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RESEARCH ARTICLE

Agent-based modeling of the effects of conservation policies on social-ecological feedbacks between cropland abandonment and labor migration

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Abstract
Context Payments for Ecosystem Services (PES) has increasingly been used in ecological conservation efforts through implementing forest policies worldwide. However, outcomes of forest policies with PES are often mixed due to the complex social-ecological dynamics.
Objectives In this study, we develop a spatially explicit agent-based model for cropland abandonment and labor migration (ABM-CALM) based on data from very high-resolution satellite images, the global positioning system, household surveys, and a population census.
Methods The ABM-CALM is used to simulate bidirectional social-ecological feedbacks within a coupled human and natural system under two large PES programs in China.
Results The simulation results show that labor migration and cropland abandonment follow nonlinear trajectories with feedback loops mediated by household capital endowment. Households tend to reduce labor allocation for migration to retain essential croplands after abandonment of marginal ones. For the reforestation program, participating households are more resilient in maintaining migration than non-participants. The model reveals the feedback mechanisms between the two concurrent PES programs through synergistic and offsetting interactions. Specifically, labor migration under higher payments of one program is more sensitive to payments of the other due to the feedback of additional cropland abandonment induced by the former program.
Conclusions Using the real-world landscape and in-situ socio-economic settings, the integrated model

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captures the dynamics of the social-ecological systems affected by PES across space and time.

Keywords Agent-based modeling · Coupled human and natural systems · Ecological restoration · Forest conservation · Labor migration · Land use change

Introduction

Human interactions with the ecological environment are intricate (Grimm et al. 2005; An 2012; Walsh and Mena 2016). Worldwide, most human activities have negative impacts on the ecosystems, causing adverse environmental change and biodiversity loss (Cook et al. 2016; Tilman et al. 2017). As the "native or pure" natural landscape is disappearing and becoming more human-dominated (Foley et al. 2005; Sannigrahi et al. 2021), efforts have been made globally to tackle challenges emerging from human-environment interactions. The United Nations (UN) identified 17 Sustainable Development Goals (SDGs), such as eradicating poverty (#1), achieving zero hunger (#2), and sustaining life on land (#15), to be achieved by 2030 (United Nations 2019). Under the UN Framework Convention on Climate Change, the objective of climate change mitigation was defined through a reduction in emissions from deforestation and forest degradation (REDD+) projects (UNFCCC 2010).

Payments for Ecosystem Services (PES) has gained a reputation worldwide for helping achieve some of the SDGs through simultaneous conservation of ecosystems and improvement of human livelihoods (Wunder et al. 2018). PES is often embedded in ecological conservation or restoration projects (Rodríguez-Ortega et al. 2018; Ding and Yao 2021), intending to incentivize environmental investments through market-based transactions from beneficiaries to land stewards (Milder et al. 2010; Long et al. 2020). A number of projects, such as REDD + that incorporate PES (Mahanty et al. 2013), have been initiated and implemented with great speed in developing countries that have the most ecologically sensitive lands. Since the late 1990s, China has led the effort of greening the Earth's terrestrial surface (Zhang et al. 2017a) through implementing a series of PES forest projects nationwide (Zhang et al. 2000). Two of the largest programs are the Conversion of Cropland to Forest Program (CCFP) and the Ecological Welfare Forest Program (EWFP). In a large part of China, the CCFP incentivizes farmers to reforest their cropland parcels on steep slopes that are prone to soil erosion (or in some cases return pastureland to grassland) by compensating the farmers the amount of grain they otherwise would harvest from the cropland. Thus, the CCFP is also known as the Sloping Land Conversion Program, the "Grain-to-Green" Program, or the "Grain-for-Green" Program. The payment rate is different between the Yangtze River Basin and the Yellow River Basin, considering the different opportunity costs in these two regions (Song et al. 2014). During the last two decades, the Chinese central government has invested over 500 billion yuan, or ~US$72.9 billion, on the CCFP (State Forestry Administration 2020a). The EWFP is a policy instrument for preserving natural forests by subsidizing rural households that own natural forests to restrict the harvesting of forest resources such as timber (Dai et al. 2009). The payment rate of the EWFP is comparatively lower, but the total annual amount received by the participating households can be higher than the CCFP due to the much larger forest areas managed. Reports show that the total area of natural forests under the EWFP has increased by 20 million ha in China since 1998 (State Forestry Administration 2020b).

A fundamental question asked by scholars and policymakers is to what extent the social-ecological benefits of these PES forest policies are sustainable. The longer-term success depends largely on behavioral change of participants and non-participants in adaptation to the conservation strategies (Jack et al. 2008; Zhang et al. 2017b). Some studies show that CCFP can potentially stimulate off-farm employment and increased income for participants by relaxing the liquidity constraints and facilitating labor transfer (Lin and Yao 2014), but the evidence of labor transfer is weak (Trac et al. 2013). Meanwhile, the EWFP was found to induce additional abandonment of agricultural land by farm households, as conserved forests may incur crop-raiding by wildlife as a negative feedback (Chen et al. 2019). From the institutional side, there exists synergistic or offsetting effects of the two programs when they are simultaneously implemented, known as concurrent payments for environmental services (Yost et al. 2020) or more broadly concurrent green initiatives (An et al. 2022). A synergy of studies from all over the world suggest that there exist non-trivial hidden linkages between concurrent conservation efforts under different policies, which may either bring additional benefits or incur undesirable losses or costs (An et al. 2022). The inconsistency of these program outcomes calls for a more sophisticated modeling approach capable of incorporating the endogenous feedbacks between humans and the natural components embedded in the local land system.

