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Understanding the role of land attachment in the emergence of hollow villages based on the agent-based complex system framework

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A B S T R A C T

Rural hollowing, associated with depopulation and cropland abandonment, is a pressing issue under the rapid pace of urbanization. Understanding the emergence of hollowed villages with the abandonment of homestead and cropland is a major objective of halting the waste use of land resources and improving rural social welfare. Here, we apply the agent-based complex system framework to explore the dynamics of rural land systems, focusing on the feedback effects of cropland abandonment and labor migration decisions that are characteristics of the hollowing process. We applied a spatially explicit agent-based model in two study areas in rural China and designed scenarios where farmers treat their cropland parcels and homesteads with and without land attachment. Experimental results show that return-migration plays a more critical role than out-migration in shaping system dynamics and preventing the emergence of hollowed villages when there is strong land attachment. The rate of cropland reclamation following the return-migration outweighs the rate of cropland abandonment, which provide negative feedback to the out-migration decision and subsequently decelerate the process of rural hollowing. Hollowed villages are a manifestation of social-ecological outcomes resulting from human-land interactions with migration trajectories and land use patterns exhibiting nonlinearity, divergence, and even unexpected changes. Our findings highlight the critical need of considering the endogenous feedback effects for policymaking. Policy that aims at rural development and land consolidation should integrate tools helping return-migrants with improved land-use efficiency in addition to rural revitalization.

1. Introduction

Rural hollowing is a widespread phenomenon commonly observed in rapidly industrializing countries worldwide (Johnson and Lichter, 2019; Llorent-Bedmar et al., 2021). This process has far-reaching consequences for the vulnerable population group in rural areas, such as feminization of agriculture and marginalization of the elderly and the poor (Tenza-Peral et al., 2022). In industrialized countries, rural population usually make up a small proportion of their total population. For instance, the rural population in the United States accounted for only 14 % of the total population in 2016 (Johnson and Lichter, 2019). During the decade of 2000–2010, approximately 38 % of Mexico's villages completely vanished, along with the depopulation trend prevailing in 61 % rural villages. This phenomenon is even more pronounced and complex in developing countries, like China, than elsewhere (Liu et al., 2010).

Since the adoption of the reform and opening-up policy in the late 1970s, China has witnessed a dramatic transformation from the old stagnant planned economy toward a vibrant market-oriented economy that has brough in profound changes in nearly every aspect of the socioeconomic structure in rural areas (Guan et al., 2018). Notably, rapid urbanization and inefficiency in the agricultural sector have both stimulated a substantial volume of rural labor migrating to the non-agricultural sector in urban areas (Chen et al., 2014; G. Liu et al.,

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2016). From 1995 to 2015, China's rural permanent population declined by 256 million due to labor out-migration to urban areas (Y. Liu et al., 2016). Rural-to-urban migration has been accompanied by and interacted with many other socio-economic factors, such as rural-urban income disparity, the household registration system, and land reform and ownership systems (Abramson, 2016; Ahani and Dadashpoor, 2021; Long, 2014), which can strongly influence the land use in rural areas (S. Liu et al., 2023; Long et al., 2010; Yang et al., 2015). For instance, out-migration of farm labor can result in a decrease in cultivated land productivity or cropland abandonment (Li et al., 2018; Zhang et al., 2014), giving rise to major concerns about future food security in China and even worldwide (Brown and Funk, 2008; Long, 2014; Stephens et al., 2018; Tan et al., 2009). Furthermore, rural out-migrants often have strong intentions to secure long-term employment in urban areas for better livelihoods, leading to the seasonal or even permanent unoccupancy in their village residence (Long et al., 2012), which is commonly referred to as the "rural hollowing" (Liu et al., 2010).

In China, rural hollowing is a phenomenon of depopulation featured by the emergence of vacant and abandoned residential land in the inner villages (Liu et al., 2010). The hollowing process can be facilitated by the non-agricultural transition with the abandonment of cropland belonging to the households (Gao et al., 2017). The concept of "hollowing" can be understood not only in terms of geography and space, but also economically. As a large number of young and educated laborers migrate to cities (Mohabir et al., 2017), the human capital attached to these migrants has also left the rural sector. Thus, "hollowing" happens in multiple dimensions, such as land use, population, rural society, and economy (Wang et al., 2021). Among them, the sustained migration of rural population is the most important factor that facilitates the formation of hollowed villages (Long et al., 2012). According to the life cycle theory (Liu et al., 2010), rural hollowing is a dynamically developing process with stages of "emergence, growth, flourishing, stability, and decline (transformation)". The formation and evolution of hollowed villages can be driven by a combination of "push" and "pull" factors (Smith, 2010). For instance, income, investment, and non-agricultural employment in urban areas are viewed as attractors, while the changing local attachments and neighborhood relationships are considered as internal forces (Gao et al., 2017; Liu et al., 2010). In fact, living in the urban areas with modern lifestyle has become the aspiration of the younger generation (De Haas, 2021).

Multiple factors (e.g., job opportunities in cities, weakened community ties, deteriorated environment) can influence the formation of hollowed villages (Gao et al., 2017). Land plays a critical role among these factors. China's land ownership system and the household registration system essentially separate the population into urban and rural groups, which are of importance to changing the attachment of migrated farmers to rural land and residences (Zhao, 2020). "Use-based" land titling, or the "land rights established through the contingent use of land", binds a certain amount of labor to agriculture. Farmers often bear a high risk of losing their land if they keep it idle or fallow for an extended period or rent it to others (de Janvry et al., 2015; S. Liu et al., 2023). Land attachment exhibits a dual nature of functional dependency and emotional attachment, making land a crucial foundation for farmers' self-reliance (Bradfield et al., 2023; Liu et al., 2022; Quinn and Halfacre, 2014). Due to the inadequate social systems (e.g., poor access to medical insurance) in urban areas for rural out-migrants, their social welfare is attached to rural land and residences, which actually serve multiple functions, such as property and social security (Ondetti, 2016; Wang et al., 2020). Therefore, migrant farmers prefer to abandon their land use rather than give up their land rights. In addition to valuing functions, farmers have a strong emotional attachment to the land. The implementation of the Household Responsibility System (HRS) in the 1980s enable rural household to gain use right for the allocated cropland parcels, owning to which farmers gradually created a deeper emotional attachment to the cropland, particularly for the older generation farmers (Liu et al., 2022). Two types of differentiation should be considered. The first is the different emphasis of reliance on land between cropland and residence although they are closely related. Farmers use cropland to fulfill its functions of providing food for surviving or expecting economic return by selling the products (i.e., agricultural income source). Homestead is for the living purpose which supports the daily activities for family members, including those migrants who occasionally visit or return (Jiang et al., 2016). The abandonment of cropland may catalyze the intension or facilitate the process of the idleness of residential areas, eventually forming the so-called "hollowed villages". The other type is the extent to which rural population attach (especially from the emotional aspect) to their land varies by generations (G. Liu et al., 2023; Liu et al., 2022). Elderly farmers are persistently unwilling to give up their land-use rights even if they intend to leave the farm (Ingram and Kirwan, 2011). However, due to generational differences, the younger generation of farmers is gradually foregoing their attachment to the land as their rational and economic awareness develops (Inwood et al., 2013; Quinn and Halfacre, 2014) and aspiration for a modern lifestyle (De Haas, 2021).

Rural hollowing is a complex process shaped by interactions between human and environmental agents, and hence can leverage existing theoretical knowledges to support the agent-based complex system framework. In particular, the Social-ecological System (SES) and Network of Action Situations (NAS) frameworks offer valuable insights into the multi-agent dynamics of rural hollowing (Ostrom, 2009; Su et al., 2024). The SES highlights the interaction between social and ecological factors, showing how labor migration contributes to cropland abandonment and its feedback loops. The NAS framework explains how actors operate within multi-level decision-making networks (Kellner, 2023; McGinnis, 2011), highlighting the relationships among emotional attachment, economic, and institutional factors that jointly drive cropland abandonment and labor migration (See Supplementary Text S1).

