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Understanding human-environment interrelationships under constrained land-use decisions with a spatially explicit agent-based model

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A B S T R A C T

Human-environment interactions drive the land-use dynamics of the terrestrial surface. Worldwide, land-based environmental conservation efforts and agricultural preservation regulations are often concurrent. Complex social-ecological feedback within the coupled natural and human systems nevertheless confounds their effects. Drawing on population-level data for a township encompassed by a national nature reserve, this study applies a spatially explicit agent-based model to understand human-environment interrelationships with household land-use decisions about cropland abandonment restricted by the agricultural preservation rule. Results show that labor migration and cropland abandonment involve feedback loops that exhibit nonlinear effects. The availability of household labor and the amount of cultivated land mediate these effects. The land-use decisions of the farm households are sensitive to the relaxation of the abandonment restriction. The prevalence of cropland abandonment in extent and size increases prominently as the restriction rule begins to relax. The model shows a clearly emerging spatial pattern of an increasing likelihood of cropland abandonment with the relaxed restriction. Abandonment is more likely on dryland parcels and parcels at higher elevations, steeper slopes, and in proximity to forest areas. The shifted distributions of cropland parcels by their biophysical and geographical features from the baseline scenario (full restriction) to the experimental scenario (complete relaxation) also demonstrate these trends. Targeting cropland parcels bearing high risks of abandonment can improve the cost-effectiveness of implementing forest restoration policies while prioritizing those with low risks for agricultural stabilization. The agent-based model is useful for explaining the underlying drivers of land change involving human decision-making. It also suggests implications for balancing trade-offs between environmental conservation and agricultural production.

1. Introduction

Human activities are pushing the Earth system to a new status. Land-use alterations and modifications are among the most prominent processes occurring on the Earth's terrestrial surface, where human and natural components maintain intimate interrelationships. Land change science emerges at the core of sustainability science (Rindfuss et al., 2004), aiming to address the challenges pertaining to the causes, consequences, and feedback loops of social-ecological processes within land systems. Through understanding how land systems change from human-environment interactions (Lambin et al., 2001; Lambin and Meyfroidt, 2011), human society can better harmonize its relation to nature, rationalize its use of vital ecosystem services, predict land system dynamics, and hence achieve sustainable development.

Among all land-use types, agricultural land is a critical and complex variable that has far-reaching impacts on ecosystems. At the local scale, farm households have the essential role of land stewardship responsible for land-use decisions (Verburg et al., 2011; Michalscheck et al., 2020).

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The local-scale decisions when aggregated can have impacts on land system change over large areas, with regional and even global implications (Crossman et al., 2013). Such implications can include biodiversity loss and ecosystem disturbance, affecting the services that biodiversity and ecosystems bring to human existence and survival (Norris, 2008; Malek et al., 2019). The existing literature has focused on studying decision-making processes that explain human-triggered land-use change in agricultural systems, but both internal and external drivers can influence the land-use decisions of farm households and intertwine with biophysical conditions across various levels (Iwamura et al., 2014; van Vliet et al., 2015; García-Jácome et al., 2020). Internal forces reflect motivations for (or the ability to) fulfilling objectives such as risk minimization in the use of resources extracted from the land. External factors, as also well documented in previous studies, include the market conditions, government policies, and socio-economic processes that influence household decisions through changing their contextual conditions (Lambin, 2010). Both formal institutions and informal rules can play roles in the behavioral changes of farmers in using their land (Ostrom, 1999; Lyver et al., 2019). A synthesis study found that economic, institutional, and technological factors, as well socio-economic drivers, can affect the dynamics of agricultural land use in Europe, whereas farmers are key moderators in the linkages among the drivers (van Vliet et al., 2015). Therefore, complex systems with multiple human-environment interactions can provide insights for land-use dynamics and their associated impacts on the environment.

In rural China, policymakers have proposed and implemented agricultural and environmental policies to regulate land use and management for social-ecological sustainability. For example, the unprecedented floods and droughts that occurred in the 1990s have raised the public's concerns about the problem of soil and water erosion, due mainly to the over-exploitation of forest resources (Zhang et al., 2000; Liu and Diamond, 2005). In response, ecological land restoration has increasingly become the focus of policy establishment along with the long-term goal of economic development (Fang et al., 2018). Two nationwide forest programs, the Ecological Forest for Public Welfare Program (EWFP) and the Conversion of Cropland to Forest Program (CCFP), stand out among all the efforts. They have directly or indirectly converted agricultural land to other use and consequently affected the livelihoods of millions of farm households (Chen et al., 2019; Yost et al., 2020). Agricultural land use is another central target of the land-based policy. As an agrarian country throughout history, the prosperity of China heavily relies on cropland to support the basic needs of the growing population (Perkins, 1969; Bryan et al., 2018; Liu et al., 2020a, b). Rapid urbanization and industrialization, however, has led to enormous loss of cropland around cities and loss of farm labor to migration to cities, as well as forests even in distant places (Xiong et al., 2020). To feed the world's largest population, the central government set a "red line" for preserving the remaining cultivated land and designating the "basic" cropland (Wu et al., 2017; Jiao et al., 2018). The two targets of land protection, namely forest and cropland, are intertwined, but the implementation of concurrent policies has not fully considered the interrelationships between them. For example, the conversion of cropland to forest policies may induce additional land abandonment under existing agricultural regulations.

Interrelationships between other farm household economic activities and land use can further complicate the effectiveness of agricultural and forest policies on rural livelihoods. These interactions are even more critically challenging in mountainous areas with less developed agroforestry systems. On the one hand, the direct conversion of cropland to forest under the restoration programs has induced additional abandonment of cropland due to the change in livelihood strategies from agricultural to non-agricultural activities (Lin and Yao, 2014; Li et al., 2018). To obtain the cash compensation, farm households are willing to shift land to planted forest (Zhang et al., 2020), allocating the freed farm labor to alternative economic opportunities including via out-migration. This unanticipated loss of farm labor may threaten food security due to the decline in cropland area. To alleviate this pressure of cropland loss, policymakers designated cropland parcels of relatively good quality as the "basic" lands not allowable for abandonment (Wu et al., 2017). This acts as a constraint over some farm households' decisions to abandon some cropland parcels (Qiu et al., 2019). The actual degree of implementation of the restriction varies with the local context, on the existence of alternative livelihoods independent of land cultivation (Song et al., 2014). Thus, the relaxation of the restriction on "basic" lands may improve the efficiency of forest restoration but simultaneously raise concerns about food production. Despite the recognized complexity in the dynamics of the rural land system, how land use change mediates social-ecological feedback and how the rule of agricultural preservation affects labor migration require further investigation.