The social-ecological dynamics under the impacts of the PES programs are well embedded in coupled human and natural systems (CHANS) (Liu et al. 2007; Kramer et al. 2017; An et al. 2020; Chen et al. 2020). Thus, the theory of complex adaptive systems can be used to guide the investigation of the dynamics of CHANS that are shaped by human-environment interactions. Such interactions operate across multiple levels (Alberti et al. 2011; An et al. 2021) and are characterized by feedback loops, resilience, and heterogeneity (Pickett et al. 2005). Agent-Based Models (ABMs) are particularly versatile in modeling complex land systems (Malanson and Walsh 2015) where landholders follow a set of rules to interact with other social agents and the environment as well as to adapt to social and ecological dynamics of the CHANS (Walsh et al. 2013). ABMs have advantages in testing alternative policy scenarios and informing policymakers to adapt future programs to specific contexts (Wang et al. 2013). Thus, ABMs have been increasingly applied in PES research to understand the policy effects (Sun and Müller 2013; Miyasaka et al. 2017; Baulenas et al. 2021). Land use decision-making is a complex process that involves human-environment interactions within multiple spatiotemporal scales that may not be effectively described by conventional statistical models, but are well captured by ABMs (Baulenas et al. 2021). The application of ABMs in land systems incorporates a wide range of social factors to explain human behaviors and the resultant social-ecological outcomes (Groeneveld et al. 2017). However, such models are often data demanding particularly when driven by real-world problems. Sun and Müller (2013) integrated an ABM with Bayesian belief networks and opinion dynamic models to study the land use change under the influence of both social networks and reforestation policies in Yunnan, China. Their integrated framework provides a flexible and generic platform for simulating agents' behavior in response to socio-environmental changes. Walsh et al. (2013) developed an ABM focusing on human-environment linkage in agricultural areas within rural villages in Northeastern Thailand and highlighted the advantages of the ABM in uncovering pattern-process relations between household wealth and agricultural production. Their research revealed that ABMs of land use models incorporate the social components into the representation of ecological landscape dynamics.

The effects of CCFP and EWFP can be modified by the complexity of the land system. The two PES programs target populations in rural, mountainous areas, with dual goals of soil and water conservation and poverty alleviation (Zhang and Putzel 2016). Land dynamics and livelihood changes are two processes essential for understanding how humans respond to the PES programs and adapt to the changing environment. Through the lens of environment-migration nexus (Bilsborrow and Henry 2012), households that send out migrants have insufficient labor for farm work and hence abandon some croplands, which may further stimulate labor migration. However, households that enroll cropland for reforestation may intensify cultivation on the remaining cropland (Liu and Lan 2018), demotivating farmers to engage in other economic activities including migration. Despite these complexities, studies have rarely explicitly modeled the bidirectional feedbacks between cropland changes and demographic processes under the two PES programs. Without considering the complex human-environment interactions (Verstraeten 2014; Yurui et al. 2019; Rositano et al. 2022), environmental conservation policies may not fully achieve their intended goals.

To advance the understanding of the CHANS dynamics, we develop a spatially explicit agent-based model for cropland abandonment and labor migration (ABM-CALM) to explore the causes, effects, and feedbacks between land use changes and demographic dynamics under the two PES programs, i.e., CCFP and EWFP. The model explicitly incorporates multilevel feedback mechanisms, within which the interaction between individual-level migration and parcel-level land-use change is mediated by household-level characteristics. Relying on real-world data, the study area for model simulation encompasses the entire township that is relatively remote from more developed areas (e.g., major cities). The major link from the remote rural area with the outside world is labor out-migration, bringing in remittances that pay living expenses, health care, education, and house construction, while the major agriculture output is crops. Therefore, labor out-migration and cropland use represent the primary human-environment interactions. ABM-CALM is developed to capture these major interactions with object-oriented programing based on data from very high-resolution remote sensing, comprehensive household surveys, the global positioning system, and a population census dataset that are integrated into geographic information systems (GIS). The model is validated and applied to test human-environment interactions under various policy scenarios that would otherwise not be practical to explore. Such scenario analysis is crucial for predicting the PES sustainability and gaining insights on the consequences of human-environment interactions for conservation policy making.

Methods

Study site

The study site, Tiantangzhai Township, is located in western Anhui Province in eastern China, belonging to the Dabie Mountain Range (Fig. 1) with abundant natural forests. Rough terrain characterizes the major topography with elevations ranging from 363 to 1729 m above mean sea level (Zhang et al. 2020). Tiantangzhai has a relatively low population density. Rural households are naturally organized into 167 resident groups in the township based on their geographic proximity, and resident groups are further grouped into seven administrative villages. A resident group usually comprises 10 to 40 households that farm collectively on large cropland tracts before the Household Responsibility System (HRS) in the 1980s. After the implementation of the HRS, the large cropland tracts were divided into small parcels and allocated to individual households (Li et al. 1998). Thus, each household independently manages several cropland parcels, usually with varying degrees of quality.

The lands, along with the residents, in Tiantangzhai make up a CHANS with interactions between the population and the lands that are typical of the vast underdeveloped rural areas in China. Most households' livelihoods are closely tied to croplands and forests, such as growing crops for food and collecting firewood as fuel for cooking and heating (Song et al. 2018). Due to the underdeveloped mountainous environments with limited sources of income, it is difficult for farmers to make ends meet via farming only. To generate more income, most households are engaged in non-agricultural activities (Zhang et al. 2019). Due to limited nonfarm job opportunities in Tiantangzhai as a small township, residents commonly migrate to cities to seek jobs. Subsequently,