So far, little attention has been paid to the emergence of hollowed village and cropland abandonment in relation to land attachment by households, particularly from the perspective of the bidirectional relationship between land use and labor migration under the agent-based complex system framework. In this study, we aim to investigate the influence of land attachment in the formation of hollowed villages resulting from the abandonment of cropland and homestead. Our research addresses this through achieving several key objectives. First, we explore how the interplay between land-use changes and labor migration dynamics shapes the patterns of cropland and residential areas. To capture this complex relationship, we utilize an agent-based complex system framework that integrates the reciprocal influences between land systems and social systems. Second, we design a parameter quantifying the extent to which farm households attach to their land, which is crucial for understanding its effect on human decision-making processes. This parameter helps elucidate how variations in labor availability relative to cropland impact land-use decisions. Third, recognizing that complex systems are context-dependent, we apply our model to two study areas with both shared characteristics and notable differences. This approach allows us to compare simulation results and derive insights that can inform strategies to mitigate rural hollowing and cropland abandonment in different regions. The findings are essential to advance theory of human decision-making in shaping system dynamics (An and López-Carr, 2012) as well as inform practices regarding land-based policymaking and rural development.

2. Materials and methods

2.1. Study areas

To perform experimental explorations of rural hollowing and cropland abandonment, we selected two rural villages in Anhui Province (China), with one from Xiuning-&-She Counties (XSC) and the other from Tiantangzhai (TTZ) Township (Fig. 1). We collected data from sampled households within the two counties and the one township,

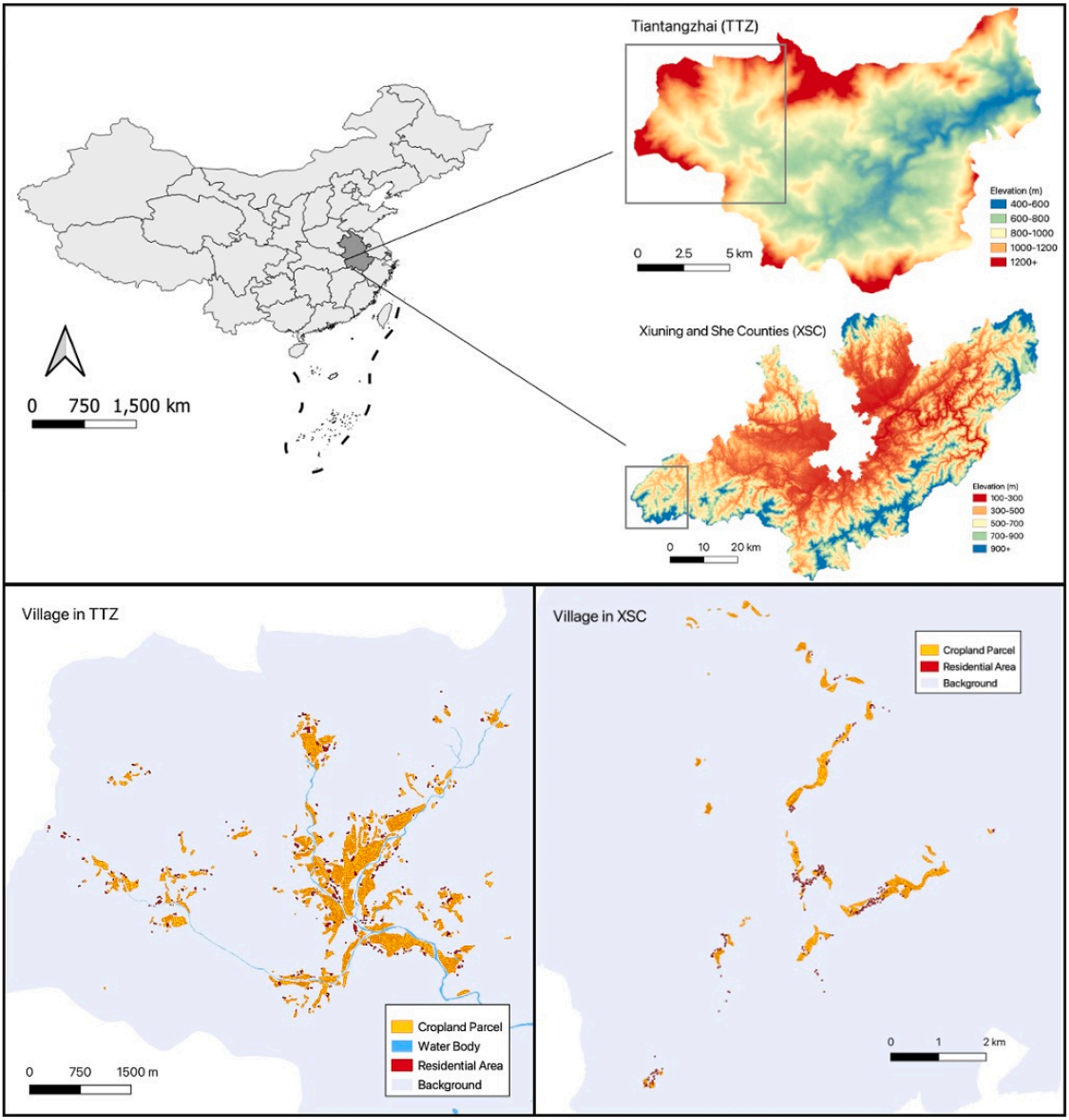

Fig. 1. Study areas: Xiuning County & She County (XSC) in southern Anhui and Tiantangzhai Township (TTZ) in western Anhui, China. The squared areas encompass the selected villages in XSC and TTZ, respectively, for spatial linkage between houses and cropland parcels as well as model simulations for the abandonment of cropland and residential areas.

which were used to initialize the model settings and design the rules for human decisions. Model simulations were conducted for agents (e.g., households, cropland parcels) within one single village in each study area. One purpose of selecting two villages from two study areas was to compare the experimental results focusing on similarities and differences in migration behavior and cropland use, which can offer comprehensive insights on the emergence of hollowed villages withing different contexts. The first study area, XSC, is in the southernmost tip of Anhui, belonging to the border of three provinces (Zhejiang, Jiangxi, & Anhui). XSC covers an area of approximately 4200 km^2 and has a subtropical warm monsoon region with abundant rainfall, with annual mean precipitation of 1630 mm and annual average temperature of 16.4°C. The terrain is mainly mountainous and hilly with elevation ranging 120–1700 m. The study area has dense forests, which accounts about 80 % of the total area. XSC covers 50 townships, each consisting of seven administrative villages. The villages are generally located at the foot of the hills on gentle slopes. The second study area, Tiantangzhai Township, is located in Jinzhai County in western Anhui, belonging to the Dabieshan Mountain Range and having an area of 189 km^2. The township is encompassed by the Tianma National Nature Reserve at the intersection of three provinces (Hubei, Anhui, Henan). Similar to XSC, TTZ has a relatively wide range of elevation (400–1700 m), featuring rough terrain with dense forests.

In both study areas, farmers usually make their living from agriculture. They used to work together on collective farms. Since the implementation of the HRS, the farmers have had the right to use and operate the cropland parcels (Lin, 1987). Farmers can choose which crops to grow, have the right to rent in or rent out cropland parcels, or even fallow and abandon the land. There are two main types of agricultural land in the study area, one dryland (i.e., land for growing soybeans, corn & tea) and the other paddy fields (i.e., land for growing rice). Due to the rugged terrain, most of the land parcels are small. Cropland yields are generally low for parcels on the hillsides. To make ends meet, more and more local households allocate their labor to non-farm activities. Local young people choose to take up non-farm work locally such as being employed in local non-farm businesses and/or migrating to other cities for non-farm work. Some households have rented out or abandoned their cropland and hence are no longer involved in farming. These out-migrants rarely return to the area, and some even abandoned their residential houses. As a result, some villages within the study areas are occupied by mostly the elderly known as "empty nesters", leading to the hollow villages.

The two study areas were also under the intervention of forest policies, including the cropland-to-forest conversion program and public welfare forest program (Bennett, 2008; Xu et al., 2022). These programs adopted the approach of payments for ecosystem services (PES) (Wunder, 2015) in environmental restoration and conservation, which compensate participating households to secure delivery of ecosystem services provided by the existing and/or restored forests. Research showed that the PES programs may stimulate rural out-migration while inducing further abandonment of cropland (Démurger and Wan, 2012; Treacy et al., 2018), potentially influencing rural development in the local areas. The impacts of the programs on household livelihoods involve complex feedback effects. For instance, crop-raiding by wildlife associated with forest regeneration can facilitate the decision-making of cropland abandonment by households, who may allocate farm labor to other non-agricultural activities such as rural-to-urban migration and local businesses (Bista and Song, 2022; Chen et al., 2019).