Under the framework of coupled natural and human systems (Liu et al., 2007), studies increasingly advocate the use of integrated approaches such as agent-based models (ABMs) to tackle complexity issues, particularly population-environment interactions within land systems (Filatova et al., 2016; Schulze et al., 2017; Wu, 2019). Models with agent-based approaches adopt a bottom-up perspective, often revealing how a system may emerge from interactions among social agents that follow established simple rules (Malanson and Walsh, 2015). Agent-based modeling methods have increasingly appeared in land change science with geospatial features in recent decades (Braasch et al., 2018; Kremmydas et al., 2018; Heppenstall et al., 2020), with many studies demonstrating its flexibility to integrate data from Geographic Information Systems (GIS) and landscape models (Schouten et al., 2013; Malanson and Walsh, 2015; Miyasaka et al., 2017). Human decision-making is an essential component in developing ABMs for land-use change, which relies on theoretical foundations in economics such as Satisficing (Simon, 1956) with the paradigm of bounded rationality. One crucial aspect of ABMs relates to the spectrum from abstract to realistic (Tian et al., 2016), for which difficulty lies in high demands for real-world data. Thus, many scientists designed ABMs for laboratory experiments in a stylized way (Magliocca et al., 2013), lacking the capacity to handle problems of reality. With the integration of spatial landscape models (i.e., those derived from satellite observations), applications of ABMs have become more powerful to capture the emergence of land patterns as influenced by human and natural forces.

This study applies a spatially explicit model, Agent-Based Model for Cropland Abandonment and Labor Migration (ABM-CALM), to explore how the cropland use constraint for agricultural preservation influences household land-use decisions and drives human-environment interrelationships. The model simulates farm households, individuals, and land parcels in a rural area within a nature reserve under the intervention of land-based policies. The simulation integrates population-level data, including satellite images, representative household surveys, and public statistics, from multiple sources for the entire study area. The spatial linkages between farm households and the cropland parcels they manage enable explorations of the geospatial patterns emerging from the social-ecological feedback. Utilizing the spatially explicit datasets enables the cross-scale modeling results to further inform land policy, to mitigate environmental degradation and enhance social-ecological sustainability. This study aims to answer the following research questions. What are the emerging patterns and dynamics of cropland abandonment due to the feedback of labor migration? And how does the adjustment of the agricultural preservation rule against the background of forest policies influence the emerging land-use patterns?

2. Data and methods

2.1. Study area and data collection

The study area in Tianma National Nature Reserve in southern-central China (Fig. 1) situates along the Dabie Mountain. It comprises three different conservation zones: residential, buffer, and restricted zones. The residential zone hosts Tiantangzhai Township, covering an

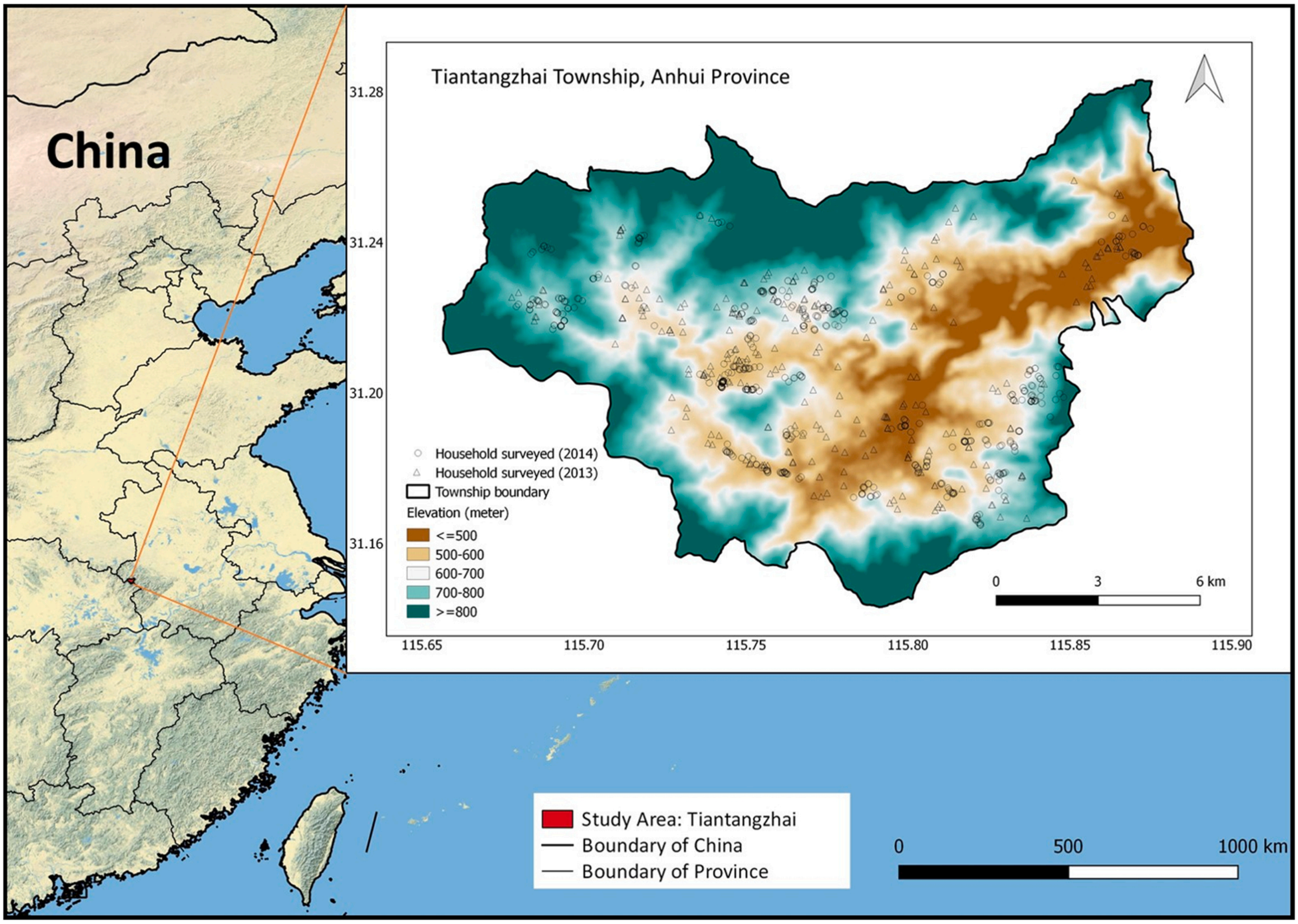

Fig. 1. Study area of Tiantangzhai Township in western Anhui, China.