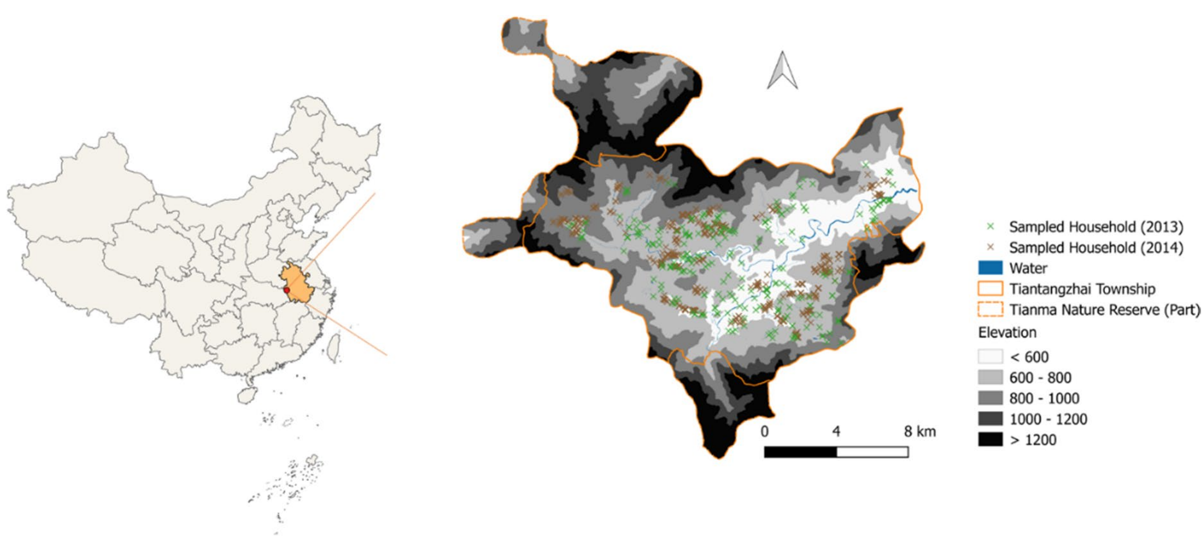

Fig. 1 Study site: Tiantangzhai Township as part of Tianma Nature Reserve in western Anhui, China

they tend to abandon cropland in marginal areas, retaining only those in higher quality sites for food supply. Compared with previous studies that focus on a single village within an administrative district (e.g., Walsh et al. 2013), the selection of the entire township as the system under investigation accounts for the potential interactions among the neighboring villages (i.e., land use change and migration dynamics). For example, individual migration within a single village can be substantially influenced by frequent information exchanges with people in neighboring villages. In our study site, a major type of interaction among the neighboring villages is residents can rent cropland from residents within the village or in neighboring villages, affecting their labor allocation.

Both CCFP and EWFP were implemented in Tiantangzhai. About 17% of rural households participate in the CCFP by converting their eligible croplands to forests. The CCFP payment rate in this area is 250 Yuan/mu/year (1 mu = 1/15 ha, 1USD = 8.2 Chinese Yuan in 2002) at the initial eight-year enrollment in 2002 and 125 Yuan/mu/year for the additional eight-year renewal. The total enrollment duration is 16 years starting from 2002 when the program began. Meanwhile, almost every household manages some area of natural forests in the township, qualifying for enrollment into the EWFP. The payment rate for the EWFP was 8.25 Yuan/mu/year at the time of the household survey in 2014. Tiantangzhai belonged to a nationally recognized county in poverty in China before 2020, so rural households are more sensitive to the PES programs than those in more affluent regions. In line with the goal of poverty alleviation, CCFP and EWFP make it possible for rural households to reshape their labor allocation, potentially assisting them to move toward sustainable livelihood options. Such behavioral changes may directly and indirectly influence their land use decisions. As the central government modified the payment scheme for CCFP and EWFP (State Forestry Administration 2015), the future of environmental conservation and local people's well-being in Tiantangzhai remains uncertain and worthy of study.

Social survey and fieldwork

We conducted household surveys to collect socioeconomic, demographic, environmental, and PES participation data in Tiantangzhai during June–August in 2012, 2013 and 2014. In 2012, we acquired demographic data (e.g., gender, birth year, marital status, and the relationship to the household head) for the entire township population. In 2013 and 2014, we conducted two household surveys and interviewed 250 and 481 households, respectively, including both CCFP-participating households and non-participating households. We recruited graduate students and trained them as interviewers for 2 weeks. For each selected household, we interviewed the household head or the person (aged 18+) who oversaw the daily business, if the head was not available. All the locations of the interviewed households were geo-located with a handheld Global Positioning System unit. The 2013 household survey was followed by fieldwork where we geo-located 1206 cropland parcels that the 250 surveyed households managed and recorded its history of uses. Other ancillary data used for model initialization include death, marriage and birth rates in rural Anhui derived from 2010 China Census and China Statistical Yearbook. These datasets serve as the basis for defining and substantiating social agents in the model.

Generation of land cover and land use map

Satellite remote sensing offers useful tool for mapping land (Liu et al. 2020; Maiti et al. 2022). The land use and land cover map at the parcel level of Tiantangzhai is the major spatially explicit input to our ABM. The map was classified based on a WorldView-2 (WV-2) satellite image captured on 7/13/2013. We first defined a seven-class scheme, including residential area (house), other built-up land (e.g., road), water, forest, cropland, grass, and bare land. We collected 500 random training samples for each class and extracted 11 features for the selected training samples, including six spectral bands (blue, green, yellow, red, near-infrared 1, and near-infrared 2), two spectral indices of normalized difference vegetation index (NDVI) (Tucker 1979) and normalized difference water index (NDWI) (Gao 1996), and three topographic indices (i.e., aspect, elevation, and slope) derived from a Digital Elevation Model (DEM). We used the Random Forest machine learning algorithm (Breiman 2001) to classify the WV-2 image. Major land-cover classes of interest are residential area (houses), forest, and cropland. With the topographic map showing CCFP locations and the assistance from staff at the local forestry station and residents, we delineated all CCFP forest stands cropland parcels and divided cropland by paddyland, dryland and abandoned land parcels. This classification resulted in 1105 parcels forming CCFP stands (i.e., CCFP parcels) and 12,236 cropland parcels. All the other forests were considered as natural forests (i.e., EWFP forests) that were designated by the local forestry station (Fig. S1). Accuracy of the classified map was assessed through comparison with Google Earth and interviews with the resident group leaders. The overall accuracy of the classification was 95% for the main classes. The raster map was then converted to a vector coverage. Household location points were distributed on resident areas, and land parcel centroids were derived to reduce computational complexity (Rindfuss et al. 2004). By overlaying the vector data of parcel locations with land cover and topographic maps, we derived biophysical and geographical conditions such as slopes and the nearest distances to forest for each land parcel.

