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Article

Multi-Agent Modeling and Simulation of Farmland Use Change in a Farming–Pastoral Zone: A Case Study of Qianjingou Town in Inner Mongolia, China

Xuehong Bai [1,2,†], Huimin Yan [1,*], Lihu Pan [3,†] and He Qing Huang [1,†]

[1] Key Laboratory for Resources Use and Environmental Remediation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; E-Mails: baixh.12b@igsnrr.ac.cn (X.B.); huanghq@igsnrr.ac.cn (H.Q.H.)

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] School of Computer, Taiyuan University of Science and Technology, Taiyuan 030024, China; E-Mail: panlyhoo@sohu.com

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: yanhm@igsnrr.ac.cn; Tel.:+86-10-6488-9004.

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Abstract: Farmland is the most basic material condition for guaranteeing rural livelihoods and national food security, and exploring management strategies that take both stable rural livelihoods and sustainable farmland use into account has vital significance in theory and practice. Farmland is a complex and self-adaptive system that couples human and natural systems, and natural and social factors that are related to its changing process need to be considered when modeling farmland changing processes. This paper uses Qianjingou Town in the Inner Mongolian farming–pastoral zone as a study area. From the perspective of the relationship between household livelihood and farmland use, this study establishes the process mechanism of farmland use change based on questionnaire data, and constructs a multi-agent simulation model of farmland use change using the Eclipse and Repast toolbox. Through simulating the relationship between natural factors (including geographical location) and household behavior, this paper systematically simulates household farmland abandonment and rent behaviors, and accurately describes the dynamic interactions between household livelihoods and the factors related to farmland use change. These factors include natural factors (net primary productivity, road accessibility, slope and relief amplitude) and social factors (household family structures, economic development and government policies). Ultimately, this study scientifically predicts the future farmland use change trend in the next 30 years. The simulation results show that the number of abandoned and sublet farmland plots has a gradually increasing trend, and the number of non-farming households and pure-outworking households has a remarkable increasing trend, whereas the number of part-farming households and pure-farming households has a decreasing trend. Household livelihood sustainability in the study area is confronted with increasing pressure, and household non-farm employment has an increasing trend, while regional appropriate-scale agricultural management is maintained. The research results establish the theoretical foundation and a basic method for developing sustainable farmland use management that can meet the willingness of households and guarantee grain and ecological security.

Keywords: farmland; coupled human-nature system; multi-agent modeling; Repast; household typology; Inner Mongolia

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1. Introduction

Farmland is the most basic material condition that guarantees rural household livelihood and national food security. Under the influences of climate disaster, social economy, government policy and rural household structure, farmland area has exhibited a remarkable fluctuating trend. Farmland is a complex and self-adaptive system that couples human and natural systems [1,2], and natural and social factors that are related to its changing process, and thus need to be considered when modeling the farmland changing process. However, traditional land use models cannot explain spatio-temporal heterogeneities and endogenous feedback mechanisms of farmland use change, and cannot accurately describe the process mechanisms of land use change from rural households' perspectives [3–5]. Multi-agent technology [4,6–8] is the most suitable method to simulate interactions between human behavior and land use change. This technology can express the complexities of land use change in a multi-disciplinary, multi-scale, multi-angle and multi-level way, and thus well reflects the dynamic feedback relationships between social economy and nature.

Since the late 1990s, a growing number of scientists have studied land-use and land-cover change using multi-agent technology, and several scholars have systematical reviewed the applications of spatial agent-based models (ABMs) used for land-use and land-cover change (ABM/LUCC). The earliest ABM/LUCC is the Indonesian irrigation system model constructed by Lansing and Kremer [9] in 1993, which paved the way for agent-based modeling to study LUCC. Parker [10] systematically reviewed the applications of ABM/LUCC and divided them into four topical areas: natural-resource management, agricultural economics, archaeology and urban simulations. Matthews [11] summarized five broad areas that ABM/LUCC includes: policy analysis and planning, participatory modeling, explaining spatial patterns of land use or settlement, testing social science concepts, and explaining land use functions. Qiangyi Yu [4] reviewed ABMs used in agricultural land use change based on theory, driving mechanisms, modeling methods and interdisciplinary applications. Other scientists such as Bousquet and Le Page [12], and Hare [13] also published summaries and reviews on ABM/LUCC.

Recently, under the influence of natural factors (net primary productivity, road accessibility, slope and relief) and social factors (household structure, economic development and government policies) [14–16], agricultural labor in the farming–pastoral zone have transferred to large cities, and allocations of household labor resources have changed drastically, resulting in diversified household livelihood patterns. In this context, farmland parcels have been abandoned and sublet, and dependency relationships between households and farmland have been broken, which challenges the sustainability of farmland use and stability of household livelihoods. Farmers and related management organizations are trying to find new ways to manage farmland; therefore, how to use farmland in the farming–pastoral zone of Inner Mongolia in the future is a question that needs to be answered by a scientific study. The farming–pastoral zone of northern China is in an eco-fragile area [17–19]. It is a sensitive belt of environmental evolution and is classified as marginal land for agriculture [15,20]. Conducting studies in eco-fragile regions has important implications for maintaining farmers' livelihood and national food security. Farmland use change in the farming–pastoral zone has received the attention of many scholars [20–24]. Until now, however, most studies focused on the spatio-temporal patterns [14,15], the driving mechanisms [14–17,22,23] and the eco-environmental effects [17,18,21] of land use change, while few studies have focused on the process mechanisms of land use change coupled with human-nature systems.

The rural household is the basic unit for changing the status of farmland use [25,26], and its livelihood strategies have a significant impact on the land use mode [27–29]. Studies on the relationship between rural household livelihood and farmland use based on household scale have been conducted by a growing number of scientists [30–37]. Integrating rural household livelihoods to study the changing trend and adaptive mechanisms of farmland systems has become a means through which sustainable development in eco-fragile regions can be realized.

To explore the management strategies that take sustainable rural livelihoods and sustainable farmland use into account, this study uses Qianjingou Town in the Inner Mongolia farming–pastoral zone as a case study area. A multi-agent model of farmland use change that synthesizes household livelihood strategies, the natural environment and the social-economic environment was constructed using the potential of sustainable farmland use and associated future users as targets. This model uses multi-agent technology to predict the farmland use change trend of the study area in the next 30 years, and clearly analyzes the process mechanisms of farmland abandonment and renting, which establishes the theoretical foundation and a basic method for developing sustainable farmland use management that can meet the willingness of households and guarantee grain and ecological security.

2. Overview of the Study Area

Qianjingou Town is located in the south of Taipusi Banner, Xilin Gol League, between 114°51′–115°49′ E and 41°35′–42°10′ N (Figure 1). Its elevation ranges from 1200 m to 1800 m. This town is located in key eco-fragile areas of dessert grassland at the northern foot of Yinshan Mountains and is a typical ecological vulnerable region in the northern farming–pastoral zone. Qianjingou Town covers an area of 600.11 km^2; its mean annual mean temperature is 1.6 °C, its annual precipitation is less than 400 mm, and it has a temperate continental climate.

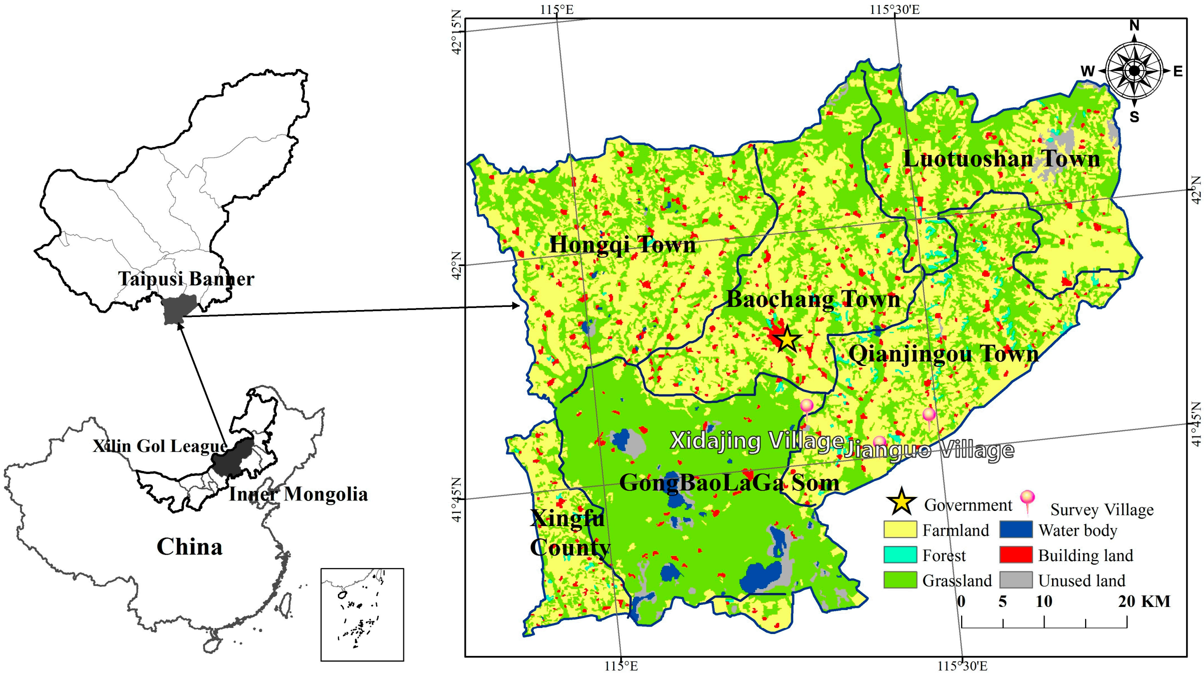

Figure 1. The geographic location and land cover types of Qianjingou Town.

Based on the natural disasters in Xilin Gol League, we determined that drought is the climatic disaster with the highest frequency in the study area. According to the existing literature [38], drought occurred 11 times in the 1960s, nine times in the 1970s, eleven times in the 1980s, and eight times in the 1990s. In the 2000s, rainfall in this league decreased significantly, while evaporation increased at the same time. The decreasing trend of summer rainfall further intensified the drought events.

Taipusi Banner is one of the key national poverty alleviation and development counties. In 2010, the population of the whole banner was 212,000, of which the agricultural population was 172,000, and the non-agricultural population was 39,000. Since 2000, allocation of labor resources in Taipusi Banner has changed considerably. The number of people who engaged in primary industry has decreased considerably (from 75,000 in 2000 to 60,300 in 2010), and the number of people who engaged in secondary and tertiary industries has increased significantly (from 26,400 in 2000 to 29,000 in 2010) [39], which indicates a clear transfer trend from agricultural labor to non-agricultural labor.