2.2. Data acquisition, pre-processing and preparation

2.2.1. Household and land survey

We obtained socioeconomic and demographic data from household surveys in the two study areas, with one of TTZ in summers of 2013 and 2014 and the other of XSC in winter 2021. We adopted a stratified random sampling technique to select the households for interview in both study areas and used pre-designed questionnaires to record detailed household information, including demographics, land use, income and expenditure information, migration, and other agricultural and/or non-agricultural activities, participation in PES programs, and governmental subsidy, and other agricultural and/or non-agricultural activities. Before conducting the household surveys, we recruited and trained graduate students as the interviewers. We conducted face-to-face interviews with village or group leaders in each village to obtain relevant information at the village level such as the resident group size. Detail descriptions of the sampling schemes and data collection can be found in Li et al. (2022) and Song et al. (2018). After excluding invalid responses, the eventual sample sizes for XSC and TTZ were 234 and 731 households, respectively. For each interviewed household, we also recorded detailed information of cropland parcels managed by the household, including parcel types (dryland vs. paddy-land), parcel area, and whether abandoned. The sampled households were used mainly to simulate agents (i.e., households, persons, and parcels) with attributes at the model initialization stage and define rules guiding their interacting behaviors. For instance, the households and their managing parcels were spatially linked based on the distributions of two attributes, including the total area of cropland managed by a household and the distance of a cropland parcel to its belonging household (see Section 2.2.3). The social-ecological outcomes emerge due to the frequent interactions among *all* agents at the population level, rather than the number of the agents (Manson, 2001; Walsh and Mena, 2013). Thus, the number of agents or the size of samples do not substantially influence our interpretation of the modeling results pertaining to the emergence characteristic. The agents for model simulations include 267 households, 867 persons, and 560 parcels in the XSC village, and 571 households, 1957 persons, and 1791 parcels in the TTZ village.

2.2.2. Spatial data processing

To make the model spatially explicit, we prepared land use and land cover (LULC) maps within the two study areas, focusing on residential areas (i.e., house roofs), cropland parcels, and forest lands. For the LULC classification and cropland delineation in XSC, we obtained two types of spatial data: 1) Land use in 2021 (30 m spatial resolution) obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/DOI/DOI.aspx?DOIID=54); 2) Administrative division from the Second National Land Survey in China, which was officially launched in 2007 and completed in 2009 with results offering an accurate and reliable representation of land use changes across China (Zhou et al., 2023). We first extracted the LULC in XSC masked by the administrative boundaries and reclassified the LULC types into four major categories, including cropland, forest, houses, and others. Then, we clipped the cropland from the maps and delineated cropland parcels via visual interpretation. In TTZ, we obtained a 2013 WorldView-2 image (2 m spatial resolution) that encompasses the entire study area (with 1-km buffer size), based on which we generated a classified map and manually delineated each cropland parcel and forest parcel (Zhang et al., 2023, 2018).

2.2.3. Spatially linking cropland parcels to households

We focus on one single village within each study area to explore the emergence of land use patterns and residential abandonment. One major task is to develop linkages between households and cropland parcels. In the selected village in TTZ, we interviewed all the resident group leaders, who helped identify all cropland parcels managed by the households that facilitate the spatial linkages. In the selected village in XSC, however, we did not have such data and hence adopted a GIS-based algorithm to link parcels to the households. All households and cropland parcels were first represented as points in two vector layers, of which the parcel layer consisted of the centroid of each parcel. Given a household, an initial value representing the total area of cropland to be managed was assigned (e.g., 10 mu, 1 mu = 666.67 square meters), practically meaning the household aimed to claim such an amount of cropland in total (i.e., 10 mu), which follows the sample distribution. Then, each household started searching for cropland parcels within a circle of a given diameter and randomly selected one parcel that falls in the circle of the range. This parcel would be assigned to the household with the parcel area added to the total area of cropland claimed. The diameters of the circles also follow the sample distribution. The searching process continued until the summed area of all assigned parcels reached the initial assigned area, with a margin of different at 1 mu (i.e., 10.0 ± 1.0 mu). The area of land to be managed would be updated by the value of the final total area of actually assigned parcels (e.g., 10.3 mu). An illustrative schematic graph of this GIS-based searching method and the simulated distributions are shown in Fig. 2. We also plotted the distribution of total areas of cropland assigned to households and compared the histogram of GIS-based simulations with that based on the sample. One issue pertains to the differentiation in spatial distributions between paddy-land and dryland parcels. In this study, nearly all cropland parcels were previously used as paddyland parcels, following the distribution of paddyland parcels. Some of the parcels were later used as dryland due to lack of water and/or depend on the needs by the household, which is not uncommon in both study areas, particularly in the selected

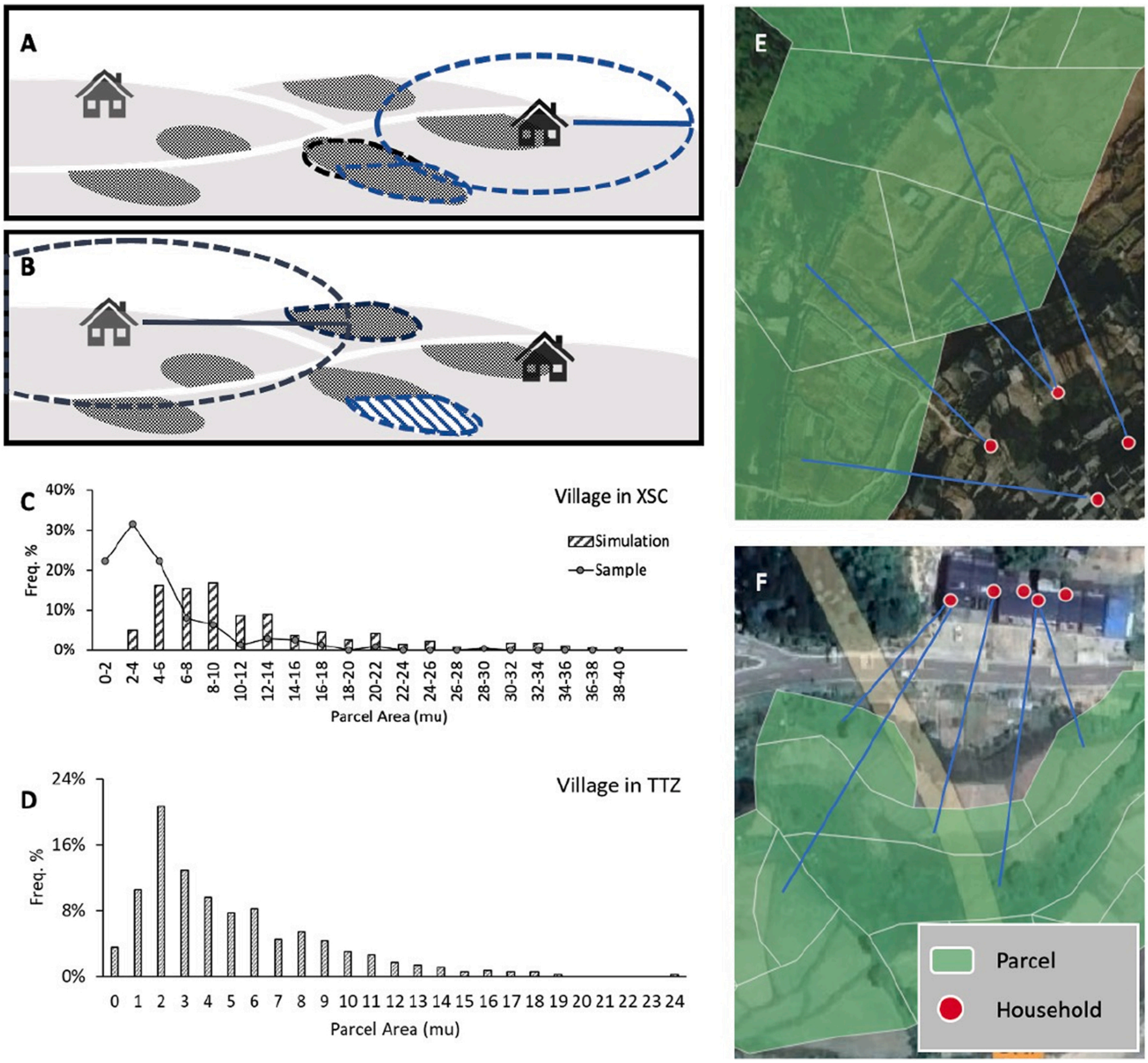

Fig. 2. GIS-based approach of building linkage between households and cropland parcels. Panels (A) & (B) Illustration of a household searching for cropland parcels. Panels (C) & (D) Comparisons of distributions of cropland areas and geographic distances between sample and simulated observations. Note that all households and parcels were obtained during the survey in the TTZ village so there was no need for simulation. Panels (E) & (F) Spatial linkages between houses and cropland parcels.

villages (Fig. S2). We labeled the parcel type for each parcel based on the reported use by the interviewed households. Therefore, our approach of spatial linkage between households and parcels can be applied to all parcels.