extent of 189 km^2. The terrain has a typical mountainous topography (elevation: 363–1729 m) with a landscape of prevalent natural forests (Han et al., 2011; Zhang et al., 2018b). The township consists of seven administrative villages with varying economic conditions and 165 resident groups that used to cultivate cropland together. Historically, a resident group is a farming unit of several households that collectively cultivated cropland in large size. After the reform of the household responsibility system in the 1980s (Ma et al., 2015), which divided large cropland into small parcels and assigned them to the farm households, each household nowadays manages cropland parcels scattered over space with some in proximity and others far away. Although the state owns the land, farm households possess the use rights for land use and management. Two major types of cropland parcels are paddyland (for growing rice) and dryland (for growing dryland crops such as corn, potato, bean). The land system in Tiantangzhai is relatively remote from the large cities nearby, so systems outside the township boundary do not substantially influence the interactions between rural farmers and the landscape within the local system. Both forest conservation policies

Table 1
Sources and processes of spatial, socio-economic, and demographic data.

Data Type	Source	Date	Size/Extent	Functions	Information
Demographic-socio-economic data	Population-level survey	Summer 2012	3596 households; 12,375 individuals	Initialize individual and household agents	Individual: age, gender, household, marital status, relation to head; household: head attributes, household size, demographic composition
	Household survey	Summer 2013	250 households; 1202 parcels	Model distribution of area of land managed by household	Amount of cropland managed by each sampled household; geolocations of cropland parcels
	Household survey	Summer 2014	481 households; 1937 individuals	Model detailed data on individuals and households; migration status of individual	Migration history of each sampled individual
Spatial data	WorldView-2 satellite image	5/13/2013	Tiantangzhai	Generate land use and cover map	Spatial features of landscape; parcel: parcel type, distance to natural forests
	Digital Elevation Model	Not applicable	Tiantangzhai	Derive topographic features of cropland parcel	Parcel: elevation, slope, aspect, topographic wetness index
	Topographic Map	Not applicable	Tiantangzhai	Delineate reforested stands under CCFP	Parcel: distance to CCFP forests
	Global Positioning System	Summer 2013	Record UTM coordinates of each sampled cropland parcel	Link parcels to households	Global Positioning System

(CCFP and EWFP) and agricultural regulations have intervened the study site (Song et al., 2018), potentially changing the local livelihoods of the farm households (Text S1, Supplementary materials).

This study draws on socio-economic, demographic, and spatial data collected from multiple sources (Table 1). We preprocess the data (e.g., data cleaning and organization) for initializing social agents (i.e., individuals and households) and environmental entities (i.e., cropland parcels) of the model. Specifically, individual attributes including person ID, household ID, gender, age, relation to the head, and marital status were from the census for the whole population in 2012, while the model simulated attributes including education, occupation, and migration status following the sample distributions based on the survey data in 2014 (Text S2, Supplementary Materials). These individual-level attributes included household IDs linked to the households and used to aggregate individual-level attributes to household-level characteristics such as household size, personal attributes of the household head. Households form resident groups with group IDs identifiable for defining neighboring households during the model simulation. A classified land use and land cover map (Zhang et al., 2018b) facilitates the assignment of household locations to the built-up areas.

2.2. Model overview and processes

This study leverages a spatially explicit agent-based model, ABM-CALM (Fig. 2), to explore the social-ecological outcomes under various levels of rules pertaining to the constraint for cropland abandonment. The model simulates the feedback between the land-use decisions on cropland abandonment and labor allocation for out-migration by rural households and explore the emerging land pattern of land abandonment under the multiscale interactions (Text S3, Supplementary Materials). The land-use and migration decisions follow the empirical rules derived from previous studies (Zhang et al., 2018a,c), where household livelihood strategies depend on factors at multiple levels.

For each simulation, the model runs for 20 ticks (years) with initial conditions set for the year 2013, corresponding to the main survey year with rich spatial data. The aim is to understand the social-ecological dynamics through human-environment interactions rather than predict outcomes, so the time frame of years was practically irrelevant. The 20-year length corresponds to the period slightly longer than the first round of the forest restoration policies (Song et al., 2014). Since the model involves stochastic processes, one single simulation in each experiment may lead to an outcome specific to the settings (e.g., an initial condition with a specific order of cropland parcels assigned to the households). Thus, the model runs for 20 parallel times and generates outputs from the mean outcomes. Based on the robust and stable outcomes, the setting of 20 times is sufficient for synthesizing the outputs from the stochasticity (Tables S4-S7).

We develop the model using Python 3.6 and test each submodule independently. Fixed geolocations of the cropland parcels at the population level provides spatial information concerning the emerging land patterns of risk of cropland abandonment. Considering the parallel simulations of the model, the model calculates the percentage of the occurrence of being abandoned among the simulations and uses the percentages (likelihoods) to generate a heatmap over the study area under each experimental scenario. In this way, the model captures the emergence and evolving patterns at a larger scale beyond the parcel level, which is more efficient for informing policy making or adjusting from a broader perspective.

2.3. Experimental design

Population-environment nexus posits the interrelationships between people and the environment (Neumann and Hilderink, 2015), which motivates the exploration of land-use change and labor migration in this study. The objective of the household agents is to minimize risk from various livelihood activities, which relies on their characteristics given certain rules. For instance, a household may allocate a member for out-migration to expect more lucrative return than activities in local areas and hence may abandon a cropland parcel when the opportunity cost of growing crops is high. Here, the model restricts the behavior of cropland abandonment via setting criteria of qualification of the cropland parcels. Conforming to the rule that farmers cannot appropriate or abandon cropland parcels featured by superior conditions with relatively high productivity, or namely the “basic” land (Chen et al., 2019), we design a set of conditions of biophysical and geographic features at the parcel location to prevent the “basic” cropland parcels from abandonment within the submodule of cropland abandonment and reclamation. When executing this submodule, among cropland parcels still under cultivation, the model first identifies the qualification of a cropland for being abandoned (i.e., not defined as “basic” cropland parcels). If the determination of qualification is true, the abandonment probability of the given parcel would be estimated by the function in Eq. (2); if the submodule determined the parcel unqualified (i.e., restricted from abandonment), a parameter (r) that relaxes the prevention rule would constrain the abandonment probability of the parcel (Fig. S1). The specific formulations are as follows.