Taipusi Banner is one of the key counties where the government implements ecological construction policies. National ecological protection policies and grain subsidy policies have an important impact on local farmland use change. The farmland area of the whole banner has a decreasing trend and the forestland area has exhibited an increasing trend since the Grain-To-Green-Program (GTGP) was started in 1999 and the Three-North Shelter Forest Program was started in 1978 (Figure 2). By the end of 2009, the GTGP had converted 46,100 hectares of cropland, of which the afforestation area was 28,700 hectares, and the forest coverage increased from 9.5% in 2000 to 14.2% in 2009. The GTGP included five towns and involved 35,569 rural households and 111,210 people [40]. The changing trend of the farmland area in 1998–2010 (Figure 2) shows that the cropland area decreased considerably because the GTGP was carried out, but increased rapidly in 2010. In 2010, the government still implemented the GTGP in Taipusi Banner, but the cash payment dropped from 2400 yuan per hectare to 1350 yuan per hectare. The first round of the GTGP was ended in 2007, and the second round was started immediately. To further stimulate food production in Taipusi Banner, protect comprehensive production ability, increase farmers' grain cultivation enthusiasm, and increase farmers' income, the government has offered farmers a subsidy of 430.7 yuan per hectare since 2004 (*i.e.*, Grain Subsidy Policy).

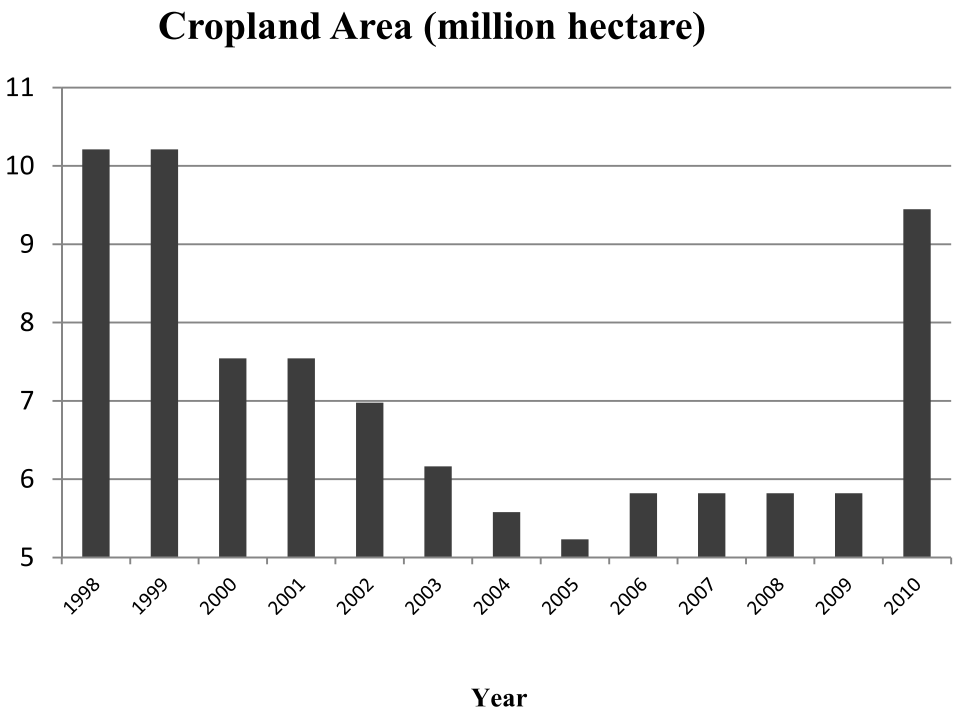

Figure 2. The changing trend of the farmland area of Taipusi Banner in 1998–2010 (Data obtained from the Inner Mongolia Statistical Yearbooks [39]).

In conclusion, influenced by the increased food demand driven by population growth, climate change and government policies, farmland resources are facing conflicts from food production and ecological protection, and the farmland area is changing continually. Income from government policies, crop production and outside employment has resulted in diversified patterns of local rural household livelihood, and the sustainable development of local household livelihoods and farmland systems is influenced by these factors.

3. Data Collection

This paper used three types of data to support the study, *i.e.*, census data, rural household questionnaires and spatial data. The census data were obtained from the statistical yearbook [41] and were used to obtain the total population of Qianjingou Town. The rural household questionnaires and spatial data are the key basis of the analysis. Because of the complexities involved with their data collection and analysis, they are described separately as follows.

Rural household questionnaires were collected by our team through face-to-face interviews in July 2011. The purpose of these questionnaires was to understand the current farmland use modes, identify the natural and social factors related to the farmland changing process, and analyze and predict the future farmland use change pattern. We selected three villages (Xidajing, Jianguo and Jiuyingpan) as the study area and interviewed members of 161 rural households. The interviewed households cover a wide range of farmer groups, including elderly peasants who stayed in the rural areas for a long time and a middle-aged agricultural labor force. This is conducive to understand different factors that influence different farmers' land use decisions. The questionnaires include four aspects: (1) the basic characteristics of the rural household family members, including age, job, education status, *etc.*; (2) family resource allocations, including number of farmers, number of migrant workers, farmland areas, amount of agricultural equipment, the cost of agricultural production, the possibilities for children to return to the rural area, *etc.*; (3) rural household economic characteristics, including agricultural income, the GTGP payments, the Grain for Subsidy Policy payments, income from renting land, the total income of the household, *etc.*; and (4) farmland use changing modes for each household, including renting, abandonment and unchanged.

Spatial data were used to describe the geographical characteristics of the study area. We collected six types of spatial data to support our study, *i.e.*, land use types, NPP (Net Primary Productivity), DEM (Digital Elevation Model), road and relief amplitude data (Figure 3). The land use data were interpreted from a 2010 TM image, and six land use types (cropland, forest land, grassland, water bodies, building land and unused land) were identified. NPP data were extracted from MOD09A1 data and computed using AGRO-VPM (Vegetation Photosynthesis Model). In this study, using the farmland layer as a mask, we extracted farmland NPP data. We downloaded DEM data with a resolution of 30 m from the USGS (United States Geological Survey) website [42], and corresponding slope data were generated using the DEM data. Road data were offered by the National Geomatic Center of China, and using these data, the accessibility data of the road network was generated using the Euclidean Distance algorithm in ArcGIS. Relief amplitude refers to the difference between the point with the highest DEM and the point with the lowest DEM in a certain area. In this study, using ArcGIS, we generated a fishnet for each 5 × 5 cells using the "Create Fishnet" command, computed the "Range" value using the "Zonal Statistics" command, and then obtained the relief amplitude value for each fishnet.

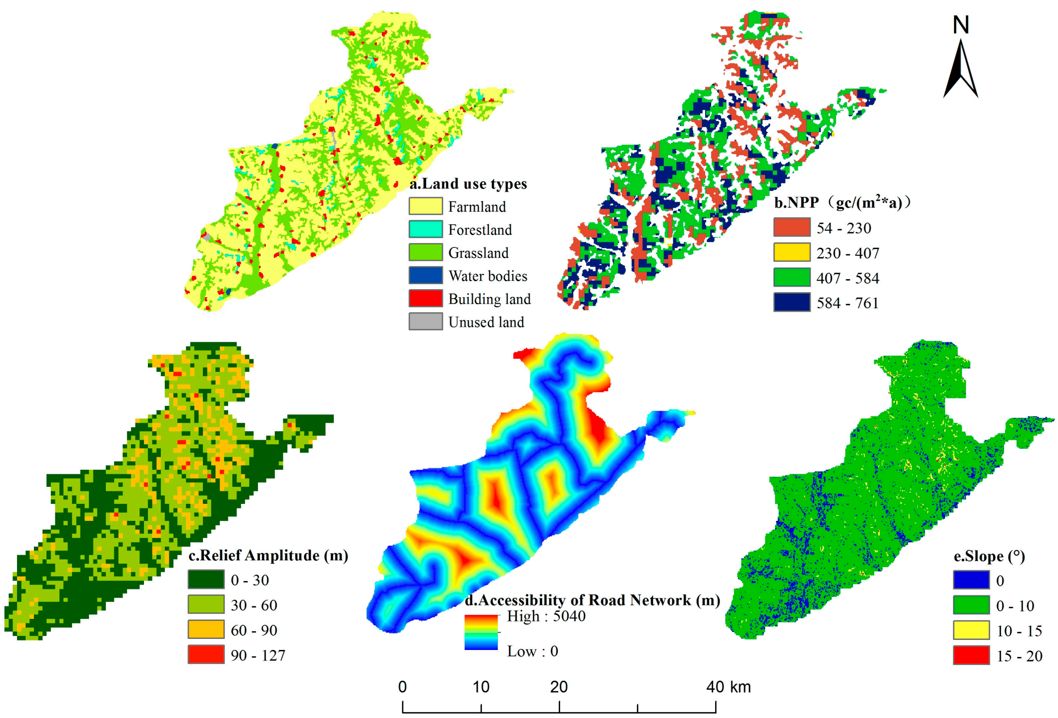

Figure 3. The geographical profiles of the study area: (**a**) land use type; (**b**) NPP; (**c**) relief amplitude; (**d**) accessibility of road network, and (**e**) slope.

4. Describing the Multi-Agent Model of Farmland Use Change Based on ODD + D Protocol

The model description follows the ODD + D (Overview, Design Concepts, Details and Human Decision-making) protocol [43] to facilitate the comparison and communication of scientists from different academic fields. The ODD + D protocol has an emphasis on human decisions, and includes the empirical and theoretical foundations for the choice of decision model. In order to compress the length of this paper, we listed the main body of ODD + D protocol. For the full edition of the model described by ODD + D protocol, Supplementary Materials 1.

4.1. Overview

4.1.1. Purpose

This model has been developed to simulate the effects of farmers' livelihood behaviors on farmland use change in a farming–pastoral zone and the effects of land quality on the farmer's land use decisions. The model aims at exploring the management strategies that take stable rural livelihoods and sustainable farmland use into account, and provides decision support for managers to maintain the sustainability of human-nature systems.

4.1.2. Entities, State Variables and Scales

In the model, entities are compromised by agents (individuals, households, household group and government), spatial units (grid cells), the environment (NPP, road, slope and relief amplitude) and collectives (list of agents and list of land plots). The model is built based on real landscapes. Landscape cells are characterized by the state variables: coordinates, landUseType (land use type), NPP, roadAccessibility (the distance to the main road network), slope and reliefAmplitude. Farmland cell is part of landscape cell, and it is characterized by the state variables: rentalFarmland (the land rent of farmland), I_{total} (the combined impacts of the four natural factors), yieldFarmland (the yield of farmland) and cellSize (the spatial resolution of grid cell). Individual agents are characterized by the state variables: coordinates, age, gender, education, farmingIncome (the farming income of individuals), maxAge (the longevity of individuals), workIncome (the migrant work income of individuals), occupationState (the occupation states of individuals). Household agents are characterized by the state variables: amountofLand (the number of plots that each household plants), amountofFamilyM (the number of family members each household has), individualAgent array (the array of family members), familyLand array (the array of farmland plots planted by each household), parent, rentState (the rent state of each plot), hireLandNumber (the number of plots hired by each household), rentGained (the total income of hired plots), selfFarmNumber (the number of plots planted by the owner), rentFarmNumber (the number of plots hired/rented out by the household), noFarmNumber (the number of plots abandoned by the household), farmerNumber (the number of farmers in the household), outworkNumber (the number of individuals who travels for a job), oldersNumber (the number of the olders),aggregationIndice (the aggregation degree of plots planted by the household), and averageLand (the area of farmland per capita). The state variables of household group agents are groupType (the type of the houseold group) and k (the maximum planting ability of each agricultural labor force). The state variables of government agent are subsidyGSP (the subsidy of the Grain for Subsidy Policy) and isGrain (whether carries out the Grain for Subsidy Policy). We listed the detailed descriptions of state variables for every entity in Tables S2–S7 as Supplementary Materials 2. The exogenous factors of the model include government policies and natural factors (land use cover, accessibility of road network, slope, relief amplitude and NPP). We overlap the layers of LUCC, NPP, slope, relief amplitude and accessibility of road network according to their coordinates.