2.3. Agent-based modeling

The purpose of ABM simulations is to understand the emergence of hollowed villages due to feedback mechanisms of household decision-making on cropland abandonment and farm labor out-migration (Supplementary Text S2). The model is spatially explicit given the geolocations of households and cropland parcels they manage, as well as their spatial linkages. The model identifies three types of agents, including individual persons, cropland parcels, and households (Table S1). Feedback loops, which can be difficult to model using conventional approaches (e.g., statistical modeling), are among the key drivers of cropland use change at the household level. The collective phenomena of cropland-use change from all households constitute the emergent property of the land systems within the study areas. Specifically, feedback effects exist through two directions between the cropland parcels and households. On the one hand, the migration behavior changes the demographic structure of the household such as the dependent-independent ratio as described by Chayanov (1966), which influences land-use decisions that have feedback to labor allocation for migration. On the other hand, cropland use demands farm labor.

The whole land system within a single village can be viewed as a complex social-ecological system with its patterns and processes driven by frequent interactions among different agents as well as between agents and the environment. For instance, one household member can learn from other members with previous migration and decide whether to migrate out via the established social-network (Massey, 1990; Xiang and Lindquist, 2014), while the land-use decision for a cropland parcel also relies on the statuses of other cropland parcels managed by other households surrounding the given parcel via the neighborhood effect (Chen et al., 2009). Such interactions may lead to cascading effects on land-use patterns and migration processes at a higher level. Thus, the system dynamic is dependent on human-decision making, which should be modeled based on existing theoretical foundations. For example, household agents are assumed to act with bounded rationality (Gotts et al., 2003; Simon, 1956), in cases where they have limited resources to obtain information about neighboring cropland parcels within a certain range, lacking the knowledge of the condition for all parcels within the study area.

Following the flowchart of research design (Fig. 3), input data

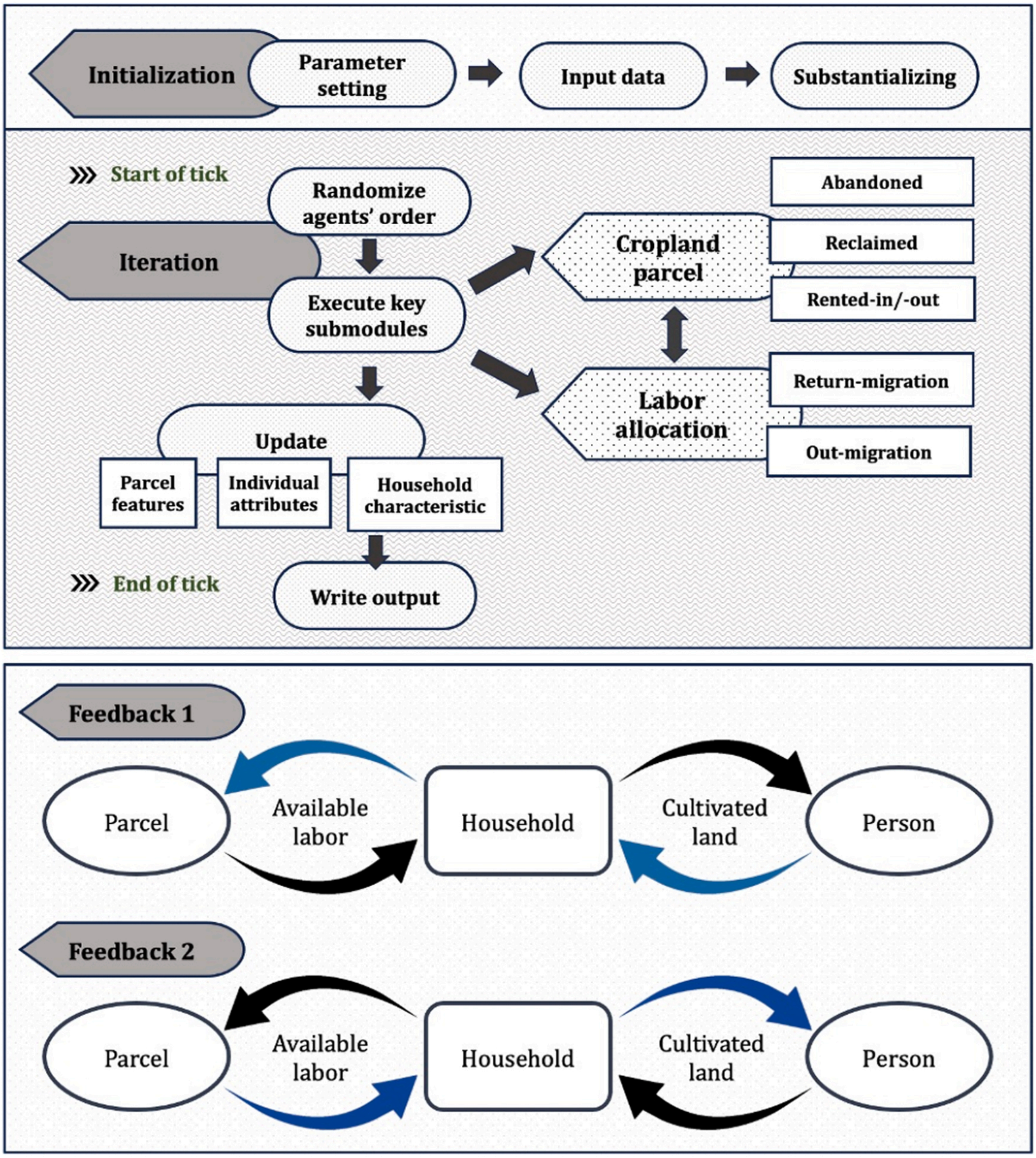

Fig. 3. Flowchart of model structure with highlight of feedback loops. Overview and processes of agent-based modeling for simulating cropland abandonment and hollowed villages due to rural out-migration (upper panel) and feedback loops between land parcels and people through household agents (lower panel). Two types of feedback are explicitly simulated: (1) The abandonment of cropland parcel(s) changes the total amount of cultivated land managed by a household and subsequently influences labor allocation decision on out-migration (direction of black arrows), which feedback to household available labor and eventually land-use decision on cropland abandonment (direction of blue arrows). (2) The out-migration process changes household demographic structure with labor available for land management (direction of black arrows), which feedback to household's total land area and eventually the allocation of labor required for land management versus out-migration. Such feedback mechanism occurs in each tick (time) step during the simulations, creating feedback loops throughout the entire simulation period.

included a list of individual agents and a list of cropland parcel agents. Household agents were initialized from the individual list by identifying the household heads and aggregating the individual-/parcel-level properties (e.g., household size, area of land under cultivation). The distributions of the initialized variables at all three levels (parcel, individual, and household) generally represent the actual distributions based on the sample data (Fig. S3, Fig. S4). Within the key submodules of the model, namely the migration and cropland submodules (Table S2), we defined a parameter representing the attachment to cropland (Liu et al., 2022; Xu et al., 2019) that can influence both return migration and land reclamation. This parameter indicates a general (complex) relationship between rural farmers and the land they manage, for which farmers fear losing the land use right known as tenure insecurity due to various factors (S. Liu et al., 2023). In each submodule and at each simulation year, a household makes land-use decisions based on the household size (i.e., number of household members currently staying at home being non-migrants) for the total area of land to cultivate. The household then determined whether to reclaim a parcel that had been abandoned in previous years for land cultivation. The household would share this information with the out-migrants from the same household, who also determined whether to return home in order to provide labor for land cultivation.

We designed experiments regarding the cases where farmers were attached to their land (Scenario 1, S1) or did not consider land as a valuable asset to keep them cultivated (Scenario 0, S0). In the former case, households tended to reclaim the abandoned parcels and meanwhile allocated more labor for farming in a way that out-migrants were more likely to return to help with agricultural activities. At the end of each year, each agent updated their time-varying attributes. For instance, all people who are students were added with one education year; households updated demographic information such as the number of members who have migration experience. We presented the emergent property of the land system by depicting the temporal trajectories of key indicators (e.g., migrants, area of abandoned cropland), as well as mapping the spatial patterns of cropland parcels (e.g., risk of cropland abandonment or reclamation) and patterns regarding household-level migration strategies (e.g., out-/return-migration of household members).

