influenced by many factors, including the social economy, climatic factors, and production conditions. During the period from 1949 to 2016, the total population of Ulanqab grew from 1.16 million to 2.74 million people, causing an increased food demand. However, the low incomes in agriculture weakened people's willingness to be engaged in farming, resulting in massive labor losses from the agricultural sector to non-agricultural sectors. Now the Grain for Green is also being implemented over a large area in Ulanqab, and 10,400 hm^2 of farmlands are expected to be returned to the forest in 2016–2020 (General Office of Ulanqab Municipal People's Government, 2018). The large-scale afforestation has effectively increased vegetation coverage (Wang et al., 2018a,b) and reduced soil erosion (Bryan et al., 2018). On the other hand, in the earliest stage of the implementation, the Grain for Green initially reduced the farming burden of farmers and exacerbate the migration of young laborers to cities for high-paying work. However, after a few years, the age of the laborers who stay in rural areas becomes older, about 80 % of the local farmers are between 50 and 70 years old (Lan, 2013). Our questionnaire survey in this study also showed that the average age of the investigated agricultural workforce reached 60.73. Consequently, the existing farmland managements are so heavy for elders that some of them choose to abandon part of farmlands. Thus, both labor losses and aging pose severe threats to current and future sustainable agricultural production. In this case, local governments can meet the food demand only by practicing irrigation agriculture regardless of declines in the groundwater table.

Various other environmental issues have emerged due to the expansion of intensive agriculture, such as soil drought, reduction of soil organic matter, and soil erosion. Moreover, natural disasters have been exacerbated by climate warming and drying in recent years (Deng et al., 2017). For example, frequent droughts (50) occurred from 1992 to 2005 in Ulanqab. Consequently, the above factors jointly lead to continued ecological degradation via a positive feedback loop in the human-land interaction.

The GDCS, which is regarded by local farmers as a suitable farming measure for semiarid and low-yield areas, has existed for nearly 300 years despite a violent evolution of the human-land interaction in the FPENC. On the one hand, adopting the GDCS transfers some of the farming pressure caused by the loss and age of the agricultural labor force by reducing the farming area requirements and simplifying the field management practices. On the other hand, there is a considerable amount of marginal farmland, such as sloped fields, that is easily prone to degradation from anthropogenic and natural disturbances. Fortunately, functions of the GDCS, such as water storage and nutrient accumulation, are conducive to soil reconstruction and thus promote the ability of farmland to resist natural disasters. There will also be fewer weeds in GDCS fields in the subsequent year. When compared with continuous cropping, there are no significant reductions in the crop yields of fields managed with the GDCS (see Section 4.1.4), which prevents the 'more fields, fewer yields' dilemma. In conclusion, the traditional cropping system (GDCS) has the comprehensive function of 'combat drought - enrich nutrients - reduce burden (CER)' (Fig. 9), which is key to avoiding ecological degradation and to protecting a harmonious human-land relationship.

5.2. Policy implications

5.2.1. The GDCS and fallow practices

The GDCS shares some common ground with fallow in the field selection and field management. Generally, the GDCS and fallow practices are more likely to be adopted in the farmlands with poor soil conditions and high vulnerability to drought. Besides, both of them are temporarily inactive practices to reduce the burden of limited farmlands. During the fallow period and GDCS period, farmers don't grow grain crops in the fields, which is favorable for the soil nutrient and soil water recovery.

Although both fallow practices and the GDCS prevent the continuous planting of crops, the GDCS differs greatly from the fallow pilot programs of China. The GDCS is a spontaneous action taken by rural households to minimize losses and maximize economic benefits. Therefore, it is characterized by small-scale uncertainty in farmers' decision-making and a lack of oversight. In contrast, fallow aims to solve a series of ecological problems, including the overexploitation of