$$\gamma_i = \frac{e^{f(P,Z)}}{e^{f(P,Z)} + 1}[q_i + r(1 - q_i)] \tag{1}$$

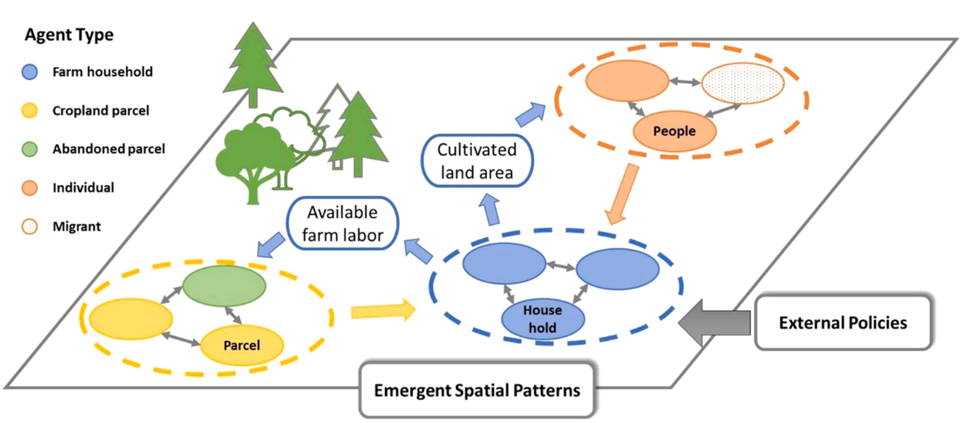

Fig. 2. Structure and processes of the agent-based model for cropland abandonment and labor migration (ABM-CALM) across multiple scales. Note: Double line arrows in gray indicate interactions at the same level (e.g., an existing migrant influences the migration decision of a current household member; an abandoned parcel influences likelihood of nearby parcels being abandoned). Single line arrows in bold render the pathways of feedback loops across different levels (e.g., the change in cultivated land at the household level due to cropland abandonment at the parcel level influences the decision making of individual migration, which feeds back to the households' decision on cropland abandonment via the reduced availability of farm labor). Policies in the gray rectangle act as external factors on household agents through providing ecosystem payments to influence land use and other agricultural regulations. With coordinates of geolocations of household agents and parcel agents, the broader landscape with land use patterns with linkages to households can be displayed in a spatially explicit way.

$$q_i(c_i) = \left\{ \begin{array}{ll} 1, & c_i \in Q \\ 0, & c_i \in Q' \end{array} \right\} \tag{2}$$

Where γ_i represents the probability of cropland abandonment under the current experimental design for cropland parcel i; the function $e^{f(P,Z)}/(e^{f(P,Z)}+1)$ estimates the abandonment probability under the condition of completely conforming the rule of preserving the cropland; q_i is a binary parameter denoting the qualification of being abandonment; c_i denotes the biophysical and geographic conditions at the parcel location; Q is the set of the criteria defining the qualification (Table S3), while Q' is the complement set of Q. Due to the different nature regarding cropland types (Ouyang et al., 2014), the criteria are slightly different between paddyland (paddy rice) and dryland (corn, potatoes, etc.) parcels. Given the observed prevalence of cropland abandonment in the study site (Zhang et al., 2018c), farm households may bend the rule to abandon cropland parcels in cases where benefits from non-agricultural activities outperforms land cultivation, which corresponds to the relaxation of agricultural preservation (r). Thus, the model tests six scenarios (experiments) pertaining to the parameter of primary interest for relaxing the abandonment prevention rule (r), with a range from 0 to 1 at a step of 0.2, i.e., 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0. When r is 0, is the farm household has a complete compliance for keeping the preserved cropland for cultivation. When r is 1, such restriction is completely relaxed and the farm household makes decision on cropland abandonment following the empirical rule, i.e., the probability estimated based on the influencing factors (Table S1).

2.4. Model verification and validation

In the literature, researchers widely used ABMs to study socio-ecological systems for the capability to account for complexities (Schulze et al., 2017). Verification and validation are critical steps after model calibration to check if a model, as an abstract representation of the real world, "correctly" delineates the system under study. Model verification is a process to confirm that the implemented model software matches the designed model structure (Crooks and Hailegiorgis, 2014). We verify our model through progressive testing by conducting a sub-module walkthrough independently and check that the submodule works as intended before compiling them within the full model. Validation is an essential tool to evaluate how well the model represents the real world simulated system, yet a one-size-fits-all validation approach for ABM is not existent (Xiang et al., 2005). As a rather realistic model in the spectrum defining the level of complexity and realism (Bruch and Atwell, 2015; Tian et al., 2016), the model draws on data from our study site, which enhances in-depth understanding of the complex system, as well as informing land-use policy making in our study area. Approaches that fit our research features and goals to validate the model can include comparing the simulation results of land use at given years with observed data obtained from independent sources such as satellite images. In addition, uncertainty analysis helps evaluate the simulation results by analyzing outcome distribution considering the uncertain factors in the model, and sensitivity analysis provides the possibility to prioritize model inputs for a better understanding of the simulated processes and to simplify the model (Ligmann-Zielinska and Jankowski, 2014). Thus, an effective way of uncertainty or sensitivity analysis is running the model with extreme values and summarizing the output space with calculated maximum, minimum, average, median, and standard deviation of the multiple outcomes from the parallel experiments (Saltelli and Annoni, 2010; Ligmann-Zielinska and Jankowski, 2014).

In this study, to better understand the systematic patterns of cropland abandonment relating to the geomorphological features, we derive analytical metrics through the total operating characteristic (TOC) curves (Pontius Jr. and Si, 2014). The TOC is a statistical method that compares a binary variable to an index variable at varying thresholds. The advantages of the TOC lie in its ability to show the four entries of a confusion matrix for each threshold, including Hits, Misses, False Alarms and Correct Rejections. The TOC also shows the diagonal entries for the confusion matrix. Cartographically, the TOC shows the size of Hits on the vertical axis and the size of Hits + False Alarms (size of spatial extent) on the horizontal axis. Due to its simple and effective way of comparing binary variables to index variables, the TOC has received wide applications across varying fields of study (Cushman et al., 2017; Shafizadeh-Moghadam et al., 2017; Chakraborti et al., 2018). Consequently, we plot the TOC curves for all the experiments of the six scenarios regarding the binary variable the cropland types (dryland vs. paddyland) and the curves of key topographic and geographic characteristics at the parcel locations. This provides direct comparison of cropland abandonment likelihoods with varying relaxation degrees and offers an indirect way of validating the model simulation.