3. Experimental results

3.1. Cropland vs. homestead functions and generational differences

Compared to the baseline scenario, both study areas show higher numbers of existing households (i.e., less abandonment of homestead) and reduced cropland abandonment under the experimental scenario where out-migrants return if only one member remains in the household (Fig. 4). In XSC, the difference in abandoned cropland areas is relatively small and consistent over time, whereas in TTZ, the gap widens over time (Fig. 4, lower panel). Additionally, there are more out-migrants and return-migrants, along with a slight increase in cultivated cropland, under the experimental scenario (Fig. S5). These results reflect how farmers differentiate between the functions of cropland and homestead. Regarding generational differences, the age composition of return migrants shows a shift toward older generations (e.g., those born before 1980) under the scenario capturing generational differences (Fig. 5). Over time, return migrants tend to be 1–6 years older in the experimental scenario in most years, as indicated by model simulations. The following interpretations are based on models simulating both land functions and generational differences within the land-use and migration submodules.

3.2. Cropland and demographic trajectories with and without land attachment

Model simulations reveal generally consistent trajectories of household and land statuses in both study areas (Fig. 6). While the number of existing households and the total area of cultivated cropland show declining trends, the number of individuals with migration experience (i.e., those who migrated at any point before the current time) first increases and then declines. Comparing the scenario with land attachment (S1) to the one without (S0), there are slightly more existing households under S1. This difference becomes evident after a few years in XSC, whereas it emerges in the last six years in TTZ. The differences in cultivated cropland between the two scenarios are more pronounced in both study areas. More cropland remains under cultivation when land attachment is considered. In TTZ, this difference increases over time, indicating the cumulative effects of feedback loops between labor migration and land use.

3.3. Land use and labor migration decisions with feedback loops through time

To better understand the feedback effects on land use and labor migration, we analyzed the annual numbers of out- and return-migrants and the total areas of abandoned and reclaimed cropland (Fig. 7). These process indicators, reflecting decision-making at each simulation tick, exhibit nonlinear trajectories over time due to the feedback loops

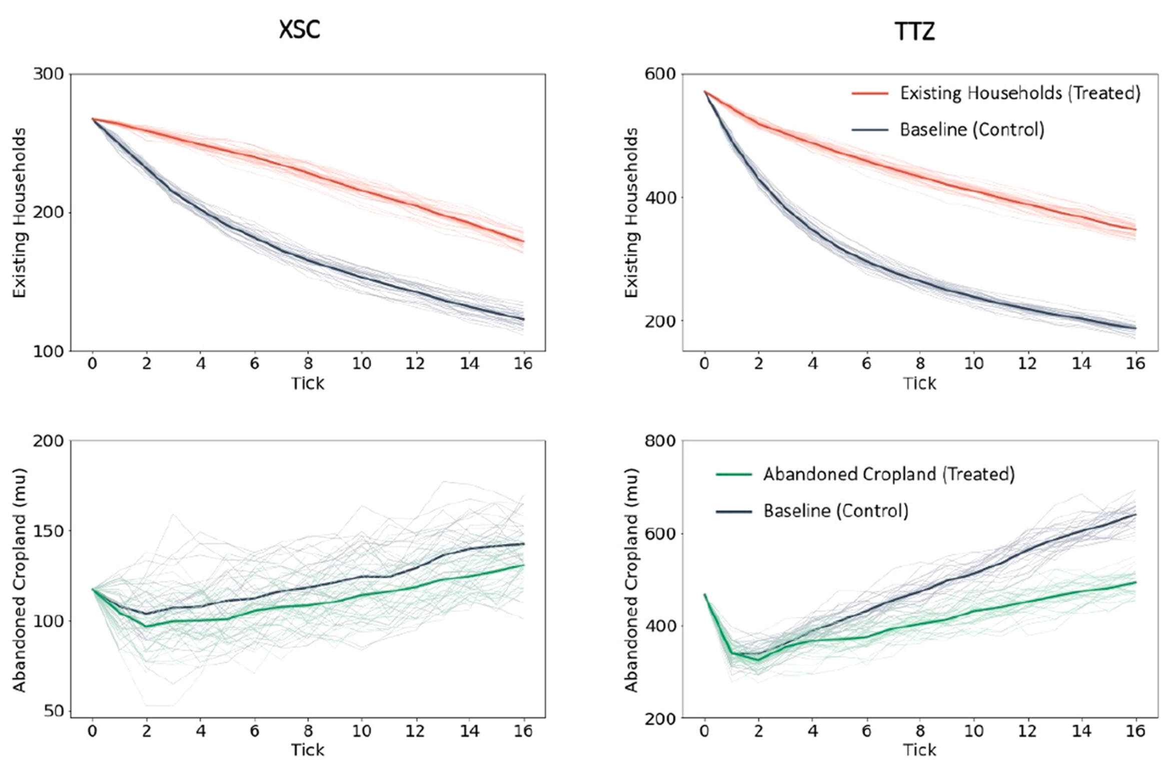

Fig. 4. Comparisons of existing homesteads of households and abandonment of cropland between treated (forced return-migration) and control (no forced return-migration) scenarios. In the treated scenario, a current out-migrant would be forced to return if there was only household member in the household in order to keep the homestead not abandoned. In the control scenario, there was no restriction from the homestead in the original place, so the household would be gone if no one return or all members moved out. The model in each scenario was run for 30 times and the mean outcomes were summarized.

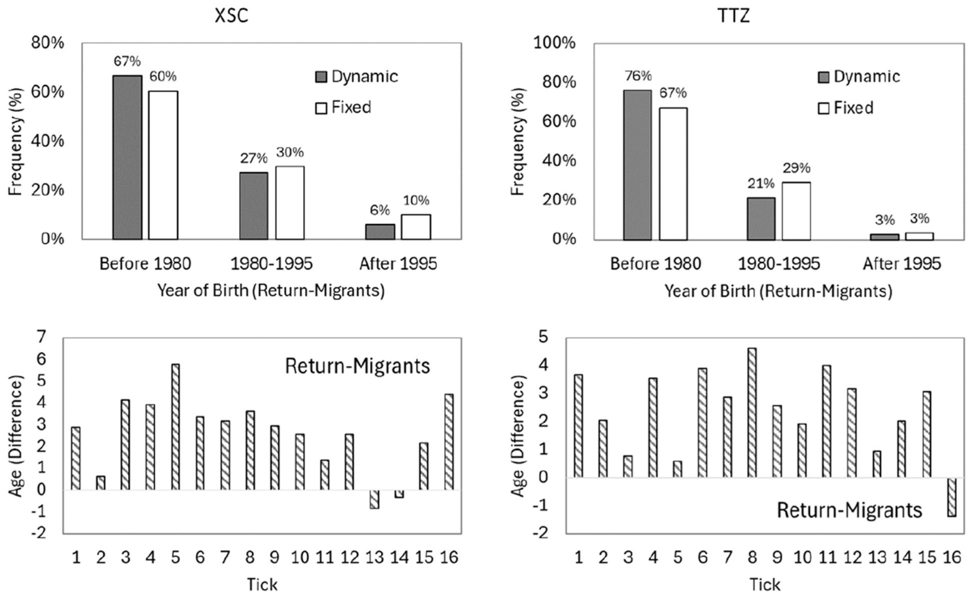

Fig. 5. Comparison of age compositions (upper panel) and differences (lower panel) for return-migrants between scenarios of dynamic and fixed levels of land attachment. In the dynamic-attachment scenario, the level of land attachment varies across generations who were born before 1980, between 1980 and 1995, and after 1995. In the fixed-attachment scenario, the level of land attachment is assumed to be uniform across all generations with different ages, corresponding to the one where the parameter was set to be 1 for all age groups.

between migration behavior and cropland use. In both study areas, out-migration and return-migration trends increase initially and then decline after 4–9 years. Overall, the number of out-migrants and return-migrants is slightly higher under S1 (with land attachment) than under S0, although this difference reverses in TTZ for the first 2–3 years.

The trends for cropland abandonment and reclamation vary between the two study areas. In XSC, cropland abandonment follows a periodic trend, with less abandonment under S1 in the first eleven years but more in the following years. This may be linked to the feedback from the slightly greater out-migration under S1—meanwhile, land reclamation under S1 peaks during the first three years and the last six years. In TTZ, cropland abandonment trends fluctuate less than in XSC, but reclamation trends show significant differences. Under S1, reclamation decreases initially before stabilization, whereas under S0, it shows a slight increase followed by a small decline. Although S1 consistently shows more reclaimed land than S0, the difference narrows over time, potentially due to return migration and the decreasing availability of abandoned land for reclamation.