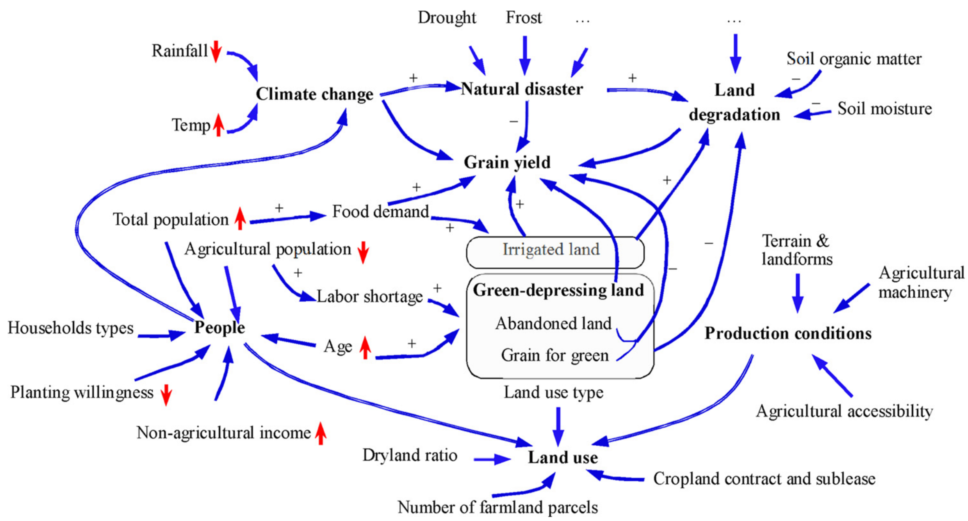

Fig. 8. The human-land interaction in the FPENC.

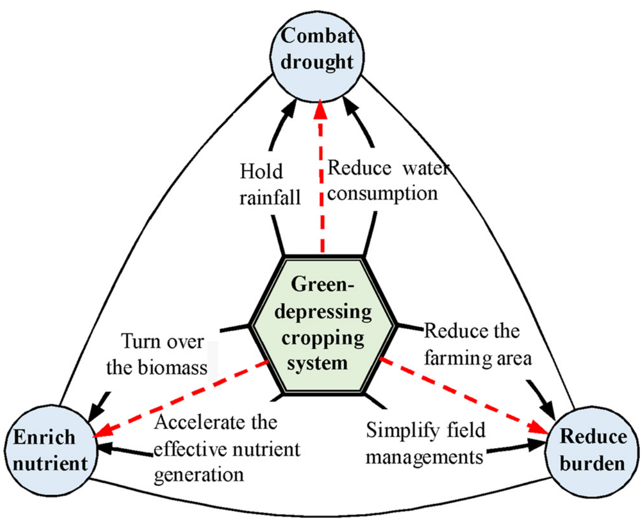

Fig. 9. The role of the GDCS in the FPENC.

groundwater (Bai et al., 2015; Zhong et al., 2019), soil pollution (Cheng et al., 2015), and soil erosion (Shi et al., 2019). As a top-down governmental program in China, the fallow pilot program covers a large area. Its actors are the central government, the local government, and rural households, which represent the policymaker, agent, and implementer of fallow practices, respectively. Farmers have strong incentives to leave fields uncultivated because of the fallow subsidy policy. If a fallow policy is going to be implemented in the FPENC, it will be necessary to work out a fallow plan including fallow region selection, field management, and fallow compensation ahead of time. The GDCS meets the national demand for fallow practices and can provide excellent policy references.

5.2.2. *Fallow policy suggestions*

The previous analysis (see Section 2) showed that the GDCS, which has long been practiced locally in the FPENC, could be a drop-in component of mandated fallow practices. For the FPENC where dry farming dominates local agriculture, fallow management can draw lessons from the traditional and ancient wisdom of the GDCS. As of now, local farmers lack even a basic understanding of fallow policies; 63 % of surveyed farmers had never heard of the fallow policy, 26 % of farmers knew a little about it, and only 11 % had a better understanding of it. However, once fully informed of the fallow policy, 88 % of the farmers were willing to allow their fields to lie fallow. The government should formulate the fallow policy based on the farmers' understanding of the GDCS and conform their policies to long-term local farming practices.

(1) Fallow region selection

Due to their poor quality and vulnerability to drought, dry sloped fields should be given priority to lie fallow. Although the quality of flat fields is better, fallow periods for flat land are also needed, but with a lower frequency. In addition, a fallow program can first be implemented with less resistance in the Houshan area because more farmers there have maintained the GDCS due to the poor climate conditions. The results of Section 4.2 indicated that farmers owning higher proportions of dryland, farmers subleasing their farmland to others, and farmers in villages with access to high levels of mechanization were more likely to participate in the GDCS. Such farmers can be mobilized to participate in fallow programs first.

(2) Field management

At present, the loss of the labor force, a lack of machinery, and the high cost of plowing means that GDCS3 basically does not exist. However, a previous study revealed that GDCS3 increased crop yield by approximately 10 % compared with GDCS2 and by 40 %–50 % compared with GDCS1 (The Inner Mongolia Autonomous Region Agriculture and Animal Husbandry Hall, 1979). Hence, we recommend that local governments be responsible for plowing farmlands to increase the proportion of the GDCS3. The timing of plowing can follow the GDCS (see Section 4.1.1). Farmers should lie dry sloped fields fallow every other year and lie flat fields fallow every two to three years. We also found that one year was enough for farmland to recover according to farmers' responses.