Development of ABM-CALM

ABM-CALM simulates causes, effects, and feedbacks between land use change and demographic dynamics (Fig. 2). Under the CHANS framework, the model is characterized by key design concepts (Supplementary Material) that are essential to achieve the stated goal. Feedback loops featuring bidirectional relationships operate within the land system through social-ecological dynamics across multiple scales. Specifically, three types of agents (individual persons, farm households, and cropland parcels) are involved in the interactions between cropland abandonment at the parcel level and labor migration at the individual level as mediated by conditions at the household level. The environment consists mainly of cropland and forests. Two intertwined feedback directions are simulated based on previous studies (Zhang et al. 2018a, 2018b). First, the abandonment of some cropland parcels changes the total amount of managed land under cultivation by the household, influencing the livelihood strategy of labor allocation for out-migration. Once the migration decision is made, the demographic composition changes due to the loss of human capital (i.e., farm labor), which can further alter land management strategies. Second, when an individual decides to migrate out for better economic opportunities, the household tends to abandon some cropland parcels due to labor loss; the abandonment of cropland changes the total amount of cultivated land by the household and subsequently influences the decisions on labor migration, which features the feedback from land use to labor allocation. The changing cultivated land feeds back to livelihood decisions on labor migration.

A total of 3597 rural households including 12,375 individuals were used as input data to initialize the model settings based on the township census data. Based on satellite images and topographic maps, houses were geo-located and land parcels were delineated. The GIS-based approach was employed to build spatial linkages between the households and the land parcels they manage (Figs. S3 and S4). Stochasticity is introduced through the assignment of

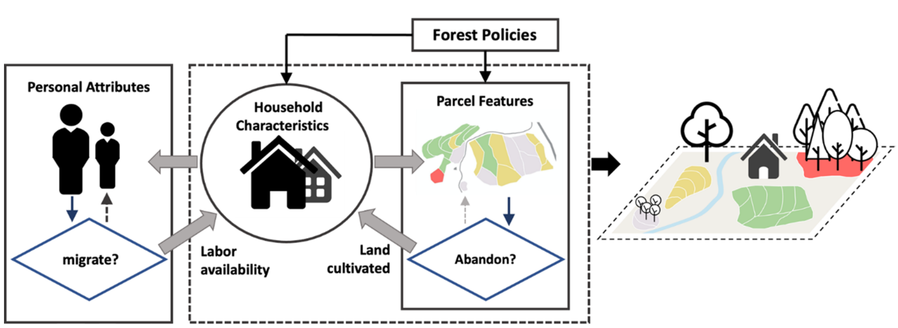

Fig. 2 Analytical framework of ABM-CALM. Blocks with solid line indicate agents at different levels and policies factors; block in dash line suggests components with spatial features. Solid gray arrows in bold indicate major feedback loops; solid black arrow in bold indicates the emergence of spatial patterns. Solid blue arrows indicate determining directions; dash arrows indicate indirect feedbacks

cropland parcels to each household in each model simulation at the initialization stage. When building the spatial linkage between households and cropland parcels, households have different levels of priority to claim unassigned cropland parcels within certain geographic distances following the order of taking actions. Thus, one single simulation may result in social-ecological outcomes under a randomized initial condition and hence cannot represent the expected paths of the dynamics. To address this issue, parallel simulations were performed. Specifically, the model was run 50 times at a set of parameters and the mean outcomes of the 50 simulations were derived and synthesized. Taking advantage of the geographic attributes (i.e., geolocations), the synthesized outcomes were spatially displayed regarding land use patterns and household labor decisions.

We developed the model using Python 3.6 and verified each critical component independent to other submodules following the guide by An et al. (2005). In each simulation, the model is executed for 20 ticks, each of which represents a time step corresponding to one year. The simulation sets 2013 as the start year (tick 0) and projects trajectories during a 20-year period (2014–2033). Validating models for complex systems with spatial attributes often presents major methodological challenges (Filatova et al. 2013). Here, we validated ABM-CALM by focusing on land use patterns. We took advantage of satellite observations and remote sensing techniques as they offer adequate measures independent of data inputs (Hofmann et al. 2015). Based on ABM simulations, we generated a risk map of cropland abandonment at the fifth year (i.e., 2018) and visually identified abandoned land through the analysis of high-resolution Google Earth images in 2018 as the reference. The initial size of the validation sample included 500 randomly selected cropland parcels. Parcels that were abandoned prior to model simulation, namely before the year of 2013 (i.e., tick 0), were masked out, leaving 404 parcels. After careful checks, parcels with high levels of uncertainty of visual interpretation were further excluded, resulting in a final sample size of 390. In addition to visual comparison, we statistically tested the difference in abandonment risks between the two parcel groups, with one from the ABM simulations and the other from the visually interpreted records. Extreme value experiments and sensitivity analysis are efficient ways of testing key parameters in model validation (Parker et al. 2003). In ABM-CALM, two major components are demographic change and land use decision submodules. The feedback loops across multiple levels operate via labor availability and the amount of cultivated land, which depend on the probabilities of return-migration and abandoned land reclamation, respectively. Therefore, we tested the changing percentages of the migration behavior (i.e., migration, return-migration, and previous migration measured in numbers) and land use decisions on different parcel types (i.e., total cropland, paddyland, and dryland measured in area) with various levels of the two parameters in combination and in extreme cases (Supplementary Material).

Geo-visualization of socio-environmental outcomes

Based on the model simulations, we exported the risk maps of parcel-level cropland abandonment and household-level migration. Since the location-specific characteristics of parcels were time-invariant, the mapping of spatial features of the parcels based on their IDs was straightforward. Here, the risk for each parcel was estimated by calculating the percentage of abandonment counts to the total number of simulations, which is an effective way to quantify the model outputs by accounting for uncertainty originated from the stochasticity of ABMs (Le et al. 2008). In addition, we created hotspot maps of cropland abandonment using the GIS-based density approach at the tick of 5, 10, 15 and 20 to capture the evolving patterns, which are more relevant to the policy such as land targeting (Chen et al. 2010). To display the migration patterns, we tracked the household with the geographic coordinates of the house locations at the initialization stage for each simulation and used the coordinates as the location-IDs for mapping the hotspots of migration. This analysis allows a detailed exploration of migration as a nonspatial characteristic from the geographical perspective, particularly in relation to cropland abandonment.