To further explore the interaction between land use and migration, we analyzed the ratio of abandoned (or reclaimed) cropland to the number of out-(return-) migrants across the two scenarios. The ratio of reclaimed land to return-migrants is generally higher with land attachment. In contrast, the abandonment to out-migration ratio shows small differences (Fig. 8). Over time, the ratio of reclaimed land to return-migrants decreases as abandoned cropland becomes scarcer but gradually rises again due to out-migration-induced abandonment. In contrast, the abandonment to out-migration ratio shows periodic trends, reflecting the relatively stable relationship between these two variables. These results suggest that return migration and associated land reclamation play a critical role in shaping the social-ecological dynamics, as shown by the reflective indicators (Fig. 6 and Fig. 7).

3.4. Spatial patterns of labor migration and cropland abandonment over space

Using the geolocations of households and cropland parcels, we generated spatial maps to visualize land-use and household demographic patterns, comparing scenarios with and without land attachment. At the parcel level, we calculated the risk of cropland abandonment or reclamation by determining the percentage of abandonment or reclamation decisions across 30 parallel model simulations. Migration behavior, however, is modeled at the individual level without spatial attributes, so we aggregated migration data to reflect labor allocation for each geolocated household. Based on the risk maps, we generated heatmaps that are more useful to identify hotspots and hence more informative for policy suggestions (e.g., land targeting for rural revitalization). The hotspots indicate places where the risk is much higher with land attachment (S1) than that without land attachment (S0).

The spatial maps comparing land use and labor allocation between the two scenarios reveal both similarities and differences (Fig. 9, Fig. S6). In XSC, hotspots of cropland abandonment are concentrated around larger patches in the central and eastern parts of the study area (upper left panel). Hotspots of cropland reclamation, however, are more dispersed, appearing in northern and western areas (lower left panel). Migration patterns show similar clustering for out-migration and return-migration, aligning with the observed land-use trends. In TTZ, the spatial patterns are more pronounced. Cropland abandonment hotspots are dispersed away from the center, while cropland reclamation hotspots dominate in remote areas (upper and lower right panels). Out-migration is more clustered in central TTZ, while return-migration extends into more remote areas. These patterns indicate that while out-migration and cropland abandonment persist, return migration and cropland reclamation are pivotal in counteracting rural hollowing processes.

4. Discussion

Depopulation in rural areas and the abandonment of cropland are widespread issues impacting social development and food security (Johnson and Lichter, 2019; Li et al., 2018; Rodríguez-Soler et al., 2020). These phenomena are often driven by land-use change and labor migration linked to broader socio-economic processes of urbanization (Abramson, 2016; Chen et al., 2014; Gao et al., 2017). In China, urban areas have experienced economic growth and population inflow, while remote, mountainous regions face rural hollowing (Long et al., 2012; Zhang et al., 2014). Research into the formation and evolution of hollow villages is crucial to better manage land resources and improve

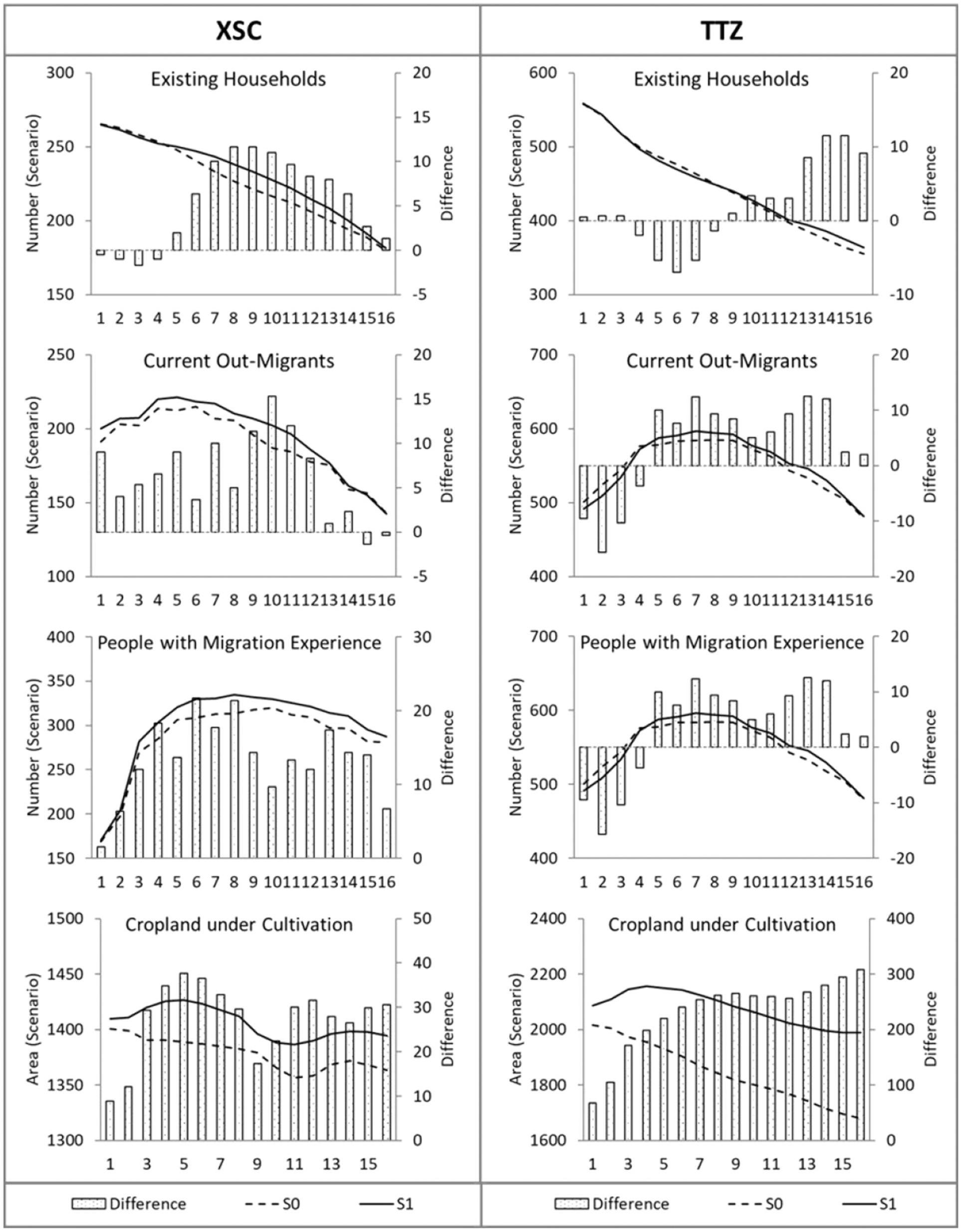

Fig. 6. Trajectories of simulated outcomes: Statuses of demographic and land information through time.

household livelihoods.

4.1. Social-ecological dynamics within land systems

This study provides a novel approach to explore rural hollowing by leveraging an agent-based complex systems (ACS) framework, focusing on labor migration and land-use decisions (Hicks et al., 2016). Decision-making at the household and individual levels is crucial for shaping the social-ecological dynamics of rural land systems. Here, we applied a spatially explicit agent-based model to simulate feedback loops between labor migration and land-use change, two processes central to the emergence (or prevention) of hollow villages. We specifically tested how land attachment influences these feedback loops and the nonlinearity of labor out-/return-migration and cropland abandonment/reclamation. Our study areas, sharing similarities and differences in socio-economic and biophysical conditions, offers generalizable insights.

A key finding pertains to the role of varying migration behaviors and household decisions in cropland use in contributing to the non-linear, sometimes "unexpected," responses in the rural hollowing process (Table S3). Traditional approaches may assume that strong land attachment results in less out-migration to retain cropland (Bradfield et al., 2023; Liu et al., 2022). However, our results suggest that out-migration and cropland abandonment persist despite strong land attachment (Fig. 7). Return-migration, in contrast, stimulates cropland reclamation (Zhang et al., 2023). Under high land attachment scenarios, the trend of cropland reclamation following return-migration is even more pronounced than rural hollowing or abandonment, driven by the growing number of return migrants (Fig. 6). This creates a dynamic where previous out-migration (including return-migrants with migration experiences) reduces the costs for other household members to migrate (Lu et al., 2022; Massey, 1990), while return migrants provide farm labor to reclaim land, offsetting labor loss due to migration (Zheng et al., 2023). The feedback effects between labor migration and land-use decision lead to higher rates of cropland reclamation relative to return migration, particularly in the early years of the process (Fig. 8).

