Complex effects of telecouplings on forest dynamics: an agent-based modeling approach

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ABSTRACT

Rural areas are increasingly subject to the effects of telecouplings (socioeconomic-environmental interactions over distances) whereby their human and natural dynamics are linked to socioeconomic and environmental drivers operating far away, such as the growing demand for labor and ecosystem services in cities. Although there have been many studies evaluating the effects of telecouplings, telecoulplings in those studies were often investigated separately and how telecoulplings may interact and affect dynamics of rural coupled human and natural systems (CHANS) jointly was rarely evaluated. In this study, we developed an agent-based model and simulated the impacts of two globally common telecouplings, nature-based tourism and labor migration, on forest dynamics of a rural CHANS, China’s Wolong Nature Reserve (Wolong). Nature-based tourism and labor migration can facilitate forest recovery, and the predicted forest areas in Wolong in 2030 would be reduced by 26.2 km^2 (6.8%) and 23.9 km^2 (6.2%), respectively, without their effects. However, tourism development can significantly reduce the probability of local households to have member(s) out-migrate to work in cities and decrease the positive impact of labor migration on forest recovery. Our simulations show that the interaction between tourism and labor migration can reduce the potential forest recovery by 3.5 km^2 (5.0%) in 2030. Our study highlights that interactions among different telecouplings can generate significant impacts on socioeconomic and environmental outcomes and should be jointly considered in the design, management, and evaluation of telecouplings for achieving sustainable development goals.

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SIGNIFICANCE STATEMENT

Rural areas are increasingly connected with other places through telecouplings, such as tourism and labor migration. However, telecouplings' effects were often evaluated separately, and their interaction remains poorly understood. In this study, we evaluated how two globally common telecouplings, tourism and labor migration, jointly affect forest dynamics in a demonstration site using an agent-based modeling approach. Although both tourism and labor migration can benefit forest conservation, we found that their interaction generates an antagonistic effect: households' involvement in tourism activities reduces their probability to have members out-migrate to work in cities and significantly diminishes the beneficial impact of labor migration on forest recovery. Our study highlights the importance of considering interaction among telecouplings in the management of telecouplings for sustainability.

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1. Introduction

As globalization continues, rural areas have been increasingly connected to the rest of the world through telecouplings – socioeconomic-environmental interactions over distances (Liu et al. 2013a). As a result, human-nature interactions in rural regions, which were primarily driven by local socioeconomic and biophysical conditions, are now increasingly affected by drivers operating at a distance, such as the growing demand for ecosystem services and labor in cities. This new anthropogenic trend has generated profound impacts on many global sustainability issues such as deforestation (Liu 2014), biodiversity loss (Dou et al. 2018), energy security (Fang et al. 2016), and climate change (Liu et al. 2015b).

Among the telecouplings that link rural areas and other places, rural-urban labor migration (rural residents out-migrate to cities for temporary employments) and nature-based tourism (tourism based on the natural attractions of rural areas) are two globally common and increasingly influential ones (Ratha, Yi and Yousefi 2015, Pulido-Fernandez, Ward-Perkins and Krukova 2015). Factors such as urban economic growth, enlarging rural-urban disparity, and development of transportation networks, have been driving a large number of laborers from rural areas to seek job opportunities in cities, especially in developing countries (Ratha et al. 2015). In China alone, the number of rural-urban labor migrants had increased from only 2 million in the early 1980s to more than 150 million in 2010 (Rush 2011). Meanwhile, there has been a rapidly growing demand for visiting the natural and cultural landscapes of rural areas, mostly by residents from cities. For decades, many rural areas around the world have been practicing nature-based tourism. For example, in the late 1990s, about 80% of nature reserves in China had developed nature-based tourism (Li and Han 2001). Several provinces in southwest China (e.g., Yunnan and Sichuan), where one of the global biodiversity hotspots is located (Myers et al.

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2000), have designated nature-based tourism as one of the major sources of their economic growth (Liu 2012).

Previous studies (e.g., Chen et al. 2012a, Pulido-Fernandez et al. 2015, Dai et al. 2012) suggest that labor migration and nature-based tourism can have substantial impacts on the human and natural systems in rural areas. Many rural residents who traditionally relied on subsistence agricultural livelihoods, are now shifting to off-farm economic opportunities made possible by these two telecouplings (Kramer, Urquhart and Schmitt 2009). This labor shift substantially mitigated the negative impacts of local farmers on ecosystems (Liu et al. 2012, Yang et al. 2013, Fox 2016). For example, previous studies (Chen et al. 2012a, Cao et al. 2009) suggest that the remittances sent back by labor migrants or revenue from tourism development, have promoted the change of rural energy consumption from fuelwood to electricity, and reduced the deforestation by farmers. With an increasing awareness of the importance of tourism and labor migration, there have been many studies evaluating their effects on socioeconomic and environmental outcomes in rural regions (e.g., Chen et al. 2012a, Liu et al. 2012, He et al. 2008, Liu et al. 2016a).