Policy scenario design

We designed multiple alternative payment schemes for CCFP and EWFP in addition to the current scheme (Table 1). The current scenario follows the schemes in practice in 2013 with payments rates of 1875 and 131.25 yuan/ha/year for CCFP and EWFP,

Table 1 Payment schemes of CCFP and EWFP for policy scenario test

Factor	CCFP payment rate	EWFP payment Rate
0.0	0	0
0.5	937.5	65.625
1.0	1875	131.25
2.0	3750	262.5
4.0	7500	525

The unit of the payment rate is yuan/ha/year (1USD = 6.15 Chinese Yuan in 2013). CCFP represents Conversion of Cropland to Forest Program. EWFP represents Ecological Welfare Forest Program

respectively. For each program, we ran the model experiments with the payment rate multiplied by a factor of 0, 0.5, 1, 1.5, 2, and 4, with 0 denoting no payments, separately. This generated a total of 36 scenarios in the combination of the two PES programs. The scenario with the factor of 1 is the same as the current scheme. We explored the different trends of cropland abandonment and labor migration under these scenarios. To reflect the social-ecological performance of PES, while accounting for the temporal features of cropland use and labor migration, we used the difference between the initial and the final statuses after the experiment regarding migration with previous experience and the total area of existing abandoned cropland.

Experimental results

Test outcomes for ABM-CALM

Before interpreting simulated outcomes, we report results from model testing and validation through three main methods: tests with extreme values of parameters, sensitivity analysis of social-ecological outcomes to key parameters, and comparison with independent data from satellite observations.

Model testing with extreme values

We test the model with extreme values of parameters that are most relevant to feedbacks between land use change and labor migration. Compared with the outputs with default values, all simulated outputs with extreme parameter values are as expected (Table 2), supporting the feasibility of ABM-CALM. As the payment duration shortens, less cropland will be abandoned during the simulation period, while limited migration behavior change is seen. A maximum value of returning probability leads to a much higher number of return-migrants, resulting in no labor migrants; a minimum value, in contrast, causes an extremely low number of return-migration with a relatively high number of migrants. Note that the few return-migrants are forced to return home when no one is living in the household (e.g., the only household member died in a year) to keep the household registration. Similar modeling outcomes are also observed for the probability of recultivating cropland, with 1 (maximum) resulting in an exceptionally large amount of cropland reclamation and 0 (minimum) none.

Sensitivity analysis of simulated outcomes to key parameters

Labor migration and cropland abandonment show different levels of sensitivity to the probabilities of returning migration and recultivating abandoned cropland (Fig. S7), both of which are as expected as well. Regarding migration, the numbers of migrants and return-migrants increase to a larger extent with a higher returning probability, but they are insensitive to the probability of abandoned land reclamation. In particular, the extent of increase in return-migrants saturates as the returning probability increases and approaches 0.5. Meanwhile, cropland abandonment is sensitive to both parameters. As the probability of return-migration increases, the degree of cropland abandonment declines for all land since the returned migrants would potentially become farm labor. Meanwhile, an increased probability of land reclamation slightly aggravates cropland abandonment. Dryland appears more sensitive than paddyland to the probability of recultivating abandoned land.

Comparison of simulated outcomes with satellite observations

Compared with the interpreted image in 2018, the simulated outcome of the validation sample parcels in 2018 (tick 5) shows an acceptable level of consistency

Table 2 Test for ABM-CALM with extreme values of key parameters

Output	Default	Tick when PES payments completely cease (Default: 20)				Probability of returning home (Default: 0.23)		Probability of renting cropland (Default: 0.16)		Probability of recultivating cropland (Default: 0.10)	
		0	**5**	**10**	**15**	**0**	**1**	**0**	**1**	**0**	**1**
Migrant number (percentage)	5364 (0.500)	5405 (0.504)	5390 (0.502)	5382 (0.502)	5374 (0.501)	4059 (0.492)	5705 (0.508)	5355 (0.499)	5379 (0.502)	5431 (0.507)	5223 (0.488)
Return-migrant number (percentage)	160 (0.231)	159 (0.231)	160 (0.232)	161 (0.229)	160 (0.229)	6 (0.002)	163 (1.000)	160 (0.228)	160 (0.228)	159 (0.238)	159 (0.226)
Abandoned cropland area (proportion)	36.4 (0.038)	33.7 (0.035)	34.4 (0.036)	35.1 (0.037)	35.7 (0.038)	37.6 (0.040)	36.1 (0.038)	36.2 (0.038)	36.3 (0.038)	27.8 (0.035)	50.7 (0.042)
Recultivated cropland area (proportion)	23.1 (0.064)	21.8 (0.063)	22.3 (0.063)	22.7 (0.063)	23.0 (0.064)	23.7 (0.064)	22.9 (0.064)	23.0 (0.063)	23.1 (0.064)	0.0 (0.000)	56.6 (0.513)
Current non-migrants	101,704	10,704	10,705	10,702	10,700	8200	11,229	10,698	10,698	10,697	10,689
Current migrants	528	528	532	535	532	3033	0	536	534	528	535
Current return-migrants	3324	3314	3324	3328	3331	878	3829	3330	3308	3304	3321
People with migration experience	8200	8225	8197	8201	8201	5694	8721	8169	8227	8209	8140
Current cultivated cropland area	926.6	948.0	938.4	930.9	930.9	919.0	929.1	926.0	926.6	747.7	1214.5
Current abandoned cropland area	389.9	368.5	378.1	385.6	385.6	397.5	387.4	390.5	389.9	568.8	102.0

All outputs are temporally averaged values from tick 1 to tick 20 to represent the overall statuses during the 20-year period. "Current" reflects the overall status at the end of each tick. The land area unit is ha. PES represents Payments for Ecosystem Services regarding the probability of cropland abandonment, both visually and statistically (Fig. S8). Two highlighted illustrations at selected zoomed-in locations demonstrate that cropland parcels abandoned in 2018 suffer relatively higher simulated risk of being abandoned (0.2 or higher), while those remaining cultivated show a lower risk (below 0.2). The difference in distributions of various risk levels between the abandoned and cultivated cropland groups further supports the validated model performance. From low to high ranges of abandonment risk, more parcels are interpreted as abandoned while less cultivated, with a statistically significant difference in mean risk of abandonment between the two groups (|t|=4.61, $p=0.000$).