In the model, 1 time step represents 1 year (the time resolution), the spatial resolution is 96 m × 96 m (for why we set 96 m × 96 m as the spatial resolution, see Section 4.3.2) and the length of period is 30 years. In China's mainland, the rural land property rights institution is a family-contract responsibility system, and the household is the basic unit of land management. This responsibility system remained unchanged for 30 years, so our simulated length of period is 30 years. The study area is 600.11 km^2.

4.1.3. Process Overview and Scheduling

Based on land use, questionnaires and statistical data, we set one farmland grid cell (0.9 hectare, one plot) to correspond to one person's farmland areas (one person occupies one farmland grid cell). The farmland areas of each household are determined by their family size. This model includes four submodels: individual state transfer submodel, household classification submodel, spatial environment distribution submodel and household farmland use decisions submodel (Figure 4). In this model, the households were divided into five groups based on the differentiation of labor allocation and household livelihood composition, and separately analyzed the farmland use behavior of five types of households (hiring, renting out or abandonment). To analyze household farmland use behaviors, two questions needed to be answered: How to determine the number of plots households want to transfer? Which plots should be transferred for each household? We used the maximum planting ability of each agricultural labor force to calculate the number of transferred plots, and sorted the I_{total} value of the plots of each household in ascending order. Four natural factors were integrated into 1 index (I_{total} value) using a weight method. Finally, we obtained the results of the farmland use state, labor state, farmland aggregation degree (FAD) and the number of five types of households in the next 30 years.

The household farmland use behavior in the study area was influenced by the family structures, economic development, government policies and natural factors (NPP, road accessibility, slope and relief amplitude). Figure 5 shows the discrete events mechanism when the model is running at time t + 1. After time t is finished, the age of the individual agents is increased by one year, and their occupation states are updated (Figure 6; for details, see Section "Descriptions of Submodels" (1)). Changing the family members' occupation states changes the household type. So after individuals change their occupation states, we need to determine the type of each household (for details, see Section "Descriptions of Submodels" (2)). Based on the relationships between household livelihood and farmland use behavior in different groups (for details, see Section "Descriptions of Submodels" (4)), we obtained the household farmland use decisions rules (no change, expanding scale, or reducing scale). Some households hired farmland while others rented out farmland, so we simulated the land renting in and hiring process bases on questionnaires. In our study, there are no migrant farmers, and land exchanging carries out between local households. About the land renting in and hiring process, two questions needed to be answered: How many plots does each household transfer? Which plots do households rent out, abandon or hire? To answer the first question, we obtained the maximum plots that each agricultural laborer can plant. Here, we use "k" to refer to this index, which was calculated from the questionnaires, and this index reflects the maximum number of farmland plots that each agricultural laborers can plant. This is only the maximum capacity of each agricultural labor force. In fact, not every agricultural labor force plants k plots. Considering the planting capacity of each agricultural labor force, we introduce k into our model to reflect the real world. If a household has m agricultural laborers, the maximum number of farmland plots this household can plant is m × k. If the number of farmland plots divided by m is greater than k, households will reduce the scale of their planting; alternatively, they will consider increasing the extent of their planting scales. To answer the second question, we need to calculate the I_{total} value of each plot planted by each household (for details, see Section "Descriptions of Submodels" (3)), and rank these plots according to their I_{total} value in ascending order. The households prefer to rent out or abandon the plots with low I_{total} value, while hire the plots with high I_{total} value. When the plots that were rented out by some households were not be hired by other households, they would be abandoned, and the land renting in and hiring process was failed; otherwise, the plots would be farmed by other households, and the land renting in and hiring process was successful.

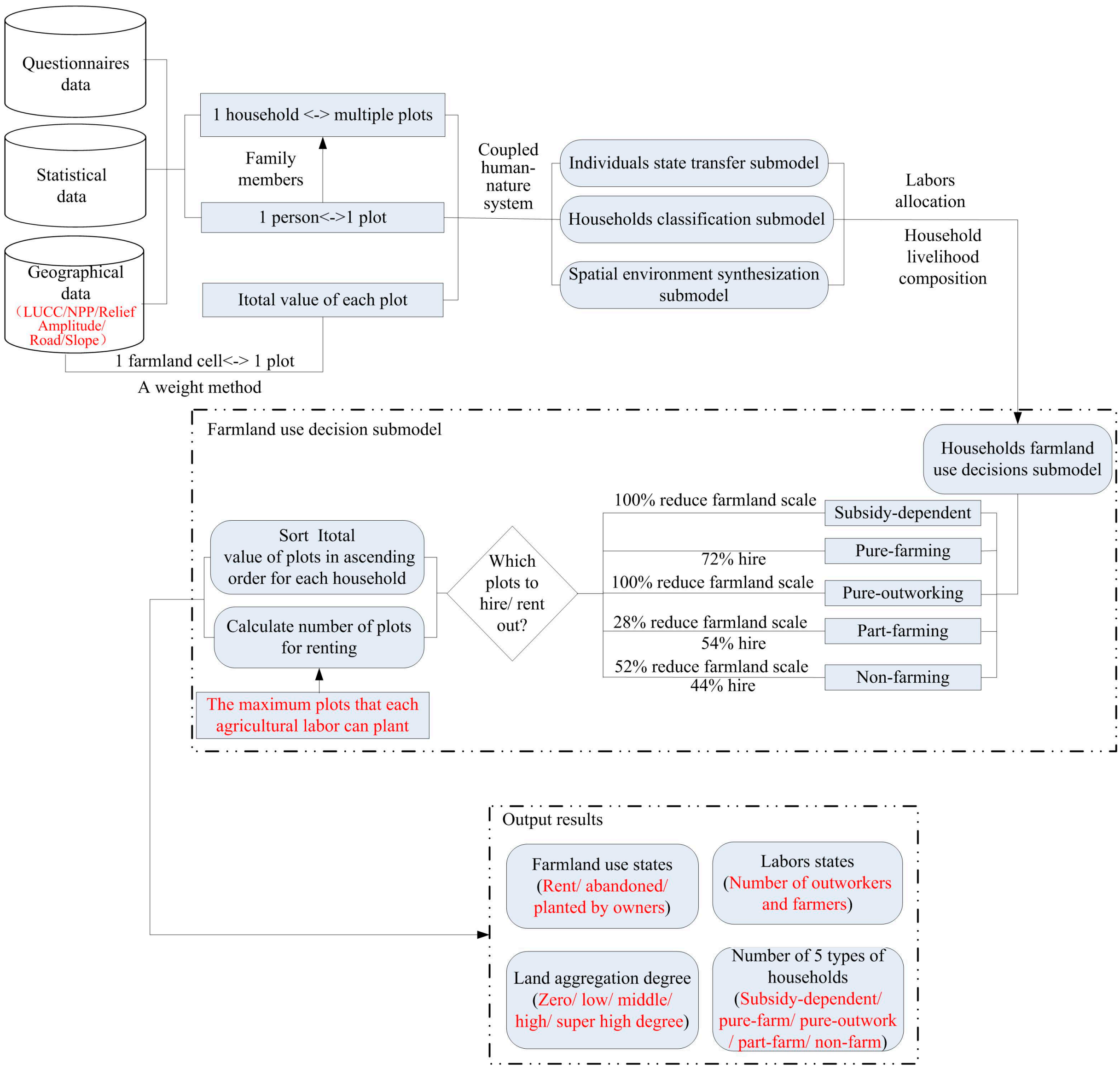

Figure 4. The conceptual framework of the model.

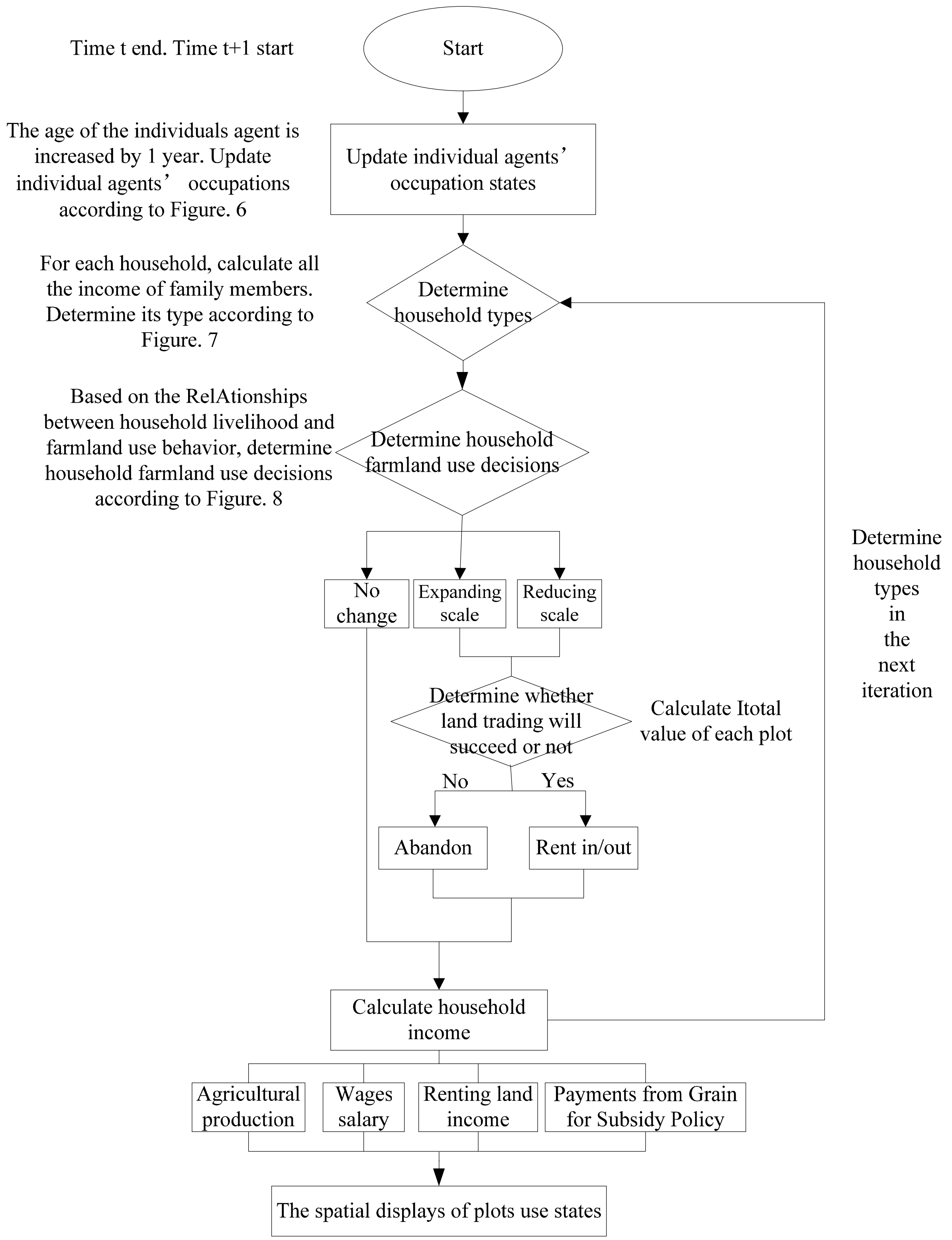

Figure 5. Flow chart of the mechanisms of discrete events when model is running at time t + 1.