3. Experiment results

3.1. Social-ecological dynamics under various levels of land-use constraint

The simulated social-ecological outcomes of the model feature key characteristics of complex systems, as reflected in the indicators pertaining to cropland management and labor migration behavior (Fig. 3). We first interpret the results on the general trajectories with underlying feedback operating between the land and population, focusing on the baseline scenario ($r = 0.0$) in which farmers comply fully with the rule of cropland preservation (i.e., complete restriction). We then describe how such outcomes differ under various scenarios of cropland use decisions with the relaxation of abandonment restrictions up to the complete relaxation scenario ($r = 1.0$) of cropland abandonment.

Referring to the baseline scenario, both land indicators (left panels) and demographic variables (right panel) demonstrate the features of nonlinearity, feedback loops, time-lag effects, and emergence. According to the simulations, cropland parcels have experienced a relatively visible proportion of being abandoned during the first few years and the rate decelerates as time moves on (Fig. 3a). Given the fixed total area of the existing cropland, rural farmers tend to abandon fewer parcels as the accumulated total abandoned area increases. This trend of declining percentages in cropland abandonment occurs over time, albeit it is trivial when abandonment is completely restricted (Fig. 3b). The trajectories of reclaimed cropland areas and proportions abandoned exhibit nonlinearity and surprises during model simulations (Fig. 3c,d), the explanation relating to the changing amount of abandoned cropland. In the beginning, the probability of abandonment is higher, as there is more cropland considered for abandonment. Thus, despite the relatively stable trend of cropland reclamation, the reclamation percentage experiences dips before a sudden surge to a peak, followed by a continuing drop. With cropland abandonment, it is found, as expected, that the overall area of cropland cultivation declines monotonically over time (Fig. 3e). Similarly, labor migration also shows interesting trajectories. Annual migration (measured as either the number or the proportion of the based population) grows during the first half of the simulation, then reaches a peak in the middle, and then starts to drop (Fig. 3f,g). This is reasonable as households tend to slow down the pace of sending out migrants to keep the remaining cropland cultivated. The number of the former migrants in the household, namely the current house members who had previously migrated but later returned, decreases through time, while its proportion is relatively stable, around 0.2 at the value set in the model.

Through comparisons of different simulations, the extent to which the trajectory shifts is different between cropland abandonment and labor migration, the latter less sensitive to the adjustment of the abandonment relaxation rule (Fig. 3, left panel vs. right panel). With the relaxation of the abandonment restriction, there is a nearly proportionate increase in cropland abandonment, both in size (area) and

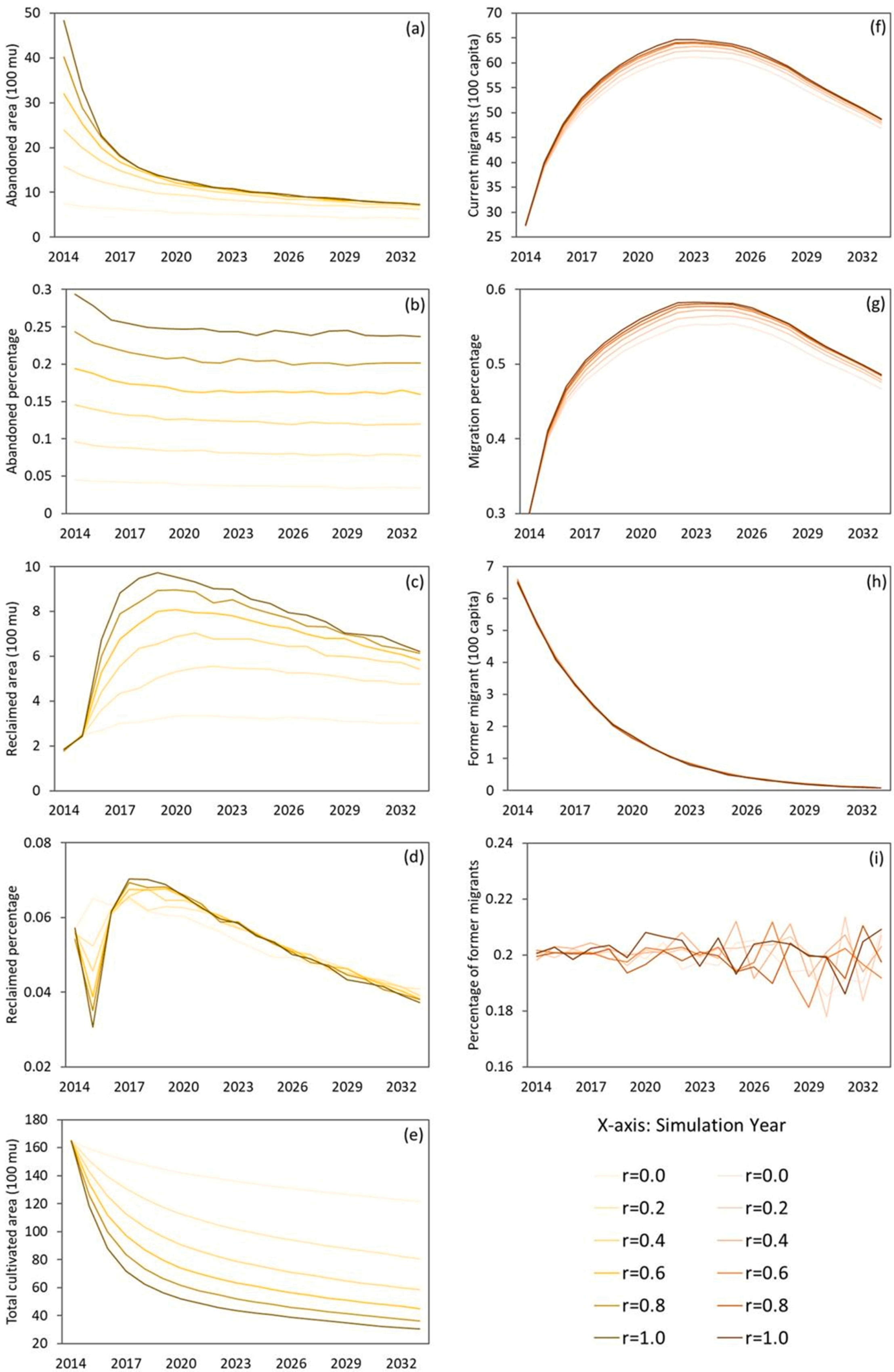

Fig. 3. Temporal trajectories of people-environment dynamics under various relaxation levels. Note: The trajectories of labor migration and cropland abandonment during 2013–2032 are outcomes resulting from feedback loops rooted within the land system, as designed in the model (Fig. 2).