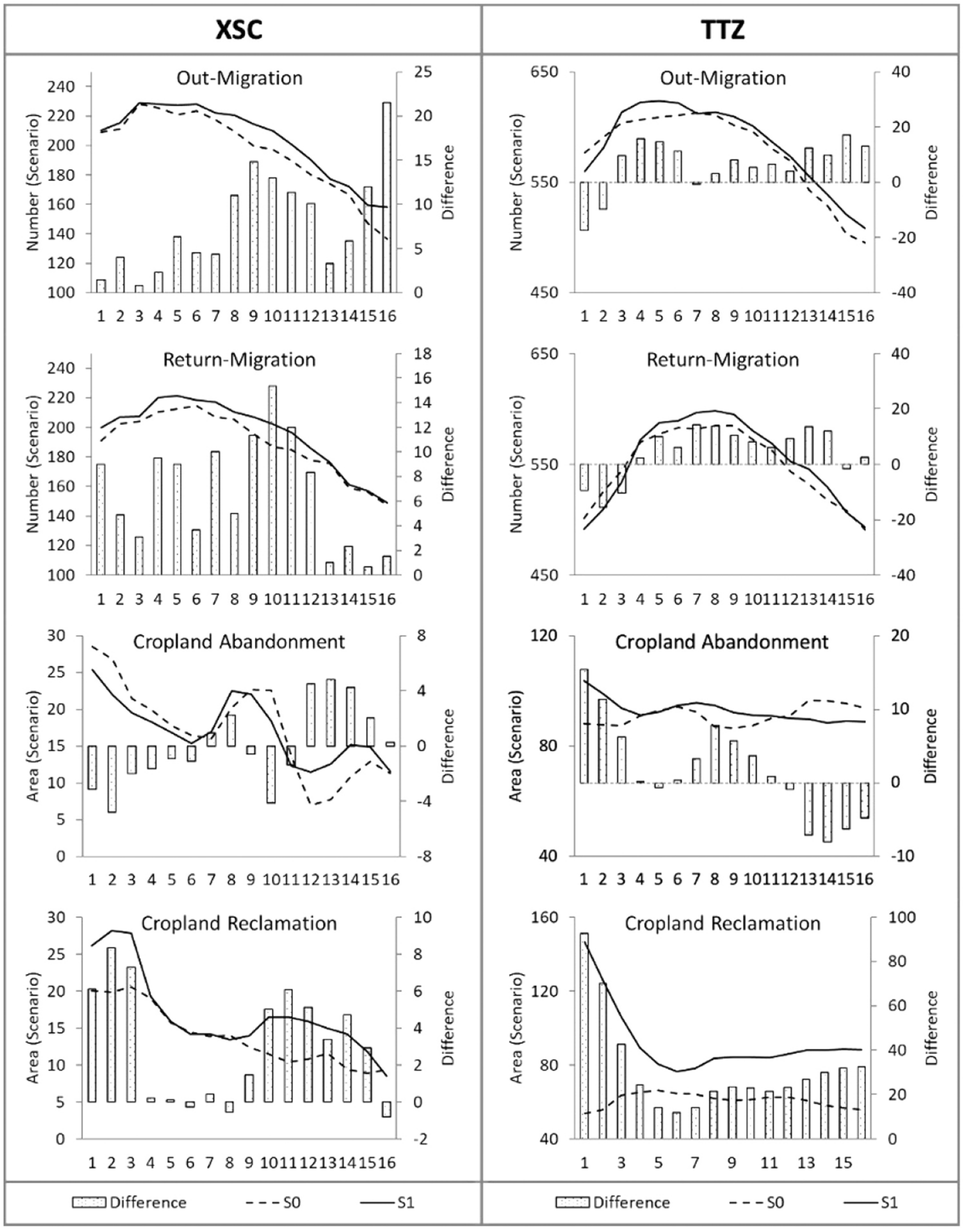

Fig. 7. Trajectories of simulated process-based outcomes for individual out-migration, return-migration, cropland abandonment, and cropland reclamation.

Ultimately, return-migration and land reclamation bolster cropland preservation and household livelihoods (Dustmann and Weiss, 2007; Mohabir et al., 2017; Ní Laoire, 2007).

4.2. Rural hollowing as emergence of feedback loops

The maps of land use and household migration reveal spatial patterns that identify areas at high risk for cropland and homestead abandonment. In our study areas, the spatial relationships between households and land parcels differ, with XSC following a valley pattern while TTZ's parcels are more dispersed. These spatial differences may explain the observed divergent social-ecological trajectories. In both areas, strong land attachment correlates with greater return-migration and cropland reclamation, which spatially cluster, mitigating the rural hollowing process (Fig. 9). While out-migration and cropland abandonment are often driven by exogenous factors like economic disparities between rural areas and distant cities (Wen et al., 2023), return-migration and land reclamation highlight the importance of endogenous feedback mechanisms within rural areas (Ji et al., 2017).

Cropland and homesteads are closely linked assets in human-environment interactions (Fig. 9). Studies of rural hollowing must adopt a holistic perspective, considering these assets collectively to understand system-level processes (Zhang et al., 2023). Our approach situates rural hollowing within a complex system framework where interactions between human agents and land parcels at the local level can lead to emergent properties at the system level. These emergent characteristics, such as nonlinearity, are critical for capturing and predicting the land-use patterns that drive rural hollowing.

4.3. Scope, limitation and future direction

Our model does not explicitly account for neighborhood effects on land-use and migration decisions (Chen et al., 2009; Lan and Liu, 2019; Xia et al., 2020), particularly at the household level, where migration decisions are central (Gray and Bilsborrow, 2014). Social networks may reduce migration costs through shared information among neighboring households (Isaac and Matous, 2017; Xia et al., 2020). Although we modeled how migration experiences within a household influence

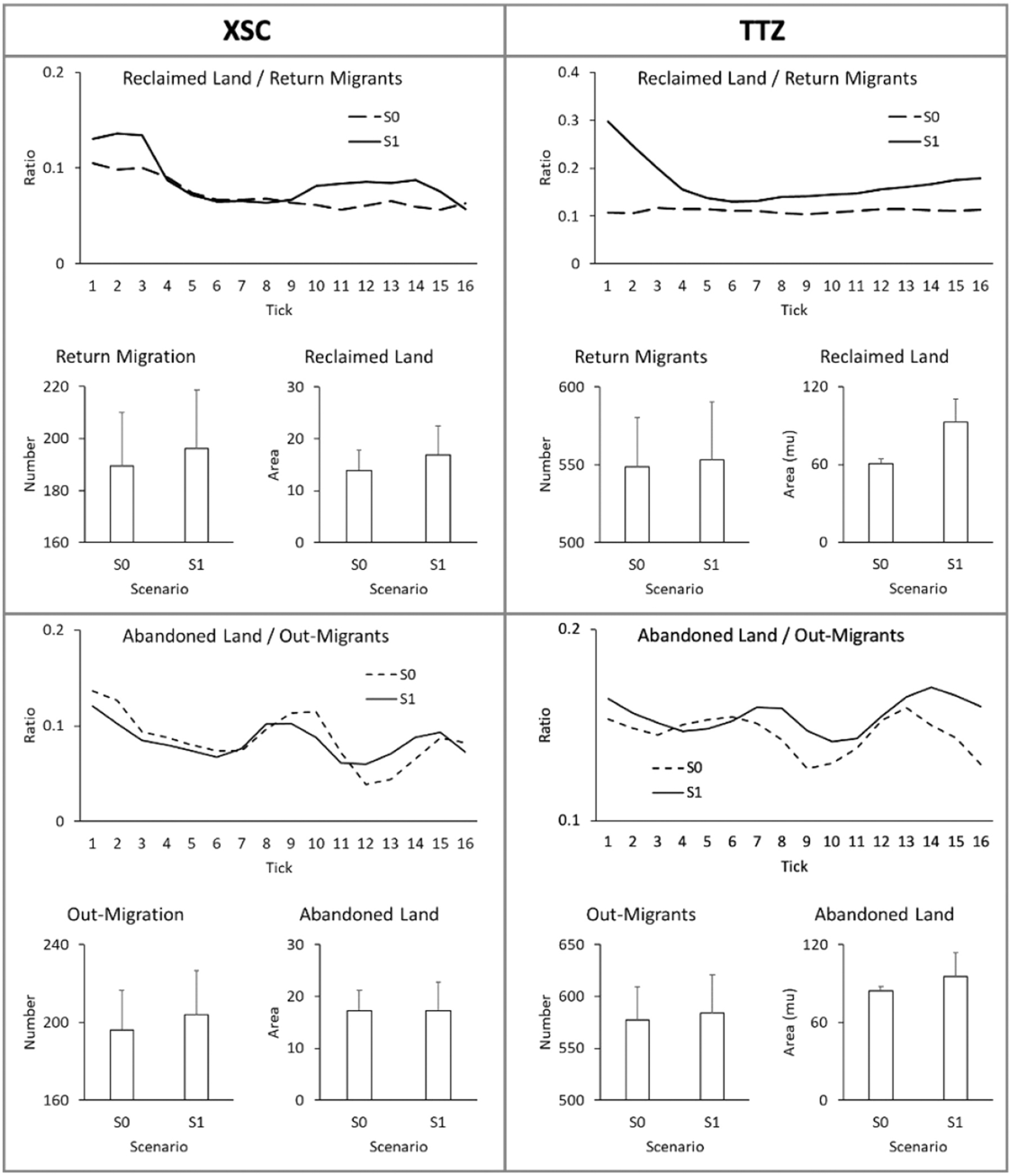

Fig. 8. Feedback loops between migration behaviors and land-use changes reflected by simulated outcomes. Ratios of reclaimed cropland area to number of return-migrants (upper panel) and ratios of abandoned cropland area to number of out-migrants (lower panel).