However, like studies on other telecouplings, the effects of tourism and labor migration were often evaluated separately and their interaction was often ignored. While both tourism and labor migration have the potential to reduce the negative impacts of local households on the environment (Chen et al. 2012a, Liu et al. 2012), tourism development may limit the growth of labor migration. Previous studies (e.g., Wong, Li and Song 2007) show that rural migrant workers in cities often lack good health insurance coverage, face substantial educational expenses for their children, experience discrimination from urban residents, and suffer high stress and depression due to social displacement. Therefore, local tourism jobs are usually more

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attractive to rural residents than migrant jobs in cities. Although income opportunities related to nature-based tourism are often seasonal (Cuccia and Rizzo 2011), a household may be less likely to utilize its surplus labor for temporary employments in cities if it can benefit from local tourism development. As a result, the possible positive environmental impacts from labor migration in a rural area with a tourism industry might be smaller than in other rural areas where tourism industry does not exist.

In this study, we integrated information from different sources and developed an agent-based model to simulate the evolution of tourism and labor migration and their effects on forest dynamics in China's Wolong Nature Reserve (Wolong hereafter). We used the agent-based model because it has a unique capacity to consider the heterogeneity and complex interactions of the human and natural components (e.g., households and forest landscape) involved in telecoupling processes. Although empirical modeling approaches like regression models can yield useful insights regarding single-step or multi-step human-nature interactions, such knowledge alone can rarely lead to in-depth understanding of long-term dynamics of coupled human and natural systems (CHANS) (An et al. 2014, An et al. 2005). Agent-based modeling can address this limitation by offering an effective way to integrate findings from empirical models with other information to simulate system dynamics over a long period and under alternative scenarios that are hard to be empirically observed (Ligmann-Zielinska and Jankowski 2007, Chen et al. 2012b, Dou et al. 2020).

After calibrating and validating our agent-based model, we used it as a scenario-envisioning laboratory to evaluate the effects of tourism and labor migration by comparing the forest dynamics under different conditions. Specifically, we simulated and evaluated forest dynamics under the following scenarios: [1] tourism and migration are not present in the model, [2] only

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tourism is present in the model, [3] only migration is present in the model, [4] tourism and migration are present in the model but their interaction is ignored, and [5] tourism, migration and their interaction are all included in the model.

2. Methods

a. Study area

Wolong (102º52′ to 103º24′ E, 30º45′ to 31º25′ N) was established in 1963 and expanded to its current size of 2,000 km^2 in 1975 (Liu et al. 1999) (Fig. 1). It provides sanctuary to over 100 wild giant pandas and more than 6000 species of plants and other animals such as red panda and golden monkey (China Ministry of Forestry and World Wildlife Fund 1989, Sichuan Forestry Administration 2015). The natural forests in Wolong are mainly composed of evergreen and deciduous broadleaf forests at lower elevations, subalpine coniferous forests at higher elevations, with understory composed of bamboo species such as umbrella and arrow bamboo (Schaller et al. 1985, Reid and Hu 1991, Taylor and Qin 1993). Besides the diverse species of plants and animals, Wolong is also home to about 4900 local residents (Yang 2013). The reserve is managed by the Wolong Administration Bureau, which is hierarchically structured with two townships under its governance – the Wolong Township and the Gengda Township (Lai et al. 2003).

"Figure 1 about here"

Before the 2000s, the reserve had few connections with the outside world. Local livelihoods relied primarily on subsistence-based agricultural activities like cropping and livestock husbandry (Zhang et al. 2018). The average annual income per capita in 1990 was only 470 yuan (72 USD, 1 USD = 6.6 yuan as of June 2016) (Lai et al. 2003). As the human population and the number of households grew, local human activities caused serious degradation of panda habitat

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by the early 2000s (Liu et al. 2001, Bradbury, Peterson and Liu 2014). Of all the human threats, cutting trees for fuelwood by local households was a major one (Bearer et al. 2008). Fuelwood was a major energy source for cooking pig fodder, cooking meals, and sometimes for heating houses during winter (An et al. 2002). Although electricity was available, local households were reluctant to switch from fuelwood to electricity, in aversion to increased household expenses (An et al. 2002). By the mid-1990s, local households consumed around 11,000 m^3 of wood annually and contributed to the rapid shrinkage of forest cover from 52% (1070 km^2) in 1965 to 35% (706 km^2) in 2001 (Yang et al. 2013, Viña et al. 2007, Liu et al. 2001).