probability (risk), except that the annual abandoned area converges by the end of the simulation due to scarcer cultivated land available for abandonment across all scenarios (Fig. 3a,b). A similar shift is observed regarding reclamation of the abandoned land, as reflected by the concave curves of the reclaimed area (Fig. 3c). The greater the relaxation degree, the higher the peak of the curve. Accompanying a higher rate of cropland abandonment, the decline in remaining cultivated land becomes more prominent during the first few years, presenting a more distinct concave curve from above (Fig. 3e). Moving onto labor migration, despite the decreases in abandonment restrictions, the peaks, along with the trendlines, of annual migration are pulled up over time only very slightly, meaning slightly more observed migrants with higher degrees of relaxation (Fig. 3f,g). Feedback loops with social-ecological dynamics, as observed in the surveys and designed in the model (Fig. 2), play a dominant role in these small changes in outcomes. Specifically, the greater abandonment of cropland under more relaxed rules frees more farm labor from land cultivation (Lin and Yao, 2014), which stimulates farmers to seek alternative activities (Zhang et al., 2019), particularly via out-migration. Following labor reallocation, households adapt to the loss of farm labor by adjusting their valuation of the remaining cultivated cropland, hence reducing their intentions to abandon more parcels and slowing out-migration over time.

3.2. Migration-environment nexus with feedback loops

To further examine the social-ecological dynamics within the nexus of migration and the environment, we compare the final-year statuses of labor migration and cropland abandonment across the designed scenarios (Fig. 4). Based on the model simulation, the number of former or return migrants do not substantially differ across the scenarios while the total number of people in the households with migration experience (i.e., total ever-migrating) increases with the relaxation of cropland abandonment restrictions (Fig. 4a,b). As a household-level factor, migration experience by previous migrants from a household tend to act as a social network that facilitates future out-migration of current, remaining household members (Fu and Hao, 2018; Massey, 1990), but this is mediated by the feedback to land use through changing labor availability in the household (Davis et al., 2017). In terms of land use (cultivated vs. abandoned), the percentage of abandoned land in the final year varies from a low level (36%) to a majority (78%) as the degree of the relaxation rises from $r = 0.0$ to $r = 1.0$ (Fig. 4c). The ratio of abandoned cropland to migrants therefore rises rapidly (Fig. 4d). Combining these results, greater cropland abandonment under relaxed constraints leads to more farm labor with migration experiences rather than facilitating further out-migration.

3.3. Emerging patterns of risk of cropland abandonment

With the simulated interactions between social agents and land based on parameters estimated from observed data, the emergence of changes in land-use patterns reveals the spatial hotspots of risks for cropland abandonment given the geolocation information of each cropland parcel (Fig. 5). The evolving patterns under increasing levels of relaxation of restrictions lead to consistent outcomes, with the trajectories shown: the effects of the relaxation are most evident when relaxation level increases from $r = 0.0$ to $r = 0.4$, with far smaller changes as the level goes beyond 0.4. In the baseline scenario ($r = 0.0$), a few small hotspots of cropland abandonment occur mostly in the western part of the study site where the topography is mostly high elevation and steep slope and the area is relatively remote, as shown in Fig. 1. When the relaxation level increases to 0.4, the risk of cropland abandonment to the west appears more conspicuous, forming three major hotspots. Other scattered hotspots identified in peripheral and remote areas in the southeastern and southwestern parts contribute to the evolving pattern. Cropland parcels in these areas are mostly on moderately steep slopes and form large clusters in the area. When the relaxation level exceeds a certain level (0.4 in this case), most of these parcels also have high risks of abandonment. In comparison, cropland at

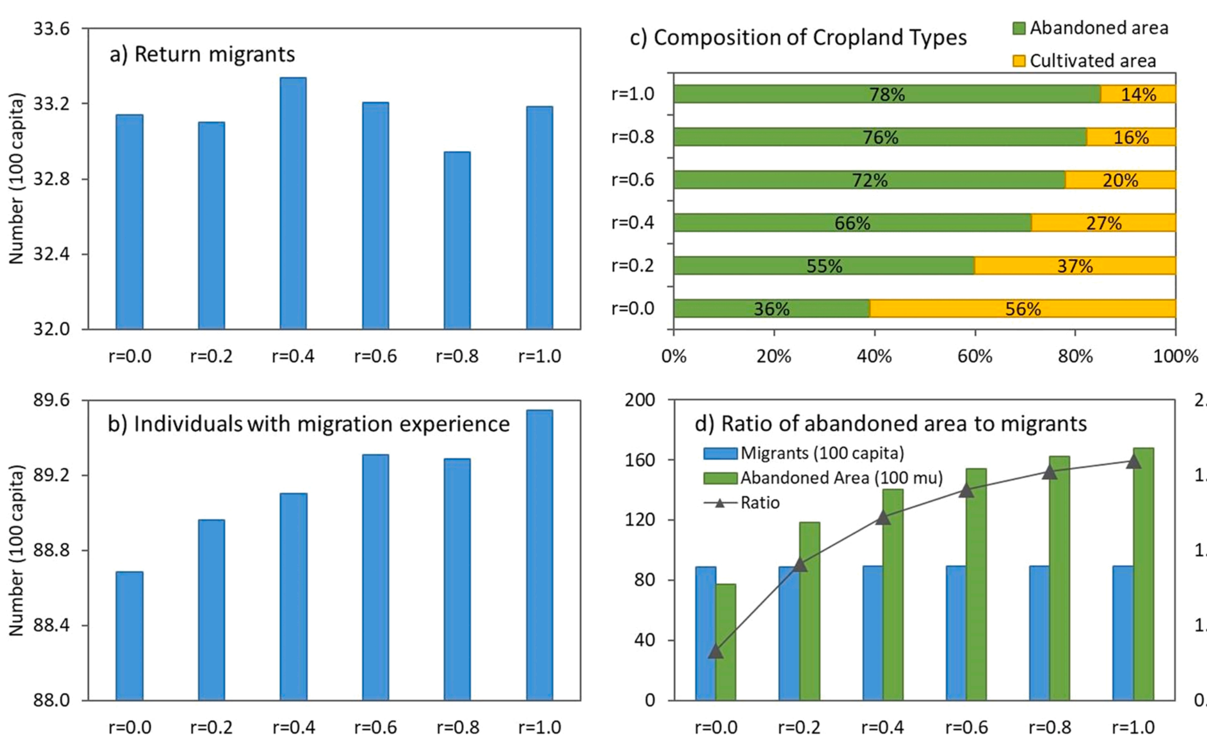

Fig. 4. Outcomes of land-population nexus represented by migrants and abandoned cropland areas at the final tick of the model simulation for feedback loops. Note: Return migrants are those who migrated before but returned home to become current household members at the time of simulation. Individuals with migration experience are either current migrants or household members who have migrated before. The ratio of cropland abandoned area to migrants reflect the relative changes between the two indicators due to the feedback loops simulated in the model.