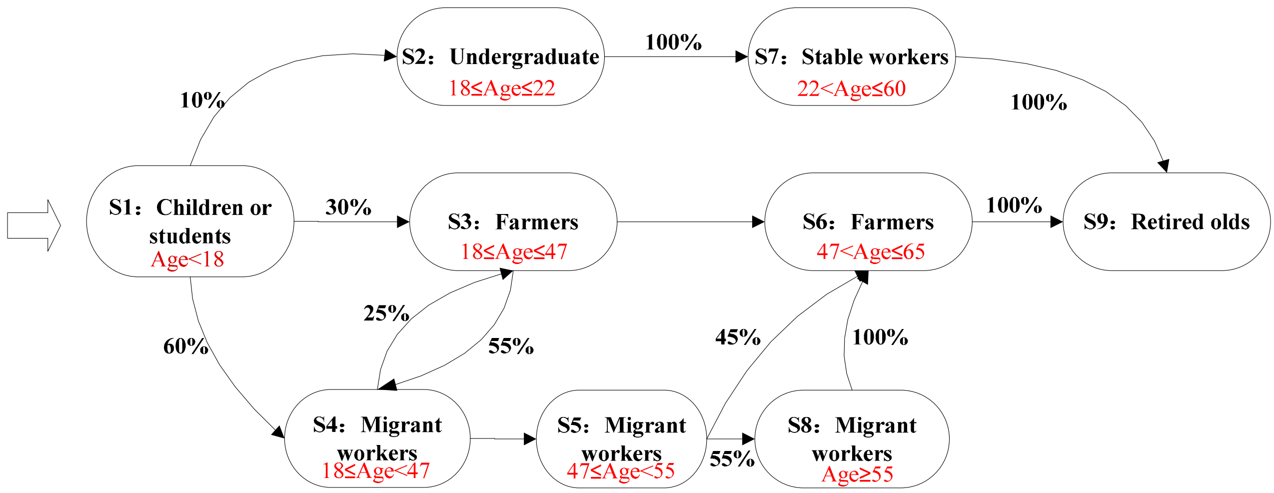

Figure 6. The changing mechanisms of the occupation state of individual agents (modified from [44–46]). Note: Six important age nodes are 18, 22, 47, 55, 60 and 65. Percentages represent the probabilities of individual agents changing their occupation state. S represents the occupation state.

Because of the popularization of agricultural machinery in the study area, one agricultural laborer can plant the area of 10 plots (9.3 hectares), *i.e.*, k is equal to 10. To illustrate this process in detail, we describe five types of households as follows. For ease of description, we use "p" to refer to the total number of farmland plots each household owns, and "q" to refer to the number of agricultural laborers.

(1) Subsidy-dependent households: 100% of households do not plant farmland.
(2) Pure-farming households: Check whether p/q is less than 10. If so, 72% of households hire farmland; they do not rent out farmland. For households who have renting in farmland decisions, they will hire q × (10 − p/q) plots.
(3) Part-farming households: Check whether p/q is less than 10. If so, 54% of households will hire q × (10 − p/q) plots; alternatively, 28% of households will decrease planting plots by q × (10 − p/q) plots.
(4) Non-farming households: Check whether p/q is less than 10. If so, 44% of households will hire q × (10 − p/q) plots; alternatively, 52% of households will decrease planting plots by q × (10 − p/q) plots.
(5) Pure-outworking households: 100% of households will rent out or abandon all of their farmland plots.

Finally, we calculated the family income of each household (including agricultural production, wage/salary, renting land income and payments from the Grain for Subsidy Policy), and spatially displayed the plot use states. At this point, time t + 1 ended, and the discrete events mechanism was terminated.

4.2. Design Concepts

4.2.1. Theoretical and Empirical Background

(1) General concept: We want to use "farmland area per capita" index to show the changing trend of farmland management area for each household. To facilitate analysis, we proposed "farmland aggregation degree (FAD)" index to indicate the farmland area increase or decrease cropped by each individual on each household basis, calculated as

$$FAD = \frac{AREA_{household}}{N_{member} \times AREA_{individual\_0}} \tag{1}$$

where *FAD* refers to the farmland aggregation degree; $AREA_{household}$ refers to the farmland area managed by each household; N_{member} refers to family size of each household; and $AREA_{individual\_0}$ refers to the farmland area of each person allocated by the government at the initialization of the model, *i.e.*, 0.9 hectare. FAD = 1, indicates that farmland per capita in this household is unchanged compared to the initialized time (*i.e.*, 0.9 hectare); FAD = 0 indicates that all farmland is rented out or abandoned by the owners, and 0 < FAD < 1 refers to households that rented out or abandoned part of their farmland. FAD > 1 indicates that households expanded their planting scales. The greater the FAD value is, the more farmland area managed by the household.

We set five intervals of *FAD*, *i.e.*, zero *FAD* ($FAD = 0$), low *FAD* ($0 < FAD \leq 1$), middle *FAD* ($1 < FAD \leq 3$), high *FAD* ($3 < FAD \leq 6$) and super high *FAD* ($FAD > 6$). Zero *FAD* refers to that all farmland is rented out or abandoned by the owners, and low *FAD* refers to households that rented out or abandoned part of their farmland. Middle *FAD*, high *FAD* and super high *FAD* refer to three levels that households expanded their planting scales. *FAD* can reflect the states of the farmland management scales and farmland management right redistributions.

At the initialization of the model, one individual was assigned to 0.9 hectare of farmland. If there are "N" family members in a household, a household will have 0.9 × N area of farmland to plant. At a later time, farmland was rented or abandoned, and the area of farmland planted by each household will change simultaneously. We can determine whether the households expand planting scales or reduce them according to the value of FAD.

(2) Hypotheses: there are four hypotheses in our study. (i) During the model running time, farmland was not reclaimed, and there was no new farmland generated. The households only plant crops on the original farmland plots. There are no new households generated in the next 30 years. Newborns do not bring new households, and they belong to the original families. (ii) During the simulated 30 years, the running rules of the model remain unchanged. The model parameters of farmland area per capita, migrant work salary, prices of naked oats, the prices of land rent and the yield of farmland are fixed. (iii) The land renting in and hiring process is carried out between local households, and it is not influenced by migrant farmers. In our study, we use I_{total} value to refer to the quality of plots. The households prefer to rent out or abandon the plots with low I_{total} value, while hire the plots with high I_{total} value. When some households attempt to rent out some plots, but other households do not hire them, they are abandoned. (iv) According to questionnaires analysis, we set the maximum plots that each agricultural laborer can plant (we use "k" to refer to this index). When the number of farmland plots

planted by per agricultural laborers is greater than k, the households will reduce the scale of their planting.

(3) The agents' decision models are based on the assumptions that, households in the same group have the same farmland use behaviors. The transitions of individuals' occupation states follow specific mechanisms (for details, see Section "Descriptions of Submodels" (1)).

We use the surveyed data to analyze the characteristics of individuals and households in the real-world. Using a probability method to get the model running mechanisms can effectively describe agents' characteristics from an overall view. Our model is based on empirical data, and these data are collected from first-hand questionnaire surveys on the spot. The data are available at yearly aggregation level.

4.2.2. Individual Decision-Making

Four types of agents were used to model the farmland use change system, *i.e.*, individual agent, rural household (shortened to household) agent, rural household group agent and government agent. Among these four types of agents, the household agent is the basic unit of the model, and the individual agent who comprises the household agent is the smallest unit of the model. If any individual agent changes its behavior, the household agent's attributes and behaviors will change simultaneously. Using the key attributes of the households, rural households can be divided into different groups. Different groups of households have different farmland use behaviors, while households that belong to the same group have the same behaviors. Non-farming groups of households prefer to rent out farmland, while pure-farming and part-farming groups of households prefer to hire farmland.

In the study area, 96.3% households have participated in the GTGP, and 97.6% households were willing to participate in this program. Because most of the households that participated in this program resulted in almost no heterogeneity with respect to whether or not a household participated in the GTGP, we did not take the GTGP into account in this study. This study only focused on farmland use change based on farmers' willingness.

The decision-making includes multiple levels. The Government agent decides the payment from the Grain for Subsidy Policy, and this decision influences the livelihood structure of households. The whole town receives the same government policy. The individual agents decide their own occupation states, and this decision influences households' livelihood strategies and structures (for details, see Section "Descriptions of Submodels" (4)), and this decision directly changes their farmland use states. These decision-makings are modeled on each farmland grid cell.

As individual agents grow older, their occupation states change correspondingly. According to study target, we divided households into different groups (for details, see Section "Descriptions of Submodels" (2)). The changing occupation states of all the family members drive the change of household types. Based on questionnaires interview, we analyzed the farmland use behaviors of different types of households.

The agents adapted their behavior to changing endogenous and exogenous state variable. All of the changes of government Grain for Subsidy Policy, economic development, family occupations structure, and family livelihood structure can influence the type of households, and households' farmland use behaviors will be changed correspondingly (see Section "Descriptions of Submodels" (2)).

Social norms or cultural values do not play a role in the decision-making process. Spatial aspect plays a role in the decision process. Through local interviews, we found that households evaluate farmland quality according to NPP, relief amplitude, road accessibility and slope. In our study, spatial heterogeneities can be presented by these four natural factors. We use the I_{total} index to express the combined impacts of these four factors (for details, see Section "Descriptions of Submodels" (3)). When households choose to plant at reduced scales, they will rent out or abandon farmland plots with inferior qualities; when households choose to plant at expanded scales, they will hire farmland plots with superior qualities. Time aspect also plays a role in the decision process. As individual agents grow older, they will change their occupation states, and their family livelihood structures will be changed correspondingly. The types of households and their farmland use behavior will be changed simultaneously.

The model includes uncertainty. Our questionnaires cover 161 households and 714 family members. However, in the whole Qianjingou town, there are 7952 households and 17,500 populations. We use Monte Carlo method to simulate households in the whole town based on sampled survey data.

4.2.3. Learning

Individual learning is included in the decision process. Through questionnaire analysis, we got the changing mechanism of the occupation state of individual agents (for details, see Section "Descriptions of Submodels" (1)). Every individual obeyed this mechanism. During the model running period, when individuals got to a certain age node, their occupation state will change to another state according to a specific probability.