This trend of net forest loss started to change since 2001 (Tuanmu et al. 2016). Between 2001 and 2007, the forest cover in Wolong recovered from 35% (706 km^2) to 37% (799 km^2) (Yang et al. 2013). Several socioeconomic and political factors may have contributed to this forest transition. One of them is the development of tourism. Although tourism has existed in Wolong since the late 1980s, the number of tourist visits then was low, and few local people benefited from it (Liu et al. 2012). In 2002, a tourism development plan was formally approved by the provincial and central government (He et al. 2008). Since then, tourism in Wolong has entered a rapid development stage and became an important alternative source of income for local households. The number of tourist visits increased by 10-fold from about 20,000 in 1996 to about 200,000 in 2006. In 2005, about 30% of local households directly benefited from tourism activities like selling bacon to tourists and working as the tour guides (Liu et al. 2012). Before 2008, when the Wenchuan Earthquake interrupted tourism development in Wolong (Liu et al. 2016b), tourism seasons in Wolong often started in May and ended in October.

Meanwhile, as China's economy has grown rapidly in its cities, the stunning rural-urban disparity attracted a rapid rise of labor migrants from rural areas to urban centers (Liang 2001, Li

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2011). In Wolong, the percentage of households with labor migrants has doubled from 12% in 2004 to 24% in 2009 (Liu et al. 2016a, Liu, McConnell and Luo 2013b). Like many other parts of the world, almost all labor migrants from Wolong find only temporary employments in cities (Chen et al. 2012a). They return to their home villages whenever needed (e.g., in planting or harvesting seasons) and rarely shift to be permanent urban residents (Fan 2008).

In addition to tourism development and labor migration, several conservation policies have been implemented in Wolong since the early 2000s, including the Grain-to-Green Program (GTGP) (also called Grain-for-Green Program) started in 2000, Natural Forest Conservation Program (NFCP) started in 2001, and Grain-to-Bamboo Program (GTBP) started in 2002 (Liu et al. 2008). Under the NFCP, local households receive payment to monitor the forest for preventing illegal timber harvesting, while under the GTGP and GTBP, local households receive payments to convert their cropland to forestland or bamboo land. Of them, the NFCP was specifically designed to reduce deforestation (Vina et al. 2016), and is believed to be the major policy that has contributed to the reductions of deforestation in Wolong after the early 2000s (Yang et al. 2013).

b. Model design

Agent-based models are composed of agents and their environment (Dou et al. 2019, An and Liu 2010). In our model, agents are individual persons and households, and landscape in Wolong is their shared environment. Agents and their environment together are treated as a CHANS, which is connected with other systems (cities) through two telecouplings: tourism and labor migration (Fig. 2). Local households affect forest dynamics mainly through collecting fuelwood. The establishment of new households often lead to small-scale forest clearing (An et al. 2006) and constitutes the other pathway affecting forest dynamics (Fig. 2).

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"Figure 2 about here"

The amount of fuelwood collected by each household is determined by its attributes, such as household size, cropland area, and whether being a tourism household and/or labor migration household. In this study, a household is named a tourism household if it directly benefits from local tourism activities. A household is named labor migration household if it has one or more members who out-migrate to cities for temporary employment. Tourism and labor migration reduce fuelwood collection by local households if the households have member(s) directly benefiting from local tourism industry or out-migrating to work in cities. Although a household can be a tourism household and a labor migration household simultaneously, tourism participation by a household reduces its probability to have labor migrant(s). This interaction is manifested in the evolution of households' attributes (being a tourism and/or a labor migration household) over time.

The interactions among local households, telecouplings, and forest dynamics were implemented in three integrated submodels: a demographic submodel, a telecoupling submodel, and a landscape submodel. Households in this study were modeled as autonomous agents that can interact with each other and with the forest. We parameterized the model using data and findings from different sources such as population and agricultural censuses, household interviews, satellite imagery, and published journal articles (e.g., An et al. 2001, Chen et al. 2014). The agent-based model was developed using the Java programming language on the Swarm platform (Minar et al. 1996). Below are detailed descriptions of each of the submodels.

1) DEMOGRAPHIC SUBMODEL

The demographic submodel simulates dynamics of persons and households. In our model,

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individual persons and households are hierarchically connected with each other (i.e., a household agent consists of a number of person agents). The demographic profile of each household agent was modeled by simulating life histories of individual person agents. Major events of individual persons include birth, marriage, aging, and death. Major household events include: [1] household formation that may occur when young adults get married, [2] change in household size when there are new members coming or old members leaving, and [3] household dissolution when there are no members left. Each household has a specific location in the landscape and its behavior is based on its attributes, including household size, number of laborers, cropland, and whether it is a tourism or a labor migration household. Household behavior is also constrained by environmental conditions like elevation and distance to the main road.

Our demographic submodel was largely adopted from the models developed in previous studies (An et al. 2002, Chen et al. 2014, An, Mertig and Liu 2003, An et al. 2005) and was initialized with data from an agricultural census conducted in Wolong in 1996. The data include age, gender, and marital status of each household member, kinship relations among household members, and the amount of the household's cropland. In 1996, there were 4053 residents in Wolong distributed in 892 households. The geocoded locations of households were measured with a GPS receiver in 2002 (An et al. 2002). Details about the modeling of the events of household and person agents can be found in the cited studies (An et al. 2002, Chen et al. 2014, An et al. 2003, An et al. 2005, An et al. 2006).