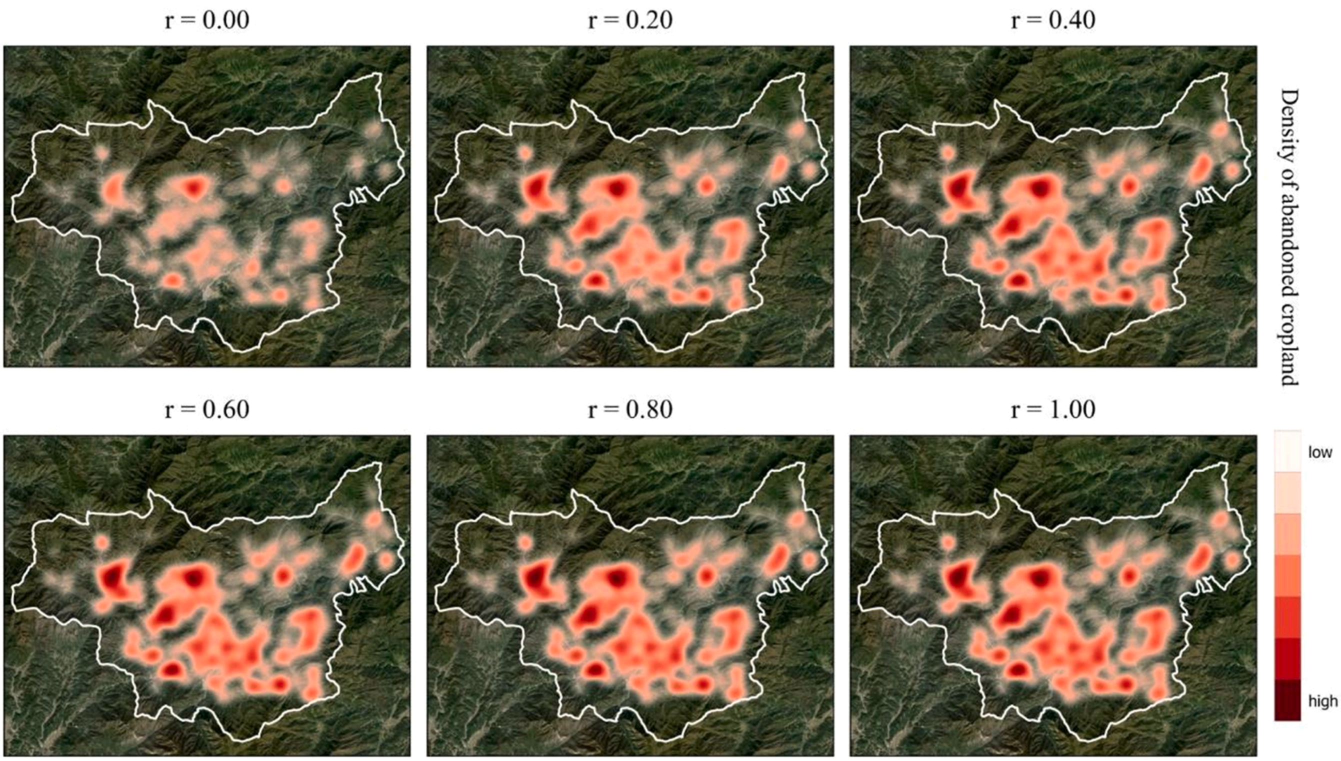

Fig. 5. Emergence of patterns of cropland abandonment risk under various relaxation rules scenarios.

lower elevations (in the east) and less remote (from the township capital) in the central part have lower risks of abandonment even in scenarios with higher levels of relaxation of rules against cropland abandonment, indicating that cropland cultivation in these areas is a more critical component of household livelihoods.

4. Discussion

Humans have been modifying the Earth's land surface increasingly over thousands of years (Foley, 2005). The coupling of human agents and environmental elements drives changes in land systems (Verburg et al., 2015), which is particularly prominent in rural areas (Rindfuss et al., 2004; Long et al., 2010; Aspinall and Staiano, 2017). Understanding human-environment interactions is at the core of advancing knowledge of land change science (Radel et al., 2019). This study applies an agent-based approach to explore labor migration and cropland abandonment in a rural area within a nature reserve. The simulated social-ecological dynamics adds to our knowledge of land system science, has potential practical implications for agricultural and environmental policies, and enriches the repository of tools for modeling integrated socio-environmental systems.

4.1. Socio-environmental dynamics within the land system

Exploring human-environment interactions in this study is a representative case for understanding the coupled nature-human complexity (Liu et al., 2007). Through the lens of labor migration and cropland abandonment, the model shows that the nonlinearity of social-ecological outcomes with time emerges due to feedback loops within the land system, recognizing the bidirectional influences between the social and ecological systems (An, 2012; Iwamura et al., 2014; Schulze et al., 2017). One interesting outcome is the different patterns and trajectories between the abandoned land and migrants through time (Fig. 3). Exploring the migration-environment nexus can shed light on addressing important pattern-process relations in land-use models (Bilsborrow and Henry, 2012; Walsh et al., 2013). The trend of growing cropland abandonment reveals the continuing shift of household livelihoods relying on natural capital (e.g., land resource), allowing more farm labor available for other activities including migration. However, the decline in the area of cultivated land gradually diminishes under the negative feedback of the migration trend which decelerates after a certain period of migration boost (10 years in this case). Farm households can adapt to the changing socio-environmental statuses by adjusting their decisions promptly, influenced by multiple factors such as previous migration experience (Ryan and D'Angelo, 2018) and the cropland in surrounding areas managed by neighboring households (Chen et al., 2012). When land becomes a scarce resource for growing crops, the revaluation of land can result in negative feedback on labor migration. These interactions across the individual, household, and parcel levels manifest key characteristics such as nonlinearity with thresholds and time-lag effects featuring the coupling of the human system and the natural system.