Collective learning is implemented in the model. Based on empirical statistics analysis, we got the farmland use behavior rules of households in different groups (for details, see Section "Descriptions of Submodels" (2)). Households in different groups will learn these rules during the simulating process. After determining the types of households, their farmland use behavior will be determined according to the preset rules.

4.2.4. Individual Sensing

Individuals are assumed to sense and consider their own ages, occupations and economic development. Households are assumed to sense their livelihood structure, economic development, government policies and farmland use states. These sensing processes are correct.

An individual cannot perceive state variables of other individuals. Because of lack of data, we did not consider the learning between individuals in our study.

The spatial scale of sensing is the grid cell. At this scale the plots state can be sensed. Through perceptions of the household agent, we obtained the weight values of four natural factors, and synthesized these natural factors into one index (I_{total} value). All other variables are just known by the agents. The costs for cognition and the costs for gathering information are not included in the model.

4.2.5. Individual Prediction

Based on the household structures (family size, age, occupation and livelihood) and the changing mechanisms of the occupation states of individual agents in the last year, we can determine which groups the households belong to in the next year. Based on the groups they belong to, we can determine households' farmland use behavior in the next year. Based on the I_{total} values of plots planted by each household, we can determine how many plots and which plots will be rented out/hired/abandoned.

Agents use FAD index (see Section 4.2.1 for detail) to estimate future conditions or consequences of their decisions. We use probability method and households types to predict households' behavior. This brings stochasticity to some extent, but households' behavior is definite from a global perspective.

4.2.6. Interaction

The interactions between households and plots are direct. The interactions between individuals and plots are indirect, and individuals have to interact with plots with the help of the household they belong to.

The interactions between households and plots depend on the livelihood strategies of households, and the whole economic benefit of plots. To simplify simulation, we divided the households into five groups based on the household economic sources and the household livelihood demand for farmland and non-agricultural laborers (for details, see Section "Descriptions of Submodels" (2)). Different groups of households have different interactions with plots. These interactions do not involve communication, and no coordination network exists in our simulation.

4.2.7. Collectives

The household agent is the basic unit of the model, and the individual agent who comprises the household agent is the smallest unit of the model. Some individuals comprise a household based on certain kinship and social relationships. Using the key attributes of the households, rural households can be divided into different groups. Households that belong to the same group have the same farmland use behaviors. The household emerges during the simulation, while the household groups are imposed by the modeler.

We first divided households into five groups (for details, see Section "Descriptions of Submodels" (2)), and determine the number, ages and occupation structures of the family members of each types of households. Because of NPP heterogeneities, we evenly distributed the plots with high or low NPP to each household. By counting family members in each household, this model allocates the same number of plots to each household. The plots that planted by the same household are distributed adjacently. The households in the same group do not have obvious spatial aggregation phenomenon.

4.2.8. Heterogeneity

The individual agents and household agents are heterogeneous in their decision-making. The occupation states of individual agents are different (for details, see Section "Descriptions of Submodels" (1)), and the farmland use behaviors of households in different groups are heterogeneous during their decision-making process (for details, see Section "Descriptions of Submodels" (4)).

4.2.9. Stochasticity

At the initialization of the model, because of lack of cadastral data, we randomly distributed households' spatial location. We allocated adjacent plots randomly to each household.

4.2.10. Observation

Farmland use states (abandoned plots, rented plots, or plots planted by owners), the number of households in different FAD intervals (zero FAD, low FAD, middle FAD, high FAD and super high FAD), and the number of different groups of households are collected from the ABM. These data were collected at the end of each year.

We counted how many of each of the five types of households in the whole town there would be over the next 30 years. We want to observe what the trend of non-farm employment is in the next 30 years so we counted the number of plots with different farmland use states. We want to observe what the trend of the number of rented plots and abandoned plots is in the next 30 years, and whether the sustainability of farmland system is endangered or not in the future so we counted the number of households in five management intervals, and we want to know what the trend of farmland management rights redistribution is in the next 30 years.

4.3. Details

4.3.1. Implementation Details

Using Java and the RepastJ toolbox [47], we constructed a multi-agent model of regional farmland use change in the Eclipse integrated development environment. The model is accessible; to any readers who want to see the source code, please email us.

4.3.2. Initialization

According to the yearbook [41], the total number of people was 17,500, and the total number of households was 7592. From the official website of Qianjingou Town [48], we obtained the total area of farmland (16,200 hectares). Using the data of the total number of people and the total area of farmland, we calculated the area of farmland per capita (0.9 hectares). To improve the simulating efficiency and facilitate the simulation of the ownerships between individuals and farmland, we set the area of one farmland plot (one plot corresponds to one farmland grid cell) is 0.9 hectare, which equals to the area of farmland allocated to each person. Therefore, one person was allocated the area of one farmland plot (one individual corresponds to one plot). To maintain consistency with the statistical data, we resized the land use raster cell size from 100 m × 100 m to 96 m × 96 m.

Model initializations include spatial environment initialization and input parameter initialization. A total of 17,056 plots and 17,056 individual agents were added into this model. The input spatial environmental layers include land use data, NPP, slope and road accessibility. Because of NPP heterogeneities, we needed to evenly distribute the plots with high or low NPP to each household. How to relate an individual agent's state variables and a household group agent's variables, and impute the individual agent and the household group agent into model space were the key steps of the initialization. The household types determine the number, ages and occupation structures of the family members. At the initialization of the model, one family member corresponded to one plot (this relationship changed at a later stage because of farmland rent and abandonment). By counting family members in each household, this model allocates the same number of plots to each household, allowing the household livelihood strategies and their farmland use behaviors to be reflected in the corresponding plots.

The households in different groups have different ages and labor structures, but there are no differences in the education states. We initialized the population, age and occupation structures of five types of households. In this model, men and women cannot marry until men are older than 22 and women are older than 20. The age difference between parents and children must be greater than 20 years, and the age difference between married couples must be within five years. The main initialization steps included:

(1) Initializing the population, age and occupation structures of five types of households (Because of complexity, we listed the tables of these structures as Supplementary Materials 3). Subsidy-dependent households lack young and middle-aged laborers, and non-farming, pure-farming and part-farming households must have young and middle-aged laborers.
(2) Calculating the farmland areas of each person using the statistical yearbook data. Using remote sensing data, we obtained the spatial location of the farmland and resized the grid resolution so that one farmland grid represented one person's farmland area.
(3) Through questionnaire analysis, we obtained the percent of each of the five types of households in the sampled data, and using the Monte Carlo method, we obtained the proportion of the five types of households in the overall data.
(4) We calculated the total farmland area of each household by multiplying the number of family members by the farmland areas of each person. Then, we allocated this number to each household.

The initialization is not always the same. Through questionnaires analysis, we obtained the percent of each of the five types of households in the sampled data. We used Monte Carlo method to get the proportion of the five types of households in the overall data. This method brings the randomness, and makes every initialization not the same. In our model, the initial values are chosen based on on-the-spot questionnaires survey, remote sensing data and census data.

4.3.3. Input Data

The model does not use input data to represent time-varying processes.

4.3.4. Submodels

The submodels represented the processes listed in "Process overview and scheduling" include individual state transfer submodel, households classification submodel, spatial environment distribution submodel, and households' farmland use decisions submodel. We will introduce every submodels in detail as follows.

Descriptions of Submodels

(1) Individual State Transfer Submodel

The individual agent refers to the family members of a household. According to the research objects, we extracted the attributes of the individual agents (Table 3). In this model, one individual agent corresponds to one farmland plot; therefore, it has x and y coordinate information. The individual agent behaviors include birthing, educating, farming, migrant working, retiring and dying.

As individual agents grow older, their occupation states (Figure 6) and household types change correspondingly. Through analyzing questionnaires, we identified six age nodes when individual agents change their occupations. When an individual agent reaches a certain age node, their occupation state will change to another state according to a specific probability. Based on existing work [44–46] and our questionnaires, we obtained the corresponding probabilities when the individual agents in each age stage would change their occupation states using questionnaire statistics. Age is not the direct driving factor that drives individuals' occupation states, and we use probability method to analyze the rules of individuals' occupation states. This method substitutes the indefinable driving forces.

The detailed descriptions of the changing mechanisms of the states of individual agents are as follows:

(i) The age of the juvenile and adult node is 18 years old. When the age of an individual agent is equal to or greater than 18 years, 10% will become undergraduates (S1→S2), 30% will become farmers (S1→S3), and 60% will become migrant workers.
(ii) The age of the undergraduate education and working node is 22 years old. When the age of an individual agent is equal to or greater than 22 years, 100% will become stable workers (S2→S7).
(iii) An important age node is 47 years. When $18 \leq$ age ≤ 47 or $47 \leq$ age ≤ 55, migrant workers and farmers will exchange with each other at a certain probability level. When $18 \leq$ age ≤ 47, 55% farmers will become migrant workers (S3→S4), and 25% migrant workers will become farmers (S4→S3). When $47 \leq$ age ≤ 55, 45% migrant workers will become farmers (S5→S6).
(iv) The age of the migrant workers stop working outside and become farmers node is 55 years. When the age of an individual agent is equal to or greater than 55 years old, 100% will become farmers (S8→S6).
(v) The age of the farmers retiring node is 65 years. When the age of an individual agent is equal to or greater than 65, farmers will stop farming activities (S6→S9).
(vi) The age of the stable workers retiring node is 60 years. When the age of an individual agent reaches 60, stable workers will retire (S7→S9).

(2) Households Classification Submodel

The household agent is comprised of individual agents, and the corresponding relationship between the household agent and the individual agent is one-to-many. The household agent's behavior and decisions are influenced by the behavior and actions of all family members. The household agent's behavior includes an increase and decrease in the number of family members (birth of newborns and death of the elderly), family livelihood decisions (travelling for jobs or performing farm work), and farmland use decisions—to farm or not to farm; and if farm, on an expanding or reducing planting scale and which plots should be planted?

The total income of the household agent is the sum of the income of all family members. The household economic sources include operating income (crop income and income from raising animals), income from wages (migrant work income), transferred income (social insurance, minimum living standard and the payments from the Grain for Subsidy Policy) and property income (income from renting land). According to the research object and the main components of the household economy, this model only takes crop income, migrant work income, renting land income and the payments from the Grain for Subsidy Policy into account. The household income was calculated as

$$I = \sum_{i=1}^{m} O_i + \sum_{j=1}^{n} A_j + \sum_{k=1}^{p} R_k + \sum_{l=1}^{q} G_l \quad (2)$$

where I represents the total income of the household; O_i represents the migrant work income of the i_{th} individual who travels for a job; m is the number of migrant workers; A_j is the crop income of the j_{th} farmland plot, and n is the number of agricultural laborers; R_k is the rental income of the k_{th} farmland plot, and p is the number of the rented land plots; G_l is the payment of the l_{th} farmland plot, and q is the total amount of farmland plots owned by the household.