2) TELECOUPLING SUBMODEL

The telecoupling submodel was designed to simulate the interactions between households and forest under five different telecoupling scenarios (see the Introduction section). Telecouplings affect the households' status of whether having member(s) work in the local

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tourism industry or out-migrate to work in cities. This status in turn affects the amount of fuelwood collected by households and forest dynamics. We estimated the probabilities of becoming a tourism household or a labor migration household using household survey data collected in 1999 and 2006.

In 1999, our research team conducted the first household survey in Wolong to collect data covering the demographic (e.g., household size, birth year, gender, and education level) and the socioeconomic (e.g., income sources, cropland area, and fuelwood collection) information of individual households in 1998 (An et al. 2001). A total of 220 households (about 20% of all households in Wolong) were randomly selected for survey with strata based on administrative groups (the smallest administrative unit in China). These households sampled in 1999 were revisited in 2006 to collect their information in the previous year (2005). There were 18 households missing from the 2006 survey due to various reasons such as deaths, migration to outside areas, or temporarily working outside Wolong during the survey period. In 1998, tourism households and labor migration households accounted for 2.7% and 3.9% of all households, respectively. In 2005, those figures increased to 31% and 22%, respectively.

"Table 1 about here"

Using the survey data of the 202 randomly sampled households in 2006, we modeled local households' participation in tourism and labor migration using logistic regression models (Table 1). When modeling the participation in labor migration, we included tourism participation status (1, Yes; 0, No) as a predictor as suggested by a previous study in Wolong (Yang et al. 2018). This is because local tourism jobs in Wolong are often more attractive than migrant jobs in cities. Rural migrant workers in cities may lack health insurance coverage, face substantial educational expenses for their children, and suffer from high stress and depression (Cuccia and Rizzo 2011).

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Therefore, if a household has access to jobs in the local tourism industry, it is less likely to have labor migrants working in cities. Our participation models (Table 1) predict the probabilities of tourism and labor migration households after the development of tourism and labor migration for multiple years. Because only a few households were tourism households or labor migration households in 1998, we approximated the annual probabilities of becoming a tourism or labor migration household by dividing the estimated probabilities by seven years (1998 to 2005). A higher participation probability of a household indicates it has a larger potential to have one or more members to work in local tourism industry or out-migrate to work in cities.

In reality, tourism or labor migration households may stop their involvement in those activities for various reasons (e.g., the laborers in the household are getting too old). However, almost all tourism and labor migration households in1998 remained the same in 2005. We therefore did not have enough observations to develop empirical models to predict the probability of a household exits the status of being a tourism household or labor migration household. In our agent-based model, we used the minimum predicted probability of all the 63 tourism households surveyed in 2006 (0.06) as the threshold below which a tourism household exits the status of being a tourism household. As time goes by, a tourism household's attributes may change and have a predicted probability less than this threshold. If this happens, the household's status changes from being a tourism household to a non-tourism household. Similarly, we determined the threshold (0.01) for labor migration households to exit the status of being a labor migration household.

Fuelwood collection by each household without considering impacts of tourism, labor migration, and conservation policy, was determined according to a previous study in Wolong (An et al. 2001), which modeled fuelwood collection as a function of household size, presence or

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absence of senior people in the household, and farmland area. Because all households in the study area enrolled in the NFCP in 2001, we did not have a control group of households to accurately estimate the impact of the NFCP on fuelwood collection. We approximated this impact using the drastic reduction in average household fuelwood collection that occurred after 2001 when the NFCP started. Of the 220 households surveyed in 1998, 189, 200, and 215 of them were revisited in 2001, 2002, and 2003 with their fuelwood collection information recorded. Before 2002, the average fuelwood collection by each household was around 12861.5 kg (12763 kg in 1998 and 12960 kg in 2001). In 2002, the average fuelwood collection drastically reduced to be around 8618.1 kg (8576.5 kg in 2002 and 8659.7 kg in 2003). We used the difference in the mean fuelwood collections before and after 2001, 4243.4 kg, as the impact of the NFCP on annual household fuelwood collection. In our simulations, this impact on households' fuelwood collection takes effect after 2001.

"Table 2 about here"

According to the results of a previous study in Wolong (Chen et al. 2012a), the impact of labor migration on household fuelwood collection was set to be 1827 kg per year. If a household starts to have member(s) out-migrate to work in cities, we deducted its fuelwood collection by this amount. We estimated the impact of tourism participation on household fuelwood collection by comparing the fuelwood collection of tourism and non-tourism households in 2005 using the matching approach (Rubin 1973). For each tourism household, the matching approach finds a counterpart non-tourism household with similar attributes, including the number of adults, household size, distance to the main road, and maximum education level of adult household members. On average, a tourism household collected 1708 kg less fuelwood than a non-tourism

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household per year (Table 2). Therefore, if a non-tourism household in our model changed to be a tourism household, we deducted its annual fuelwood collection by 1708 kg.