Socio-environmental dynamics under forest conservation policies

ABM-CALM simulations reveal nonlinear socio-environmental trajectories under the PES programs (Fig. 3). Based on the trajectories of labor migration and cropland abandonment (Fig. 3, left and middle panels), the system does not reach equilibrium before the end of the model simulation. When considering the relationship of the two variables (Fig. 3, right panel), the system appears to achieve a state of quasi-equilibrium, as the ratio of cropland abandonment to labor migration fluctuates within a relatively small range of values, as observed in other ABM studies (Tian et al. 2016). Regarding labor migration, the annual probability of labor migration experiences a sharp increase from 0.30 to the peak of 0.55 after the tenth year (tick 10) and then drops to a value below 0.5. The migration probability of CCFP-participants is overall higher than that of non-participants, and the discrepancy widens during the first 10 years and remains stable afterwards. For participants, the number steadily increases to a small extent in the beginning and generally maintains a certain level after the seventh year, albeit with a looming decline. Non-participants exhibit a more prominent convex shape, as the annual number of migrants doubles during the first 10 years and then declines by 25%. Regarding land use, the probability and area of cropland abandonment show declining but decelerating trends. Comparatively, the participant group is associated with higher risk of annual cropland abandonment than the counterpart. The extent of cropland abandonment, particularly in the first few years, is less for CCFP-participants than non-participants. As the remaining cultivated cropland becomes scarcer over time, the continuing decline of abandoned cropland feeds back to individual decisions with less likelihood of labor migration. This can be further supported by examining the trends of abandoned area per migrant. In the beginning, the ratio of cropland abandoned area to migrant numbers falls to a very low level due to the sharp growth in migration, but this trend is short-lived when the migration likelihood drops faster than cropland abandonment.

Geographic emergence and evolution of socio-environmental patterns

The spatial patterns of the estimated probabilities of cropland abandonment and labor migration reveal clusters of entities and agents at the parcel and household levels, respectively (Fig. 4). Parcels with high risk of being abandoned tend to be in areas where higher elevations and rougher terrain are the primary feature of the topography, while parcels in middle

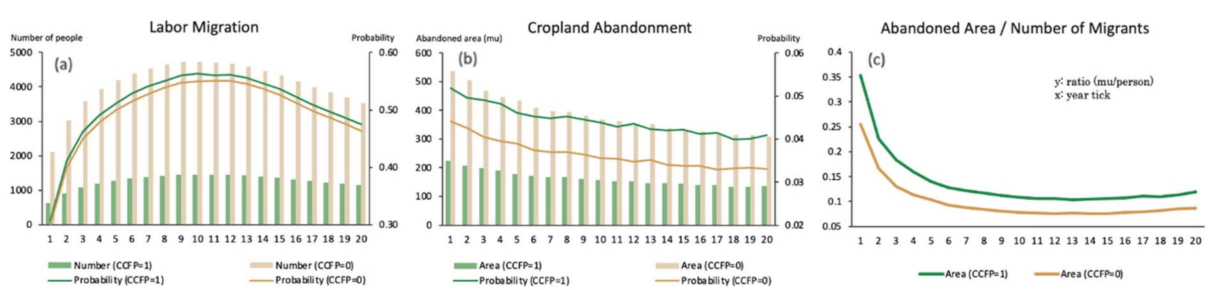

Fig. 3 Socio-environmental dynamics under PES programs. Temporal trajectories of **a** rural migration, **b** cropland abandonment, and **c** abandoned area per migrant. Households are divided two groups of CCFP participants (CCFP = 1) and non-participants (CCFP = 0)

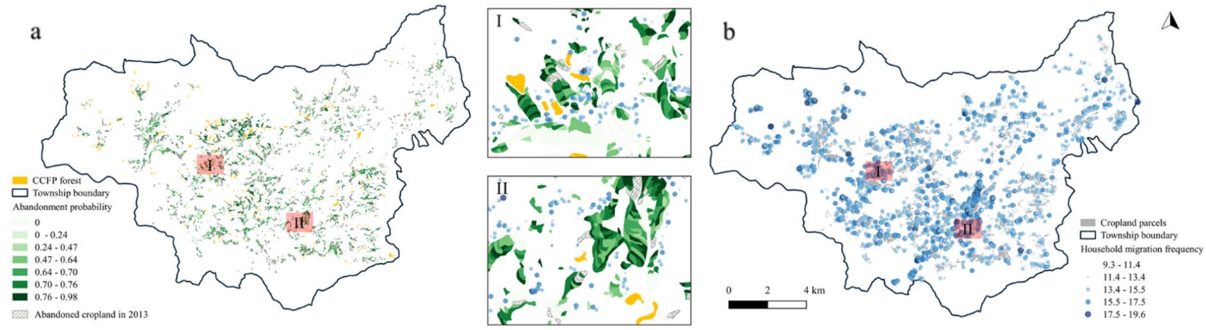

Fig. 4 Emergence of spatial patterns of **a** parcel-level cropland abandonment and **b** household-level migration frequency at the end of the model simulation

west (i.e., moderate slopes) and northeast (i.e., low elevations) are less likely to be abandoned. Notably, parcels in proximity to CCFP and EWFP forests parcels are exposed to higher risk of being abandoned, reflecting the geographically indirect effects of the two PES programs on land use decision. In the meantime, household-level estimations of labor migration also display heterogeneous distributions of the demographic process over space. A substantial increase of migration in the township center was characterized by relatively higher population density and northwest with higher elevation. In areas with lower elevations and lower frequency of migration such as northwest and northeast, several households exhibit comparatively higher probability of labor migration. In the model, households have been randomly linked to the house locations within a village where the overall social contexts among households are relatively homogenous. This suggests that the location-specific properties (e.g., elevation, slope) and geographic factors (e.g., distance from cropland parcels to nearest forest or other neighboring abandoned cropland) influence the labor migration by households.