(3) Fallow compensation

Investigations on the management of fallows are required (Oliver et al., 2010). A low willingness to adopt the GDCS and a high proportion of the PGDCS necessitates introducing a subsidy policy in the FPENC. Our rural household survey illustrated that if farmers in the Qianshan and Houshan areas received subsidies of 227 and 250 yuan per mu, respectively, they would prefer to maintain their drylands as fallow.

(4) Uncertainties in the MGDCS

At present, the NGDCS dominates the GDCS in the FPENC. Although the MGDCS is very rare, various experiments have addressed the use of green manure crop applications to replenish soil fertility and crop yields (Fu et al., 2019). Farmers of Yongshan Village in Fengzhen found that the MGDCS with *Vicia cracca* increased the crop yield in the coming year by 30.07 % compared with the GDCS2 (Fengzhen Extension Station, 1981). Huang (2017) explored the effect of the MGDCS with *pacesetters* on soil properties through a controlled trial and showed that it could not only increase the nitrogen, phosphorus, and organic matter contents in the soil but also improve the soil structure and reduce soil salinity (Huang, 2017). Chen et al. (2017), Sainju et al. (2016), and Nasrollahi et al. (2017) found that *alfalfa*, a kind of leguminous forage crop, could enhance soil carbon and nitrogen stocks and reduce nitrogen leaching (Sainju et al., 2016; Chen et al., 2017; Nasrollahi et al., 2017). However, it is noteworthy that planting green manure crops leads to an increase in soil water consumption (Chen and Qu, 1985). Therefore, further study on the comparison of the comprehensive benefits between the NGDCS and the MGDCS is needed in the FPENC, where there is serious water stress.

6. Conclusions

In this study, we resolved the historical and current evolution of the human-land relationship in the FPENC surrounding the development of the environmentally friendly land use practice called the GDCS. After more than 300 years of development, the GDCS has evolved according to farmers' initiatives and farmers' field management methods. An approach to map the GDCS fields using multi-source satellite data was proposed. The GDCS is currently still a widely distributed and common land use practice in the FPENC, and a large proportion of the GDCS fields are sloped farmlands, which severely suffer from serious soil and water loss.

To determine farmers' willingness to adopt the GDCS in the FPENC, we used a questionnaire survey in Ulanqab. From the surveys, we learned that less than half of the investigated farmers had adopted the GDCS in 2018. In addition, a large number of Gfarmers tended to adopt the PGDCS as a result of poor crop growth, regarding it only as a way to prevent additional losses within a single year rather than as a routine farmland conservation measure. Due to the relatively worse economic and climatic factors, the Houshan area had a higher proportion of Gfarmers than the Qianshan area. Moreover, the traditional cropping system could significantly increase the yield of all kinds of crops in the subsequent year.

Inherent characteristics of the rural household, characteristics of farmland use, management condition and natural environment jointly determined the farmers' willingness to adopt the GDCS. The results of the BLR model suggested that farmers owning a higher proportion of dryland, farmers subleasing their farmland to others, and farmers in villages with access to high levels of mechanization, farmers in the villages close to the county and farmers in the regions with less rainfall were more likely to engage in the GDCS. Moreover, the GDCS could combat the effects of drought, enrich the soil nutrients, and reduce the farming burden, all of which played an important role in maintaining a harmonious human-land interaction in the FPENC. In conclusion, the aim of this land use practice is to maintain sustainable farmland use in areas with harsh natural conditions rather than produce the highest possible yield. We conclude that a local fallow policy—including fallow region selection, field management, and fallow compensation—should be based on the traditional and ancient wisdom of the GDCS. Fallow programs should be implemented first in regions with high proportions of dryland and sloped fields, a small resident population, high levels of mechanization and high farmland transfer rates. Fallow compensation policy is required to improve farmers' willingness to participate in the program.

CRediT authorship contribution statement

Xin Chen: Conceptualization, Methodology, Validation, Visualization, Writing - original draft. **Li Jiang:** Writing - review & editing. **Guoliang Zhang:** Investigation, Validation. **Lijun Meng:** Investigation, Visualization. **Zhihua Pan:** Resources, Supervision. **Fei Lun:** Writing - review & editing. **Pingli An:** Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104917.

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