"Figure 3 about here"

The decision process of each household's status - become or stop being a tourism or a labor migration household - over time is summarized in Fig. 3. If a household is not a tourism household, we calculated its probability to be a tourism household based on its attributes at this time step using the logistic model in Table 1. If a household is already a tourism household at the current time step, we compared its participation probability with the threshold (0.06) to judge if it is still eligible to be a tourism household. If the tourism household's participation probability is less than the threshold, its status will be changed from being a tourism household to be a non-tourism household. Similarly, if a household is not a labor migration household, we determined if it can become a labor migration household based on its probability to have labor migrants. If a household has already been a labor migration household, we evaluated its eligibility at this time step by comparing its participation probability with the threshold probability (0.01). Only labor migration households with predicted probabilities larger than this threshold can maintain their status of being labor migration households. Households' statuses regarding labor migration and tourism participation were then used to calculate their fuelwood collection.

3) Landscape submodel

The landscape submodel simulates forest dynamics with specific consideration of household fuelwood collection, establishment of new households, and other environmental conditions (e.g., elevation and slope). Our simulation focuses on a 6 km-buffer region around all households (Fig. 1) because almost all deforestation activities in the study area happened within the distance of 6

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km from the households (Linderman et al. 2005). The total area of the simulated natural landscape is 553 km^2. The landscape is represented in our model as a digital “world” consisting of 90×90 m cells. Each cell has a set of attributes including elevation, slope, aspect, and forest status (forest or nonforest). The elevation, aspect, and slope were obtained based on a digital elevation model derived from a topographic map (Liu et al. 2001). The forest cover information of the landscape cells was initialized with a published binary forest (forest/nonforest) map derived from Landsat Thematic Mapper images acquired in 1997 (Liu et al. 2001). The classification of the satellite images was performed using unsupervised digital classification based on ISODATA technique (Jensen and Lulla 1987) and was validated using ground-truthing data. The accuracy of the forest cover map is about 80% (An et al. 2005, Liu et al. 2001).

"Table 3 about here"

Landscape cells may experience deforestation (from forest to nonforest) or forest recovery (from nonforest to forest). The forest change of each cell is determined by empirical models obtained from a previous study in the reserve (Chen et al. 2014). According to this study, the deforestation or forest recovery probability of each cell was a function of the cell’s elevation, slope, aspect, distance to forest edge, and impacts of fuelwood collection by local households (Table 3). Fuelwood collection has a significant positive effect on forest loss ($p < 0.001$) and a significant negative effect on forest recovery ($p < 0.001$) (Table 3). Household fuelwood collection was translated to fuelwood impact on each cell across the simulated landscape using the equation developed by Chen et al. (2014):

$$FI_i = \sum_{dis_{ij}<6km} fuelwood\ collection_j / dis_{ij}$$

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where FI_i is fuelwood collection impact on cell i; dis_{ij} is the distance from household j to cell i; $fuelwood\ collection_j$ is the annual fuelwood collection by household j. The fuelwood impact on forest dynamics is therefore an inverse-distance weighted aggregation of all households within 6 km buffer from the cell, which reflects the fact that forests closer to households are more likely to be degraded or logged.

At every time step, we calculated the deforestation probability for each forest cell and recovery probability for each non-forest cell to determine their forest status (forest or nonforest). For a detailed description of the construction and validation of these forest change models, please refer to the cited study (Chen et al. 2014).

c. Model validation

In this study, we validated the agent-based model by comparing the simulated landscape, demography, and telecoupling-related statuses with the corresponding observed patterns at the whole Wolong level. For the demographic submodel, we calibrated it with the 1996 agricultural census data and ran it for 10 years. To consider the influence of stochastic processes in our model, we used the mean results from 20 runs for validation. We compared the simulated mean population size and mean number of households with those obtained from the 2006 household registration data. For the telecoupling submodel, we compared the simulated percentages of tourism households and labor migration households in 2005 with the observed values from our household survey data. If the difference between observed and simulated values is less than the observed mean yearly change (change in the observed values divided by the number of years between the observations), we considered the model simulation as having good validity.