4.2. Environmental conservation and agricultural preservation

The application of the integrated model offers far-reaching implications for better managing natural resources and reconciling food security and environmental conservation within the context of agricultural and forest policies. As in many rural areas around the world, policies within different scopes have been established and implemented to achieve the goal of sustainable development (Jiao et al., 2018; Liu, 2018; Lyver et al., 2019; García-Jácome et al., 2020). However, human behavioral changes and adaptations under policies and regulations may cause unexpected and mixed results in both negative and positive directions (Yang et al., 2018).

In this study, outcomes from scenario tests suggest that the abandonment level converges to the greatest after the relaxation degree reaches or exceeds a certain level despite the imposed restriction of abandonment (Fig. 4 and Fig. 5). More specifically, the situation of cropland abandonment becomes the worst when ignoring more than half of the abandonment cases. Meanwhile, after simulating the scenarios for several years, farm households would abandon most cropland even if the relaxation extent is low, i.e., the restriction remains strong with few lands abandoned at the initial stage. Based on our model simulation, such micro-level decisions under the influence of the policy relaxation would possibly lead to a converged consequence of the agricultural land system with prevalence of cropland abandonment, as observed in other areas (Li et al., 2018; Bista et al., 2021). This may explain the experimental outcome that the area of abandoned cropland outperforms the migrating trend, but such a trend becomes weaker as the relaxation of constraints increases to a certain level. Policymakers can anticipate and leverage these outcomes in both agricultural and environmental sides. The forest restoration programs should prioritize cropland parcels with high risks of abandonment to increase the cost-effectiveness via lowering costs incurred by land targeting (Chen et al., 2010). Meanwhile, cropland parcels that are less likely retired are the focus of agricultural preservation for food security due to their relatively high opportunity costs considering alternatives. In the latter case, the geographic connection of agricultural land and conserved forest land (Fig. S3 and Fig. S4), namely the distance from cropland parcels to the nearest forest edge, features one of the complexity issues that should be considered to reconcile the (potential) conflicts among policies with different objectives.

4.3. Agent-based methods as key tools of modeling land system dynamics

Drawing on population-level datasets in a rural site, ABM-CALM demonstrates the complexity and unexpected emergence from processes functioning within the land system. The interactions among agents and the environment under rules across spatial, temporal, and organizational scales supports the emergence of the land system (Malanson and Walsh, 2015; Verburg et al., 2015; Wu, 2019). From a bottom-up perspective, the model explicitly simulates feedback loops between cropland abandonment and labor migration while simplifying less relevant processes (e.g., food production, alternative livelihood activities). The relative remoteness of the township to cities makes the land system a suitable system under little influence by material and information outside the township. One major connection is labor out-migration, which is the focus of the model. Furthermore, the rich data at the population level for realistic ABMs overcomes the methodological barrier for solving real-world problems in human-environment studies (An et al., 2005; Tian et al., 2016). For instance, limiting the scope to a single village within the township may weaken the assumption that other households from different villages do not significantly influence household decisions of labor allocation and land use through confounding factors such as marriage, land renting-in or renting-out. Studies suggest that ABMs should better connect with existing theories relating to human decision-making (Groeneveld et al., 2017; Bourceret et al., 2021). In ABM-CALM, the theoretical background encompasses the paradigm of bounded rationality and those pertaining to migration behavior (Davis and Lopez-Carr, 2014; Neumann and Hilderink, 2015; Radel et al., 2019). Regarding migration, other household members with migration experiences may positively influence an individual through social networks (Massey, 1990; Ryan and D'Angelo, 2018; Zhang et al., 2018a).

4.4. Limitations and future directions

In ABM-CALM, the demographic submodule models out-migration based on individual attributes and household characteristics, but higher-level factors, such as the labor market and national policies can confound the migration behavior (Ryan and D'Angelo, 2018). In addition, the model restricts the migration with a fixed probability of return-migration, which can be dynamic through time. Similar settings apply to the land-use decisions on reclaiming and renting cropland parcels. This leads to the future direction of testing the abandonment of both rural residence and agricultural land, also known as "hollow village/township" (Liu et al., 2014; Long et al., 2012; Zhou et al., 2021). Moreover, the model implicitly simulates the interactions between the agricultural and environmental policies but needs to fully address the synergies and trade-offs through better designed policy scenarios. Finally, informal rules such as social norms can play a role in the decision-making process of land use (Lyver et al., 2019).

5. Conclusions

Changes in land systems are anthropogenic impacts on the Earth system. In rural regions, policymakers often implement both agricultural and forest policies to enhance social-ecological sustainability of the land system. This study leveraged an agent-based model to explain land-use changes and demographic dynamics with constrained household land-use decisions under the context of agricultural preservation and forest conservation. Two channels are cropland abandonment and labor migration, with their feedback operating in the rural land system. Given the implications for elucidating trade-offs and synergies between environmental protection, food security, and socio-economic development, this study emphasizes the need of using an integrated model for simulating the outcomes of resource-based rural livelihoods, as well as agricultural-environmental systems with interactions between different components and entities.

The answers to the research questions posed in this study are as follows. First, what are the emerging patterns and dynamics of cropland abandonment due to the feedback of labor migration? The findings show that the probability of cropland abandonment follows a nonlinear trajectory with a monotonically decelerating decline due to the negative feedback from labor out-migration. Spatially, the hotspots of cropland abandonment are more likely appear in areas with high elevations, steep slopes, and poor accessibility to households. Second, how does the adjustment of the agricultural preservation rule against the background of forest policies influence the emerging land-use patterns? The relaxation of the agricultural preservation rule can substantially increase the risk of cropland abandonment. The hotspots of cropland abandonment quickly emerge when the relaxation just begins and appear mostly in proximity to the edge of forests under CCFP or EWFP.

The findings provide insights for policymakers to consider feedback loops when implementing policies or imposing regulations to better manage land resources and reconcile potential trade-offs. They suggest caution for policymaking for the adjustment of cropland preservation since the risk of cropland abandonment is sensitive to the relaxation of constraint even at a relatively low level. Finally, the emerging pattern of cropland abandonment in combination with the adjusted regulation for agricultural preservation can strengthen the efficiency of land targeting for conservation purposes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2022.100337.

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