The existing studies on household type classification [2,11,12,49,50] did not consider the relationship between the allocation of labor resources and farmland use change, and this study fills this gap. According to the household economic sources and the household livelihood demand for farmland and non-agricultural laborers, we divided the households into five groups: subsidy-dependent, pure-farming, part-farming, non-farming and pure-outworking groups (Figure 7). Households in the pure-farming group rely on farmland and agricultural labor, and crop income is their entire income; households in subsidy-dependent group rely on government subsidies and they do not have agricultural or non-agricultural incomes; households in the pure-outworking group do not have agricultural labor, and all laborers travel to their jobs; households in the part-farming group have both non-agricultural and agricultural labor, and farming income is their main income; and households in the non-farming group have both non-agricultural and agricultural labor, and non-farm income is their main income. Through analyzing the questionnaires, we found that the subsidy-dependent, pure-farming, part-farming, non-farming and pure-outworking group households accounted for 8%, 15%, 25%, 41% and 11%, respectively.

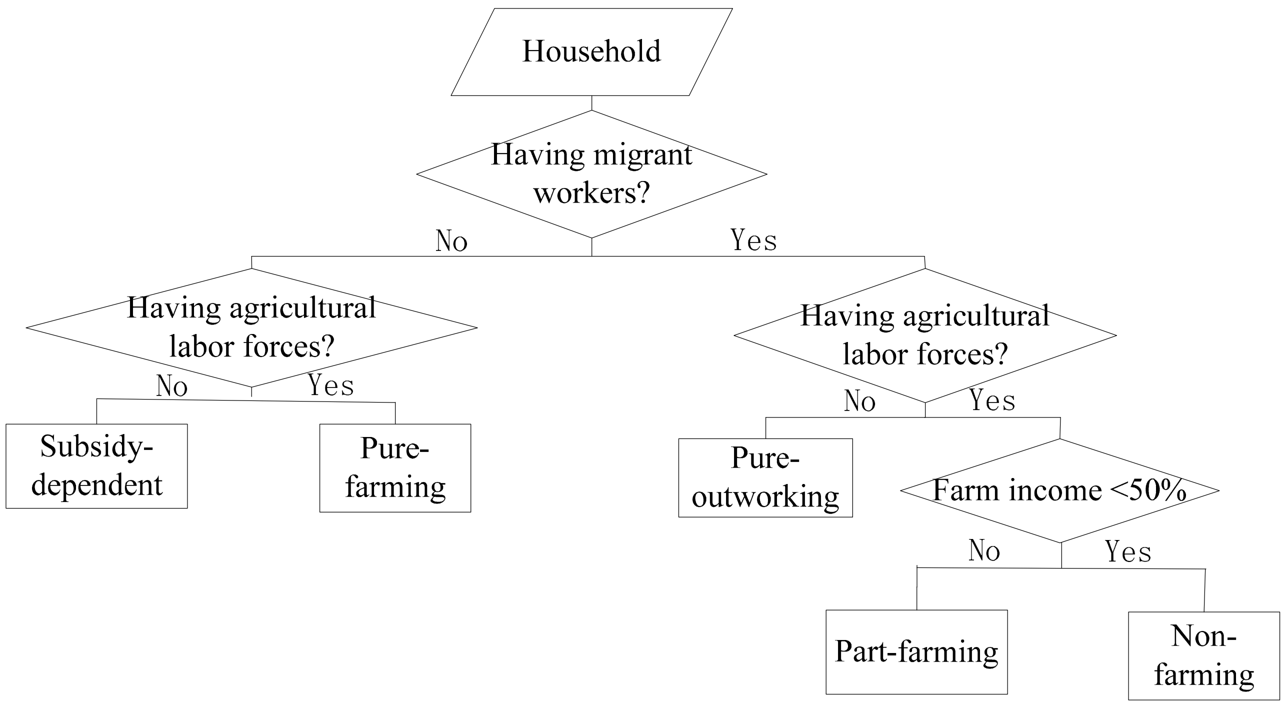

Figure 7. The decision-making tree of the household group classification.

(3) Spatial Environment Synthesization Submodel

Through local interviews we found that households evaluate farmland quality according to NPP, relief amplitude, road accessibility and slope. When households choose to plant at reduced scales, they will rent out or abandon farmland plots with inferior qualities; when households choose to plant at expanded scales, they will hire farmland plots with superior qualities. To describe farmland quality, we need combine these factors into one index [44,46]. We use the I_{total} index to express the combined impacts of these four factors. The greater the I_{total} value is, the better the farmland quality is; the calculation formula is

$$I_{\text{total}} = I_{\text{npp}} \times W_{\text{npp}} + I_{\text{road}} \times W_{\text{road}} + I_{\text{slope}} \times W_{\text{slope}} + I_{\text{ra}} \times W_{\text{ra}} \quad (3)$$

$$W_{\text{npp}} + W_{\text{road}} + W_{\text{slope}} + W_{\text{ra}} = 1 \quad (4)$$

In Equation (3), I_{npp}, I_{road}, I_{slope} and I_{ra} refer to the influences of NPP, road accessibility, slope and relief amplitude, respectively. W_{npp}, W_{road}, W_{slope} and W_{ra} refer to the weights of NPP, road accessibility, slope and relief amplitude, respectively. The sum of these four weights is 1 (Equation (4)). I_{total} is a function with values between 0 and 1; therefore, we needed to normalize these four impact factors to 1 (Equations (5)–(8)).

$$I_{\text{npp}} = NPP/NPP_{\text{max}} \quad (5)$$

In Equation (5), NPP_{max} refers to the maximum NPP. We divided the NPP value by NPP_{max} for normalization purposes. Obviously, the greater the NPP value is, the greater the I_{npp} value is.

$$I_{\text{road}} = 1 - Road\_Dist/Road\_Dist_{\text{max}} \quad (6)$$

In Equation (6), $Road\_Dist$ refers to the distance to the road network, and $Road\_Dist_{\text{max}}$ refers to the maximum distance to the road network. Here, we divided the $Road\_Dist$ value by $Road\_Dist_{\text{max}}$ for normalization purposes. Obviously, the greater the $Road\_Dist$ value is, the smaller the I_{road} is

$$I_{\text{slope}} = \begin{Bmatrix} 1, slope \le 5 \\ -0.1 \times slope + 1.5, 5 < slope \le 15 \\ 0, 15 < slope \le 20 \end{Bmatrix} \quad (7)$$

Equation (7) is the normalized segmented function of the slope. Based on China's forest law enforcement regulations, the slope is divided into three classes. If the slope is greater than 20°, the farmland is not suitable for planting. Between 5° and 15°, the impact decreases linearly from one to zero. Obviously, the greater the slope value is, the smaller the I_{slope} value is.

$$I_{\text{ra}} = \begin{Bmatrix} 1, ra \le 30 \\ -ra/75 + 1.4, 30 < ra \le 75 \\ 0.4, 75 < ra \le 127 \end{Bmatrix} \quad (8)$$

Equation (8) is the normalized segmented function of relief amplitude, and ra refers to relief amplitude. If the ra is smaller than 30, the geomorphic type of the farmland is a plain, and the I_{ra} is equal to one; if the ra is between 30 and 75, the geomorphic type is a hill, and the I_{ra} decreases linearly from one to 0.4; if the ra is greater than 75, the geomorphic type is a highland, and the I_{ra} is equal to 0.4 [51].

(4) Households' Farmland Use Decisions Submodel

This study analyzed each type of household farmland use behavior based on a probability method that was used by several scientists [44,52,53]. Farmland use decision behaviors of the household groups include renting out, renting in, and abandonment of farmland. The households within a group have the same farmland use behaviors. The percent of each type of household and of each type of household that transferred their farmland are shown in Figure 8. The households in the non-farming group constituted the largest part of the total households (41%). The number of households in this group who reduced the scale of their farmland was the highest (52%), and the percent of households who rented in farmland was 44%. The households in the part-farming group comprised the second largest part of the total households (25%). The percent of households who rented in farmland was 54%, and the percent of households who reduced the scale of their farmland was 28%. The number of households in pure-farming group was the third largest (15%), and the percent of households who rented in farmland was 72%. Because of farmland dependencies, the households in this group did not reduce the scale of their farmland. The number of households in the pure-outworking group was the fourth largest (11%). Because of a lack of agricultural laborers, the households in this group did not plant farmland, and they rented out or abandoned all of their farmland. The number of households in the subsidy-dependent group was the lowest (8%). Because of a lack of laborers, the households in this group rented out or abandoned all of their farmland.

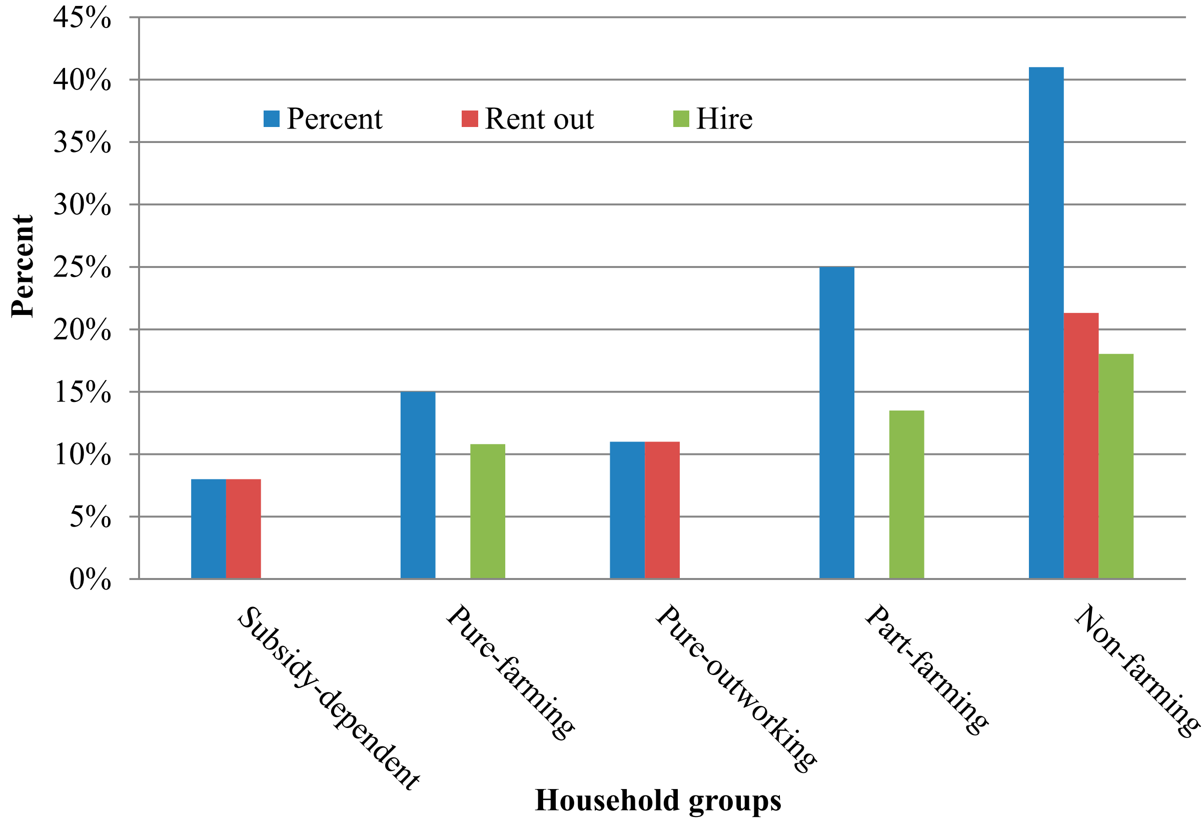

Figure 8. The percent of each type of household and the percent of each type of household that rented in/hired their farmland.