We validated the impacts of tourism and labor migration on fuelwood collection, and impacts of fuelwood collection on forest dynamics together by comparing the simulated forest

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distributions in 2007 with a published empirical forest cover map in 2007 (Viña et al. 2011). This 2007 forest cover map was derived from a digital classification of the imagery of Landsat Thematic Mapper. The map was validated using ground truth data and has an accuracy of 82.6% (Viña et al. 2011). The comparison between simulated and actual maps was performed using a receiver operating characteristic (ROC) curve (Hanley and McNeil 1982) with a random sample of 5000 pixels (2500 forest pixels and 2500 nonforest pixels) from the empirical forest cover map as the validation dataset. The predicted probability of being forest of the sample pixels was calculated by averaging simulated binary forest maps of the 20 runs. We used the area under the ROC curve (AUC) as a measure of the overall accuracy of the simulated forest maps. The values of AUC ranges from 0 to 1, where a value of 1 indicates perfect accuracy, while a value of 0.5 implies that the accuracy is no better than a random guess (Araújo et al. 2005).

d. Simulation experiments

After validating our model, we simulated the dynamics of households and forest under five different scenarios to evaluate the effects of tourism and labor migration: (1) without tourism and labor migration; (2) only with tourism; (3) only with labor migration; (4) with both tourism and labor migration but ignoring their interaction; and (5) with both tourism and labor migration including their interaction effect. When running scenario #1, we ignored the impacts of tourism and labor migration by setting all households' probabilities being tourism and labor migration households to be zero throughout the simulations. When running scenario #2, we ignored labor migration by setting the probability of labor migration to be zero for all households. Similarly, when running scenario #3, we set tourism participation probability to be zero for all households. When running scenario #4, we ignored the interaction between tourism and labor migration by setting the coefficient of the negative impact of tourism participation on the probability of labor

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migration to be zero. When running scenario #5, tourism, labor migration, and their interaction all took effect. In these simulations, the numbers of tourism and labor migration households in 1996 were assumed to be zero. We ran all simulations for 34 years (from 1996 to 2030). Because the landscape submodel was calibrated using the 1997 forest cover map, it started running one year later than the demographic and telecoupling submodels.

3. Results

a. Model validation results

Our validation results (Table 4) indicate our model performances accurately. The difference between the mean predicted human population and observed human population in 2006 was 17, which was less than the observed mean yearly population change (45 per year) from 1996 to 2006. The predicted number of all households was 1176, which was 21 less than the observed value (n = 1197) and less than the mean annual change (31 per year). The predicted percentages of tourism households (28.9%) and labor migration households (22.2%) were close to their observed values (31.2% and 21.7% respectively) in 2005. The differences between observed percentages of tourism and labor migration households in 2005 and simulated means of them (2.3% and 0.5%) were all less than the observed mean yearly changes (3.1% per year and 2% per year) from 1998 to 2005. The example simulated forest map in 2007 were also close to the empirical forest cover map (Fig. 4). The AUC value of the simulated maps (n = 20) is 0.743, indicating good simulation accuracy.

"Table 4 about here"

b. Forest and household dynamics under different scenarios

As expected, both tourism and labor migration have contributed to the forest recovery that

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occurred after 2001 (Fig. 5). In all the five simulation scenarios, the total forest area decreased between 1996 and 2001, and then started to recover at a gradually decreasing rate. Under the scenario without considering the effects of tourism and labor migration (scenario #1), the predicted forest area in 2030 is 361.2 km^2. Under the scenario only with tourism (scenario #2) or only with labor migration (scenario #3), the forest areas in 2030 are 387.4 km^2 and 385.1 km^2, respectively. The difference in the 2030 forest area between scenario # 1 and scenario #2 is 26.2 km^2, which represents the cumulative effect of tourism development on forest dynamics throughout our simulation period (1996 to 2030). The difference in the 2030 forest area between scenario #1 and scenario # 3 is 23.9 km^2, which represents the cumulative effect of labor migration on forest dynamics from 1996 to 2030.

"Figure 5 about here"

The development of tourism reduced the number of labor migration households by 22% (Fig. 6). Under the scenario that did not consider the negative impact of tourism participation on the probability of labor migration (scenario #4), the number of labor migration households in 2030 is predicted at 675 (42.2% of the total), while under the scenario that considered this negative impact (scenario # 5), the number of labor migration household in 2030 is 554 (34.6% of the total) (Fig. 6). The difference in the number of labor migration households in 2030 under scenario #4 and scenario #5 is 121, which represents the cumulative effect of tourism development on growth of labor migration throughout our simulation period from 1996 to 2030.

"Figure 6 about here"

This interaction between tourism and labor migration has an evident impact on forest

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dynamics (Fig. 5). Under the scenario with both tourism and labor migration but without considering their interaction (scenario #4), the forest area in 2030 is 407.1 km^2, which is 3.5 km^2 higher than that under the scenario that considered this interaction effect (scenario # 5). In short, development of tourism decreases labor migration in the area, which subsequently negatively affects forest cover.

4. Conclusion and discussion

Our agent-based model provides an efficient way to integrate the information from empirical statistic models and other sources to evaluate the impacts of different telecouplings on environmental outcomes at the landscape level over a long period of time. Our results demonstrated that telecouplings can interact and generated evident impact on the forest dynamics in rural areas. By analyzing labor migration and tourism in tandem, we show that the interaction between these two telecouplings significantly attenuate their positive impact on forest recovery across the landscape. While both tourism and migration increase forested area, their interaction results in a lower forest gain. Using the Wolong case study, we argue that potentially related telecouplings should be evaluated jointly rather than separately to reveal their actual effects on socioeconomic and environmental outcomes.