To further explore how emerging socio-environmental patterns evolve over space and time, we provide the heat maps of cropland abandonment and labor migration at different simulation ticks based on GIS-based density estimation (Fig. 5). During the first 10 years, only one prominent hotspot of labor migration emerges in the township center where elevation is lower, while cropland abandonment appears more prevalent with one hotspot in the northwest where elevation is higher. During the last 10 years, labor migration becomes more identifiable in higher elevation areas, leading to two more hotspots located in western part of the study area; these hotspots are

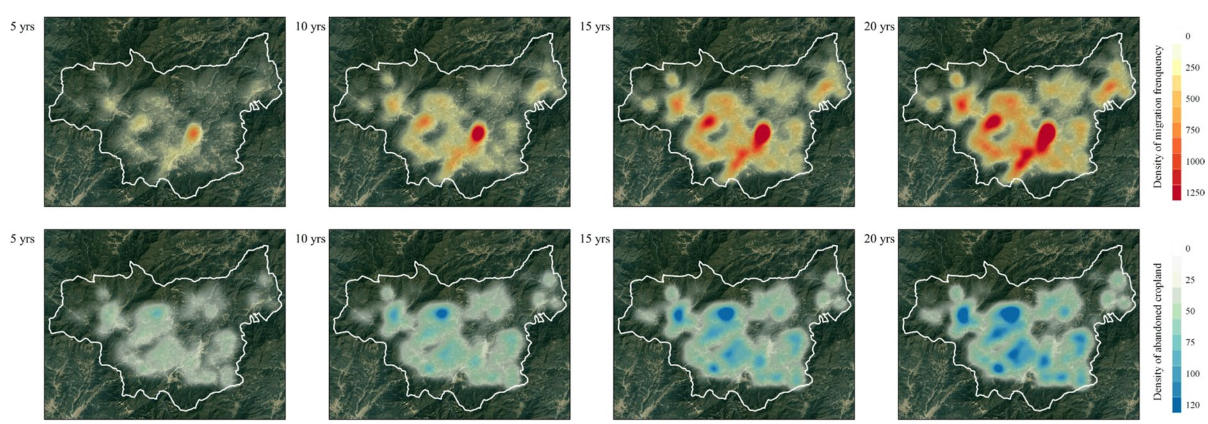

Fig. 5 Hotspots of cropland abandonment and migration frequency evolving through time

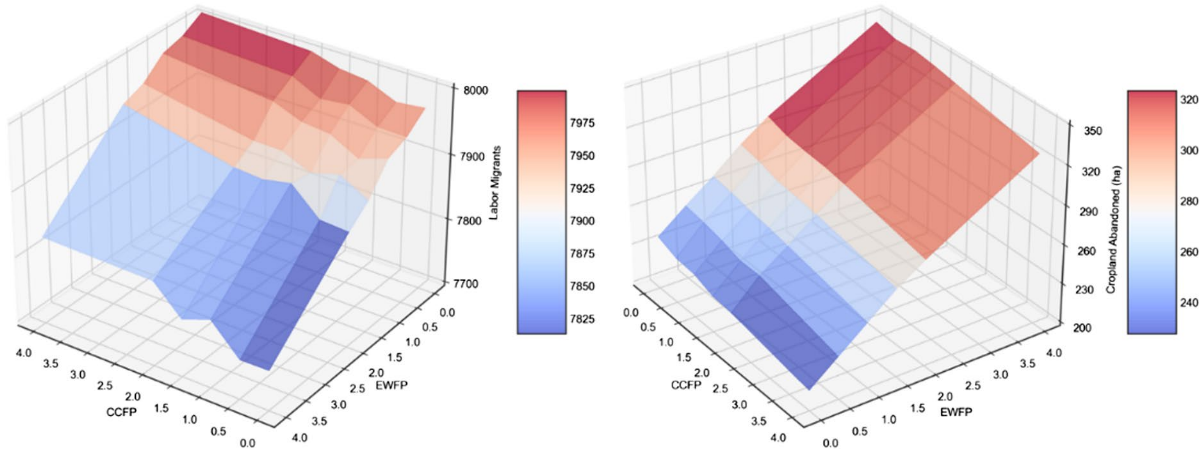

Fig. 6 Policy scenario test. Z-axis denotes difference of **a** the number of migrants or **b** the area of abandoned cropland from initial to final states. In both panels, x-axis and y-axis denote the factor for alternative payment schemes of the two PES programs

close to places where the evolving hotspots of cropland abandonment are also detected in the western and northwestern areas. Similarly, as the central hotspot of labor migration expands with a larger scope, the concentration of cropland abandonment also turns into remarkable hotspots in the township center.

Scenario test with various PES schemes

Scenario analysis suggests different social-ecological outcomes of the two concurrent PES programs under various payment schemes, as manifested by the changing difference from the initial year to the final year (Fig. 6). For labor migration simulation, higher CCFP payments tends to facilitate labor migration leading to more individuals with previous migration experience. In contrast, as EWFP payments rise, the increasing rate of the number of people with migration experience becomes relatively low. An interesting finding regarding the two concurrent PES programs is that the tendency of labor migration increases due to CCFP under a high EWFP payment scenario is greater than that under a low EWFP payment scenario. For example, if no EWFP payment was received, the number of individuals with migration experience would increase with 3.5% when the CCFP payment rate grows from 0 to 7500 yuan/ha/year. However, the magnitude of growth in migration probability would nearly triple (10.0%) if the EWFP payment rate was 525 yuan/ha/year, a rate four times that under the current scheme.

Cropland abandonment is much more sensitive to EWFP payment than to CCFP payment. More areas of cropland are abandoned by households in response to the increase in the EWFP payment rate, although this positive association is slightly offset by the CCFP given a CCFP payment rate. If the EWFP payment rate increases from 0 to 525 yuan/ha/year and the CCFP payment rate remains fixed at 7500 yuan/ha/year, the abandoned cropland area would expand from 212 to 327 ha, an increase of over 50%, at the end of the simulation. Along with the labor migration, the synergies and/or tradeoffs of the two concurrent programs, as also found in other areas (Yost et al. 2020), can be explained by the feedback loops between labor migration and cropland abandonment. When EWFP payment rate is high, an extra amount of cropland will be abandoned, which feeds back to household labor allocation for migration; consequently, the effect of an increased CCFP payment rate would be confounded by the extra abandoned cropland, making labor migration decision more sensitive to the CCFP.

Discussion and conclusions

Payments for Ecosystem Services has been embedded in various conservation projects for decades to combat human-induced environmental adversities (Ezzine-De-Blas et al. 2016; Silva-Muller 2022). Despite numerous favorable environmental outcomes, neutral or unclear consequences simultaneously persist in non-trivial numbers, incurring "failures" of many conservation investments (Romero 2012). The success of the PES programs depends on the extent to which the service providers secure the ecosystem services through sustainable land use management (Wunder et al. 2018; Qi et al. 2022), which is often driven by complex socio-economic and ecological feedbacks (Lambin and Meyfroidt 2010; Báliková and Šálka 2022). Thus, one of the practical questions of primary interest is how the PES programs can be tailored to the social-ecological context of the land system to enhance the conservation sustainability.