out-migration decisions, we did not account for neighborhood effects on return-migration (Dustmann and Weiss, 2007; Mohabir et al., 2017). Additionally, the model's land-use submodule simplifies labor inputs, excluding distinctions between intensified agricultural activities and non-agricultural work undertaken by return migrants. Labor migration is a complex socio-economic process (Giefer and An, 2022; Tian et al., 2016), driven by factors like agricultural and non-agricultural labor markets, inputs, and outputs, as well as diverse livelihood strategies, which are beyond the scope of this study. External shocks, such as the COVID-19 pandemic, also affect migration trends, as seen in differences between our study areas where surveys were conducted before and after the pandemic (Fig. S7). Another source of uncertainty arises from the stochastic spatial linking of households and cropland parcels at the model's initialization stage, which can influence migration and land-use outcomes. Future research should address these limitations by revisiting surveyed households to obtain more detailed data on neighboring households' migration and land-use strategies, household relocations, and the connections between households and their cropland parcels. Additionally, incorporating the dynamics of homestead demolition and new house construction could further enhance our understanding of rural hollowing processes.

5. Conclusion and policy implications

Rural hollowing, characterized by depopulation and land abandonment, can lead to negative consequences, such as inefficient land use and hindered rural development. Our study applied an agent-based complex systems framework to model the bidirectional relationships between

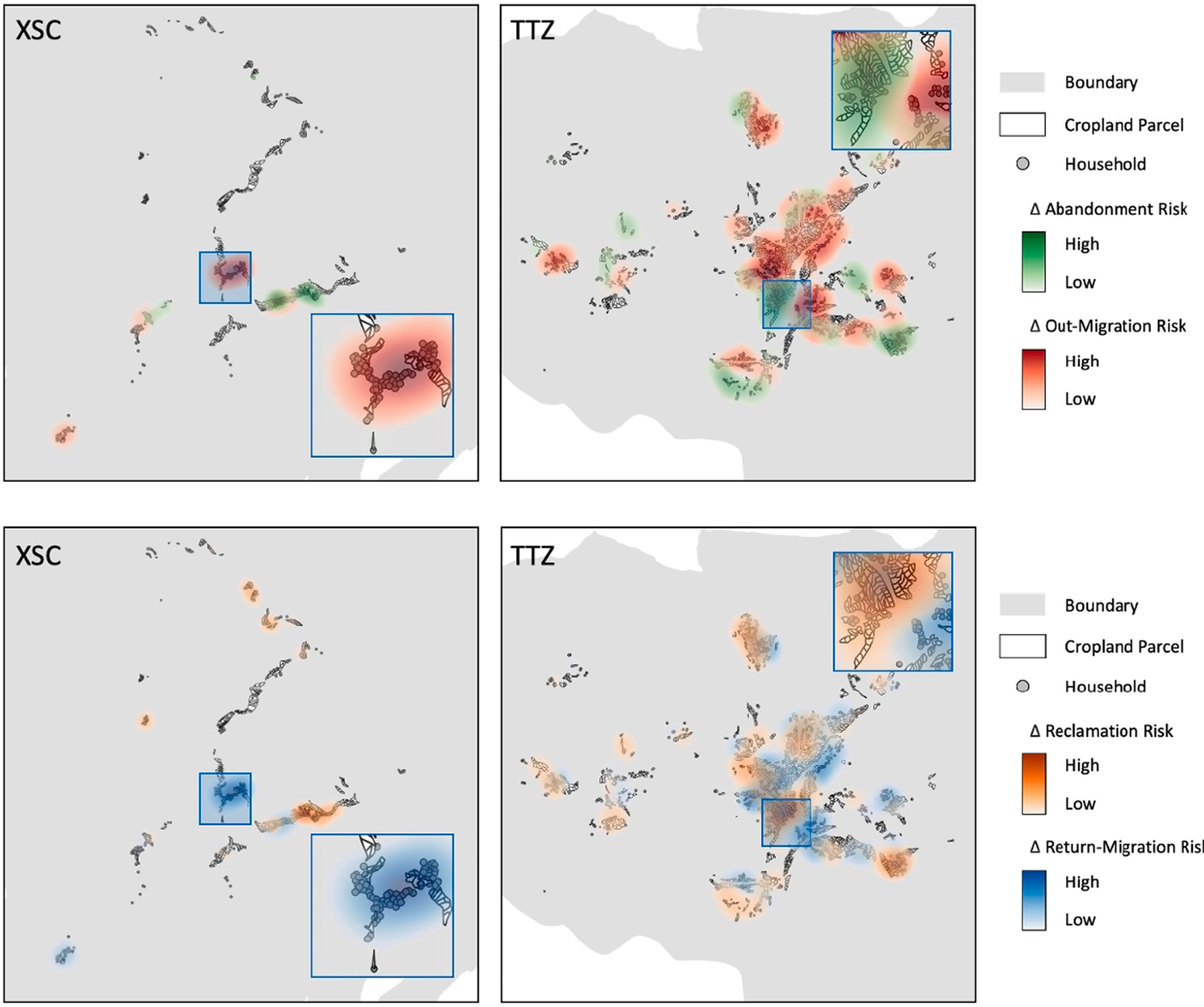

Fig. 9. Heatmaps of risk of cropland abandonment and labor out-migration (upper panel) and land reclamation and return-migration (lower panel) regarding the difference between scenarios with and without land attachment. The density function uses the difference of risks based on model simulations as the weight for heatmap generation.

Fig. 10. Abandonment of residential houses and cropland parcels. Photo (A): Hollowed village with abandoned residential land in Xiuning & She Counties (XSC). Photo (B): Abandoned paddy rice land parcels in Tiantangzhai Township (TTZ).

labor migration and cropland use, shedding light on the evolution and formation of hollow villages. The findings indicate that while out-migration and cropland abandonment are prevalent, return migration and cropland reclamation play a critical role in preventing rural hollowing. Households with strong attachment to their land are more likely to receive return migrants, who help preserve cultivated land through reclamation, thereby mitigating the hollowing process. The agent-based modeling approach proved effective in capturing emergent patterns, as it accounts for nonlinearity, reciprocal feedback, and regional divergence under different scenarios and socio-economic and biophysical contexts. These insights suggest several policy implications for land consolidation and rural revitalization. To prevent rural hollowing, policymakers should consider the rural system as a coupled human-natural system where population dynamics and land use are intricately linked. Out-migration, often associated with cropland abandonment, can facilitate the abandonment of residential homesteads. However, return migration offers opportunities for better land management and rural livelihood improvement. Policy initiatives should aim to integrate return-migration support into cropland preservation strategies to enhance food security and livelihood sustainability. Addressing and eliminating the negative feedback loop between cropland abandonment and labor loss due to out-migration can decelerate or even halt the rural hollowing process, leading to improved land-use efficiency and more sustainable rural development.

CRediT authorship contribution statement

Qi Zhang: Writing – original draft, Validation, Software, Methodology, Conceptualization. **Jing Hu:** Writing – review & editing, Visualization. **Chun Dai:** Writing – review & editing, Data curation. **Cai Jin:** Writing – original draft, Formal analysis, Data curation. **Jing Cao:** Formal analysis, Data curation. **Conghe Song:** Writing – review & editing, Supervision. **Richard E. Bilsborrow:** Writing – review & editing, Investigation. **Tan Li:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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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.landusepol.2024.107441.

Data availability

Data will be made available on request.

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