We note that our estimation of tourism's long-term effect on labor migration may be conservative. This is because we only observed the influence of tourism on individuals staying in the area rather than migrating to cities. Therefore, we did not include the potential effect of tourism on labor migration by attracting labor migrants to come back to only work in the local tourism industry. We hypothesize that, with the inclusion of this attraction effect of tourism on labor migration, the reduction of reforestation would be even more pronounced compared to the results in Fig. 5. We did not observe this effect and include it in our current agent-based model

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perhaps because the tourism development in Wolong was at its early stage and this attraction effect had not been evident yet. As the tourism industry is recovering from the impact of the Wenchuan Earthquake in 2008, future studies in Wolong and other places should also evaluate and consider this negative impact in their analyses.

Results from this study have important implications for management of tourism and labor migration. For example, like Wolong, many rural areas implemented tourism development programs with substantial investment and support from governments (Zhao et al. 2021, Yang et al. 2021). To maximize the efficiency of tourism development programs in providing environmental benefits, these programs may target rural areas where the level of labor migration is low to avoid limiting the positive environmental effect of labor migration. On the other hand, labor migration policies in urban settings may play an important role in mitigating the negative effect of tourism on labor migration. This negative impact occurs mainly because labor migrants in cities often have to confront many difficulties (Li 2011). Therefore, management interventions that help overcome these hardships (e.g., offering equal job opportunities for migrant workers) should be considered to increase the benefits labor migrants could obtain from this off-farm livelihood. The increase in benefits farmers could obtain from labor migration may promote tourism households to also have labor migrants and enhance the labor shift from on-farm to off-farm activities.

In our model, we only considered the impact of tourism on forest through reducing fuelwood collection because tourism development in Wolong remained at its early stage and did not generate other evident impacts on forest (Liu et al. 2016b, Liu 2012). Although nature-based tourism is widely perceived to be clean and non-consumptive because it relies on existing natural, cultural, and historical resources, unregulated tourism development can cause serious

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degradation of ecosystems (Dai et al. 2012). The actual impacts of future tourism development in Wolong on forest dynamics will depend on its design and management. Besides avoiding direct disturbances into the forest (e.g., clearing forest for tourism infrastructure development), we suggest that future development of tourism should also increase the share of benefit local households could obtain from it. Economic leakage (i.e., tourism revenue flowing to outside investors or managers rather than locals) is a common issue that plagues the development of tourism in many rural areas around the world (Kiss 2004). Previous studies (He et al. 2008, Liu 2012) in Wolong also found that only a small fraction of revenue from tourism development (<5%) went to the local community. This issue may have constrained the impact of tourism participation on fuelwood collection because less income would be available for local households to afford the energy shift from fuelwood to cleaner energy like electricity.

Although the telecoupling interaction illustrated in this study is antagonistic, i.e., one telecoupling weakens the other, synergetic interactions also commonly exist among telecouplings. For example, the panda loan is another important telecoupling linking Wolong and other places (Liu et al. 2015a). Every year the China Conservation and Research Center for the Giant Panda, a panda breeding center and tourism site in Wolong, loans captive pandas to zoos inside and outside China. The panda loans have significantly increased the media exposure of Wolong. For example, around 20% of all media reports found in LexisNexi® about Wolong are related to panda loans (Liu et al. 2015a). The spread of information about Wolong may have in turn boosted the tourist visits to Wolong. About 24% of visitors to the Wolong breeding center in 2005 expressed that they had previously read media reports on Wolong and 29% of them saw television program about Wolong before the visit (Liu et al. 2015a). This indicates that a synergetic interaction effect may exist between the telecouplings of panda loan and tourism.

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Currently, neither synergetic nor antagonistic interactions among telecouplings have been well studied (Liu et al. 2013a, Kapsar et al. 2019). They deserve more investigations in the future to improve the understandings of the dynamics of telecouplings and their effects on socioeconomic and ecological outcomes.

Our study also illustrates that agent-based models are useful tools to understand interrelated effects of telecouplings. Human-nature interactions are often complex and vary across different settings (Liu et al. 2007, Liu et al. 2013a). Agent-based models provide flexible tools to effectively integrate empirical knowledge, findings, and data from different sources to characterize the heterogeneities and interactions of the human and natural components in a CHANS. This lays a foundation to understand dynamics of human-nature interactions under telecouplings across space and time. With a validated agent-based model, we can further explore the trajectories of the system dynamics under different telecoupling scenarios that cannot be observed empirically.