Most of the households in the pure-outworking, subsidy-dependent and non-farming groups reduced the scale of their farmlands; therefore, we draw the conclusion that non-farming livelihood was closely related to the reduction in household farmland. The households in the pure-outworking and non-farming groups mainly make a living by renting out farmland and working outside, and they have little dependency on farmland. Households in the subsidy-dependent group rely on government subsidies (GFGP payment, Grain Subsidy Policy payment, social insurance, *etc.*), and they reduced the scale of their farmland because of a lack of labor. The households in the pure-farming and part-farming groups mainly make a living by farming. Because of the strong dependency on farmland, few of them rented out or abandoned their farmland, and most of them rented in farmland.

Parameters of the Model

We listed the main parameters and their default values of the model in Table 1. From Table 1, we can see the data sources and changing rules of these parameters. We listed the common variables in front of Table 1, while the parameters of each submodel are listed separately below the corresponding submodels.

Table 1. The main parameters and their default values of the model.

Parameters	Meaning	Initial Values	Data Sources	Changing Rules
averageLand	Farmland areas per person	0.9 hectare	Statistical yearbook	Fixed
maxDeathAge	Longevity	65–100	Questionnaires	Randomly changed
numAgents	Total population	17,500	Statistical data	Changed at the next time slice
FAD	The FAD of farmland plots for each household	1	Questionnaires	Changed at the next time slice
nppClass	Npp classes (gc/(m^2 × year))	Class 1: 584–761 Class 2:407–584 Class 3: 230–407 Class 4: 54–230	Remote sensing data and questionnaires	Fixed
Individual agents state transfer submodel				
ageNode	The age nodes that individuals change their occupation states	18, 22, 47, 55, 60, 65	Questionnaires	Fixed
probability	The probability individuals change their occupation from one state to another.	0–100%	Questionnaires	Fixed
Household classification submodel				
percentage	The percentage of non-farming, pure-outworking, part-farming, pure-farming, subsidy-dependent groups	0.41, 0.11, 0.25, 0.15, 0.08	Questionnaires	Changed at the next time slice
everEarned	Work income per person	10,000 yuan/year	Questionnaires	Fixed
subsidyGrain	Payment of Grain Subsidy Policy	430.7 yuan/hectare	Questionnaires	Fixed
cropPrice	Price of naked oats	2.49 yuan/kg	Questionnaires	Fixed
landYield	Yield of farmland	NPP1: 1500 kg/hectare NPP2: 1125 kg/hectare NPP3: 750 kg/hectare NPP4: 375 kg/hectare	Remote sensing data and questionnaires	Fixed

Table 1. *Cont.*

Parameters	Meaning	Initial Values	Data Sources	Changing Rules
rentPrice	Prices of land rent	NPP1: 600 yuan/hectare NPP2: 525 yuan/hectare NPP3: 450 yuan/hectare NPP4: 375 yuan/hectare	Remote sensing data and questionnaires	Fixed
Spatial environment allocation submodel				
cellSize	The spatial resolution of each grid cell	96 m × 96 m	Remote sensing data, questionnaires and statistical data	Fixed
weight	The weights of 4 factors, which are used to combine the 4 factors	$W_{npp} = 0.4$, $W_{road} = 0.2$, $W_{slope} = 0.2$, $W_{relief} = 0.2$	Questionnaires	Fixed
I_{total}	The combined index of 4 natural factors	Range from 0 to 1. Need calculation.	Remote sensing data and questionnaires	Fixed
Households' farmland use submodel				
k	The maximum plots that each agricultural laborer can plant	10	Questionnaires	Fixed
numofTransferPlots	The number of plots each household wanted to transfer	Need further calculation.	Questionnaires and need further analysis	Changed at the next time slice

5. Results

5.1. Model Output Variables

5.1.1. Farmland Use States

Farmland use states include planted by the owner, rented to other households and abandoned by the owner. Therefore, we can analyze farmland management right redistributions from a new angle. If most farmland plots are not planted by the owners, the dependency relationship between farmers and farmland will be broken, and the sustainability of farmland system will be influenced correspondingly. If farmland is abandoned by farmers, farmers will not make a living by farming. They have to seek other livelihood sources, but temporary and migrant working brings risk and instability. Farmers' livelihood stability will be influenced. Furthermore, abandoned farmland results in a reduction in food production, and national food security will be threatened accordingly.

5.1.2. Farmland Aggregation Degree

Section 4.2.1 introduces the definition of FAD. This index can reflect farmland management right redistributions, and we can determine whether the households expand planting scales or reduce them according to its value.

5.1.3. Number of Households

We analyzed the sequence diagram of quantitative variation of different types of households as well as the sequence diagram of the quantitative variation of migrant workers and farmers.

5.2. Results Analysis

5.2.1. Farmland Use States

The changing trend of the farmland plot use states in the study area from 2010 to 2040 from a spatial and statistical perspective is shown in Figure 9. At time t = 1, 71.99% of the plots are planted by their owners, while 8.84% and 19.17% of the plots are abandoned and rented, respectively. As time progresses, the farmland management rights gradually change, and a growing number of plots are rented or abandoned. At time t = 20, the number of abandoned plots reaches a maximum (26.00%). From time t = 1 to time t = 21, the number of abandoned plots exhibits a slowly increasing trend. At time t = 1, 8.84% of the plots are abandoned, while at time t = 21, 12.22% of the plots are abandoned. After time t = 21, the number of abandoned plots shows a rapid increasing trend, and at time t = 29, this has exceeded the number of rented plots (At time t = 29, 23.49% of the plots are abandoned). The existence of abandoned farmland endangers food production and the sustainability of farmland system; therefore, we need to take rational measures to improve current farmland abandonment states.

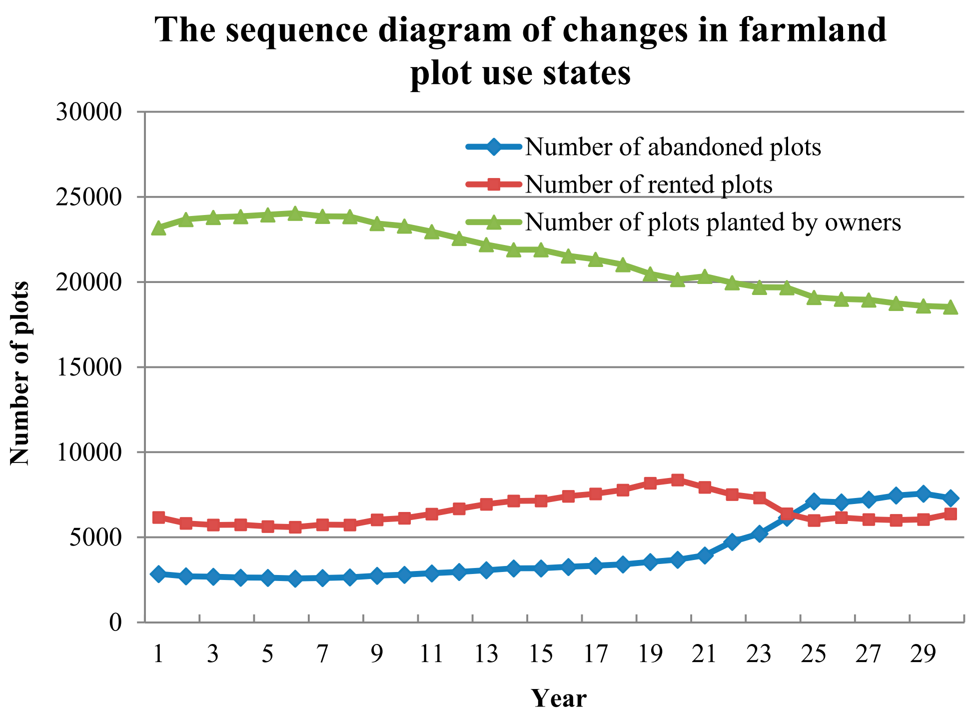

Figure 9. The sequence diagram of changes in farmland plot use states in the next 30 years.

5.2.2. Farmland Aggregation Degree

The number of households in five FAD intervals in the next 30 years is shown in Figure 10. At time t = 1, 63.95% of the households have farmland plots in the low FAD interval (short for low FAD households), 29.03% of the households have farmland plots in the zero FAD interval (short for zero scale households), while the values for the middle FAD households, high FAD households and super high FAD households are only 3.46%, 2.72% and 0.84%, respectively. This indicates that 63.95% of the plots are planted by owners, while 29.03% of the households do not have farmland to plant. As time progresses, the phenomenon of farmland management right redistribution becomes increasingly obvious. The number of low FAD households shows a gradual decreasing trend, while the number of zero FAD households shows a gradual increasing trend (at time t = 16, it has exceeded the number of low FAD households). The number of middle FAD households shows a gradual increasing trend (at time t = 1, the value is 3.46%; at time t = 30, it has increased to 15.18%). The high FAD households and super high FAD households account for lower amounts and generally do not show obvious changes.

The gradual increasing trend of the zero FAD households shows that the number of households without farmland for planting exhibits an obvious increasing trend. For these households, the dependency relationship between the household and farmland has been broken, and the farmland sustainability has been threatened (If the rural households have no farmland to plant, they will have to seek other unstable means of livelihood. Their livelihood stability will be endangered.); low FAD households have an obvious decreasing trend, and after time t = 16, the number of these households is less than the zero FAD households. This indicates that the number of households who maintain former planting scales or reduce planting scales shows a decreasing trend. After time t = 16, the zero FAD households account for the greatest amount. The low number of high FAD and super high FAD households indicates that the phenomenon of farmland hired by minority households is not obvious, and farmland management scales in the study area have been well maintained.