Guided by the coupled human and natural system (CHANS) framework (Liu et al. 2007; Levin et al. 2013), we address the question by developing a spatially explicit ABM to capture the endogenous relationships between humans and the environment (Filatova et al. 2013; Malanson and Walsh 2015). We develop ABM-CALM to assess the performance of China's two renowned forest PES programs, EWFP and CCFP, focusing on feedback loops between cropland abandonment and labor migration as representative social-environmental processes of a CHANS. Through the integration of the agent-based approach, geographic information system and remote sensing, the experimental outcomes elucidate how the CHANS patterns emerge under various PES scenarios over space and time. The model uses population-level datasets within the study site, which overcome the difficulty of fully capturing the interactions among agents that are key to understanding the emergence of land use patterns. At the initialization stage, one challenge is building spatial linkages between households and cropland parcels. We designed a GIS-based algorithm to assign cropland parcels to households within each village. This process involves stochasticity as each household claims different parcels in different model simulations. Households within the same villages nevertheless have similar contextual conditions (e.g., environment, socioeconomic status), and such stochasticity may not severely affect the simulations outcomes.

Our ABM-CALM simulation reveals nonlinear trajectories of labor migration behaviors and cropland abandonment decisions resulting from social-ecological feedback loops, heterogeneity, time-lag effects, and multiscale interactions, as found in other regions (An et al. 2020). The model simulates a CHANS where human decision-making plays the critical role in shaping the dynamics of migration and cropland use (Rindfuss et al. 2004). Overall, migration in the first few years shows a growing trend, accompanied with a relatively higher rate of cropland abandonment. As cultivated cropland becomes scarcer, households tend to decelerate the rate of labor allocation for migration, subsequently bending the migration trajectory downward (Fig. 3). With the intervention of the CCFP, the additional retired cropland for reforestation makes it possible for households to allocate extra farm labor for non-farm activities (Treacy et al. 2018). This may explain the finding that CCFP-participating households are less affected by the negative feedback of reduced cultivated cropland and are able to maintain the migration level in the long term, whereas non-participants have more cropland to take care of, allocating more labor for land management. The way labor migration responds to cropland abandonment, and vice versa, is heterogeneous over space and time, and their interrelationships can be constrained or facilitated by the geographic conditions (Figs. 4 and 5). For example, households located in higher elevations (in the west of the study area) are observed to exhibit emerging hotspots of both labor migration and cropland abandonment, but hotspots in the township center with lower elevation do not appear to abandon cropland until labor migration lasts for a sufficiently long period. These findings indicate that ABM-CALM is capable of representing the complex human-land interplays and generate novel insights to the existing knowledge about directional effects of off-farm employment on land arrangement (Lieskovský et al. 2015; Yan et al. 2016; Xiong et al. 2021; Zhang et al. 2022) or the way in which land management influences migration behavior (Mullan et al. 2011). A major conclusion is that the modeling of land system dynamics should incorporate the endogenous feedback loops that operate as key glue of the human-environment connections.

Through scenario tests, a finding of practical importance for forest conservation policies pertains to the varying performance of one PES program with different payment levels of another when the two are concurrently implemented. A previous study found a negative relationship between two concurrent PES programs in another area in China (Yost et al. 2020). In fact, the spillover effects of concurrently implemented PES programs are ubiquitous globally but have received little attention so far in many relevant case studies (An et al. 2022). By focusing on different perspectives of PES, our modeling results advocate the necessity of uncovering the mechanisms regulating the system to shed light on how social-ecological dynamics shape the policy impacts. The complexity of the CHANS as seen in ABM-CALM is manifested not only from the direct offsetting effects of CCFP and EWFP, but also from the indirect feedbacks of their effects: the positive effect of CCFP on labor migration appears to diminish with less EWFP payment. The discrepancy can be understood through the positive feedback of land use change to household livelihood behaviors. With sizable EWFP payments, additional subsequent abandoned croplands make farm labor more available for alternative activities (Zhang et al. 2018b), while more CCFP payments offer great financial support to make it possible for household to send migrants out (Song et al. 2014). These mechanisms uncover the previously unrecognized linkages from policy (i.e., PES programs) to behavior (i.e., livelihood decisions), known as the *policy-behavior* spillover effect (An et al. 2022), which may help better coordinate policy practices under such concurrent PES scenarios in the future.

Feedback loops in a CHANS are major mechanisms that drive the dynamics of land use and labor migration. Leveraging such feedbacks assist policymakers to design programs with enhanced conservation efficacy and mitigated tradeoff effects. Based on the findings in this study, policy implications are as follows. First, the design and implementation of PES programs aiming for ecological conservation and/or restoration need to account for the social-environmental processes at the household level, including labor allocation and land use decision. Companion measures that support rural out-migration in a sustainable way complement the reforestation efforts with better land targeting and household enrollment and more secure land tenure (Li et al. 1998; Chen et al. 2010). Meanwhile, retiring and enrolling cropland parcels at high risk of being abandoned with feedbacks from non-agricultural activities improve the conservation efficiency and reconcile the potential conflicts with other policies that may carry different goals such as agricultural preservation (Chen et al. 2019; Zhang et al. 2022). Such considerations benefit the co-design of agricultural and environmental policies to achieve synergies between ecological recovery and food security. Thus, attention should be paid to concurrently implemented PES programs, as the case of EWFP and CCFP (Yost et al. 2020; An et al. 2022). Future PES initiatives or extensions should anticipate the hidden linkages between concurrent payments as they may either bring co-benefits or incur funding waste. Lastly, spatial models with agent-based approaches can be advantageous tools to inform the design and practice of similar PES programs. Better understanding of these interacting processes with such sophisticated models as ABMs are critical not only for preserving targeted ecosystem services but also for improving vulnerable rural livelihoods along the way towards achieving social-ecological sustainability.

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Declarations

Competing interests The authors have not disclosed any competing interests.

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