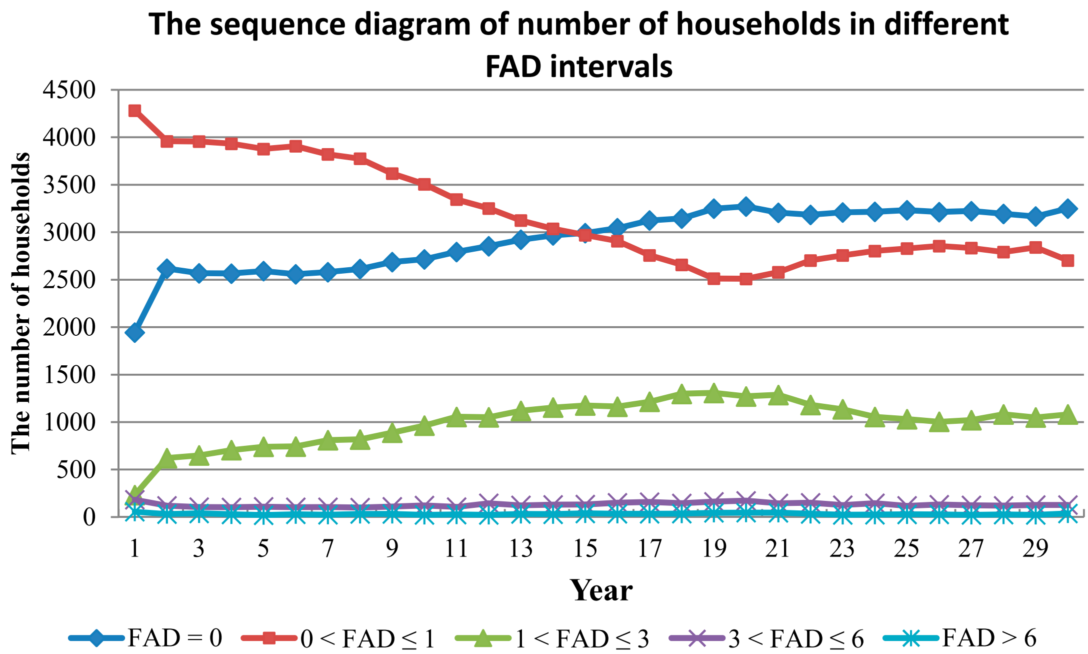

Figure 10. The sequence diagram of the number of households in different FAD intervals in the next 30 years.

5.2.3 Distribution of the Number of Different Types of Households

We obtained the percent non-farming households, part-farming households, pure-farming households, pure-outworking households and subsidy-dependent households in the initial year based on the questionnaire data. Using the Monte Carlo method, we obtained the information for all households in the study area using the questionnaires. The sequence diagram of the change in the number of the different types of households in the next 30 years is shown in Figure 11. As observed from Figure 11, the number of non-farming households has an increasing trend. There are 2824 households at time t = 1, while there are 4210 households at time t = 30. The number of part-farm households has an opposite trend. At time t = 1, the number of this type of household is 1761, which decreases to 413 at time t = 30. The number of pure-farm households has a slowly decreasing trend. At time t = 1, the number of this type of household is 1044, while at time t = 30, it has decreased to 237. The number of pure-outwork households shows an approximate linear increasing trend. At time t = 1, the number is 860, which increases to 2297 at time t = 30. The number of subsidy-dependent households has a decreasing trend. At time t = 1, the number is 1001, while at time t = 30 this has decreased to 332. The trends of the number of the five types of households indicate that non-farm employment has an increasing trend. An increasing number of farmers make a living as migrant workers. Once part-time job opportunities decrease, they will be faced with unemployment. This indicates that the stability of a growing number of household livelihoods will be threatened in the next 30 years.

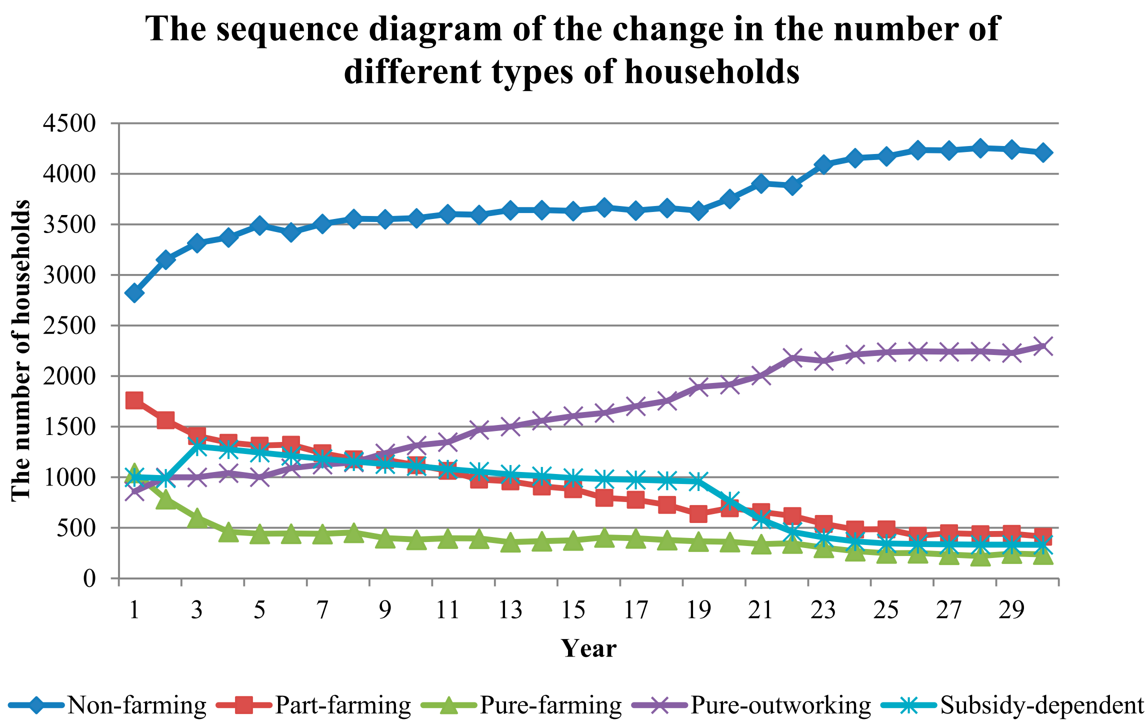

Figure 11. The sequence diagram of the change in the number of different types of households in the next 30 years.

6. Discussion

Agent-based modeling takes a bottom-up approach to predicting system-level properties as an emergent product of the interactions between agents that represent individuals [11,54–56]. The attributes and behaviors of the agents are the basic elements of ABMs, and four types of agents were included in this model. The coupling of natural factors and social factors, and the construction of interaction mechanisms of these factors are the key steps in the model. We describe the model based on ODD + D protocol, to facilitate the comparison and communication of scientists from different academic fields.

The application fields of ABM/LUCC mainly focus on natural management, agricultural economics, archaeology and urban simulation [10,57]. The existing studies of ABM used in agricultural land use change mainly focus on simulations of new technologies adoption, crop type selection and agricultural labor allocations. Agent-based modeling can efficiently explain the process mechanism of farmland use change and is the most suitable method to simulate the dynamic interactions of human behavior and farmland system change. However, the running mechanisms of the existing studies are relatively rough, such as missing first-hand questionnaire data [58,59], or ignoring household typologies and the relationship between household livelihood and farmland use change [23,25,26,57]. Some studies [23,25,26] set one household occupying one plot (farmland grid cell), which can only express households that rented or abandoned their entire farmland. In fact, most households only rented or abandoned part of their farmland; therefore, these studies cannot describe the practical land renting in and hiring situation. Our study set one person occupies to one plot, and this can exactly fill this gap. The land renting in and hiring process is divided into two steps, *i.e.*, calculating the maximum number of plots that each household can plant, and determining, which plots households rent out, hire or abandon. We listed the I_{total} value for the plots of each household in ascending order. If the plots are not hired by households, they will be abandoned.

In our study, we used the farmland use states and farmland management scale to illustrate the farmland management right redistributions from a new angle. Abandoned farmland endangers the sustainability of food production; zero scale households have no farmland to plant, and their livelihood stability is endangered. If farmers have little farmland to plant, they will have to seek other, unstable means of livelihood. Once work opportunities decrease, their livelihood stability will be endangered correspondingly. These two indexes can effectively and efficiently reflect the states of households and the farmland.

We collected remote sensing data, empirical field questionnaires and statistical data to support the model, and strived to maintain the running rules close to the reality. However, because of data accessibility, household heterogeneities, household decision-making complexity and running rules simplification, several follow-up studies need to be conducted to improve our study. The shortcomings of our model mainly include the following: (1) The heterogeneity of family living consumption was ignored, and the heterogeneity of household agricultural inputs and crop types was not considered. (2) We used a probability method to analyze household farmland use behavior [44,45,50]. However, to explain the individual agent state changes from migrant worker to farmer more clearly, we need to determine the exact process mechanisms. (3) We did not include scenario analyses related to precipitation, evapotranspiration or policy variations in this model, which need to be analyzed systematically in the next step. (4) Households' farmland use behaviors are easily affected by off-farm opportunity, demographics and education [27,60–62]. A link to the theory on the role of demographics and opportunity costs of off-farm employment in agricultural structural change has remarkable impact on the running mechanism of the ABM, and needs to be analyzed in the following work. Scenario analyses of changing opportunities of education, and life expectancy are valuable research directions that we will conduct these studies in the future work.

7. Conclusions

Farmland is a complex and self-adaptive system that couples human and natural systems. Natural factors and social factors that are related to its changing process need to be considered when modeling the farmland changing process. This paper took Qianjingou Town in the Inner Mongolia farming–pastoral zone as a study area, and a complex adaptive system and agent-based modeling were used as a theoretical basis and method. By synthesizing natural factors (net primary productivity, road accessibility, slope and relief) and social factors (government policies, household family structures and economic development), and using household typology and the relationship between household livelihood and farmland use, we obtained an understanding of the current farmland use change rules. Based on this understanding, we scientifically predicted the farmland use change trend for the next 30 years. We integrated NPP, relief amplitude, road accessibility and slope into one index using weight factors. We used family size to allocate the same size farmland plots to each household, and the household livelihood was obtained based on the corresponding plots. These processes can be used to provide scientific descriptions of coupled, self-adaptive and complex human-nature systems. This study established the theoretical foundation and a basic method for developing sustainable farmland use management that agrees with household willingness and guarantees grain and ecological security.

We divided the households into different groups (subsidy-dependent, pure-farming, part-farming, non-farming and pure-outworking groups) based on differences in labor resource allocations and livelihood compositions, and this clearly represents the relationship between household livelihoods and household typologies. Over the next 30 years, the number of part-farming households and pure-farming households exhibits an obvious decreasing trend, which clearly indicates non-farm employment of household livelihoods. The increasing trend of the number of pure outwork households greatly threatens the sustainability of a growing number of household livelihoods.

Based on a probability method, we analyzed each type of household farmland use behavior, and efficiently conducted an analysis of the different types of household farmland use characteristics based on the relationships between household livelihood and farmland use. Using the probability method to determine the probabilities of individual agents converting to farmers or migrant workers can simplify the model running mechanisms, and this is convenient for devising model running rules. Over the next 30 years, the number of farmland plots planted by owners has a decreasing trend, while the number of rented and abandoned farmland plots has an increasing trend, which makes the phenomenon of farmland management right redistribution increasingly obvious. In the next 30 years, 23.46% of farmland plots will be abandoned, and this endangers the sustainability of local farmers' livelihood and food production.

We defined the "farmland management scale" index to quantitatively analyze the farmland management right redistribution characteristics from a household perspective. After the next 16 years, zero management scale households will become the dominant element, which indicates that the sustainability of most household livelihoods is threatened. The obvious decreasing trend in the number of low management scale households indicates that the number of households who maintain or reduce former planting scales will decrease. The low number of high and super high management households indicates that farmland management scales have been well maintained.

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Author Contributions

Huimin Yan and He Qing Huang designed the questionnaire and model running mechanism. Lihu Pan and Xuehong Bai devised the structure of the ABM in Java and the Eclipse environment. Xuehong Bai set the running rules, finished the simulation and wrote the paper. All authors read and approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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