We note that our model mainly focuses on simulating the processes operating within Wolong. We did not specifically consider factors associated with tourism and labor migration in other places because our study aims to understand how labor migration and tourism jointly affect forest dynamics in Wolong (not other places). We framed our study as a telecoupling research to underscore the fact that Wolong is telecoupled with other systems, and our study highlights that telecoupling flows can affect forest covers at the landscape level through influencing agent behaviors. Future research can build upon our study to include other systems and answer other questions. For instance, the nature-based tourism in Wolong may shape urban sustainability through affecting the environmental awareness and behaviors of tourists from cities. A future study may integrate such results with our findings under the framework of telecoupling and

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assess the possible synergy between sustainability in Wolong and cities.

Like all other models, the agent-based model is a simplified representation of the real world. For example, some of the life history events of person agents in our model such as death, child birth, and marriage were simplified as stochastic processes. However, modeling the key dynamic interactions using the agent-based model helps us to improve the understanding the complexities of long-term effects of telecouplings (e.g., nonlinearity, Figs. 5 and 6). We hope that the perspectives and methods proposed in this study can be useful for investigating the effects of telecouplings in Wolong and other CHANS around the world. With improved understanding of telecouplings, policy makers and scientists may be able to develop effective strategies to manage telecoupings for maximizing their positive effects and mitigating their negative effects in an increasingly telecoupled Anthropocene.

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TABLES

Table 1 Logistic estimations of labor migration and tourism participation by households in Wolong.

Variables \ Models	Labor migration	Tourism participation
	Coefficient (SE)	Coefficient (SE)
Tourism participation	-1.47 (0.56) **	-
Household size	-0.19 (0.16)	0.26 (0.14) †
The number of adult (age > 18) household members	1.04 (0.20) ***	-0.12 (0.16)
Average age of adult household members	-0.013 (0.029)	-0.012 (0.023)
The maximum school years of adult household members	-0.084 (0.075)	0.26 (0.14) ***
Log transformed distance to main road (m)	0.076 (0.13)	-0.20 (0.10) †
Township (Gengda: 1; Wolong: 0)	-0.33 (0.42)	0.33 (0.34)
Constant	-2.13 (1.68)	-2.85 (1.35) *

(1) Significance: † $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

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Table 2 The impact of tourism participation on household fuelwood collection estimated using the matching approach.

	Results
Impact estimate using matching (kg) (1)	-1708 *** (488.5)
Γ sensitivity (Wilcoxon) (2)	2.4
Γ sensitivity (Hodges-Lehmann) (3)	1.2
[Number of treated and control]	[63,139]
Means of the treated and the control (kg)	5063.5, 7341.4

(1) The numbers in parentheses of this row are Abadie-Imbens standard errors.

(2) The value of Γ at which the null of zero effect would fail to be rejected at $p = 0.05$ level based on Wilcoxon signed-rank p value.

(3) The value of Γ at which the lower bound of 95% confidence interval for the Hodges-Lehmann point estimate of the effect includes zero.

(4) Significance: *** indicate statistical significance at 0.001 level.

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Table 3 Summary of the logistic estimations of forest gain and forest loss from the previous study in Wolong (Chen et al. 2014).

Parameters \ Models	Deforestation	Forest recovery
	Coefficient (SE)	Coefficient (SE)
Elevation (100 m)	-0.008 (0.014)	-0.008 (0.011)
Slope (degree)	0.001 (0.006)	-0.009 (0.006)
Aspect (Parker scale (Parker 1982))	-0.054 (0.008) ***	0.064 (0.01) ***
Distance to forest edge (m)	-0.019 (0.001)	-0.014 (0.001) ***
Fuelwood impact (m^3/m) (2)	0.031 (0.008) ***	-0.009 (0.008)
Total fuelwood (m^3)	0.20 (0.003) ***	-0.023 (0.003) ***
Constant	347.46 ***	1.792 ***

(1) Significance: *** $p < 0.001$.

(2) Fuelwood impact on a cell is defined as the summation of fuelwood impact on the cell by all households within the 6 km buffer, and each household's impact is defined by its fuelwood collection divided by its distance to the cell.

(3) Because these models were built based on observed forest change for six years (1994 to 2000), the annual forest change (gain or loss) probabilities of landscape cells are the estimated probabilities using the above models divided by six as suggested by (Chen et al. 2014).

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Table 4 Comparisons of model predictions of population size, numbers of all households, tourism households, and labor migration households to observed values.

Factors	Observed value	Observed mean yearly change	Model mean	Difference between model mean and observed value	|Difference|< observed mean yearly change
Population in 2006	4504	45	4487	17	Yes
Household number in 2006	1197	31	1176	21	Yes
Tourism households in 2005 (%)	31.2%	3.1%	28.9%	2.3%	Yes
Labor migration households in 2005 (%)	21.7%	2%	22.2%	-0.5%	Yes

(1) The observed mean yearly change is calculated by dividing the observed change by the number of years between the observations.

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FIGURES

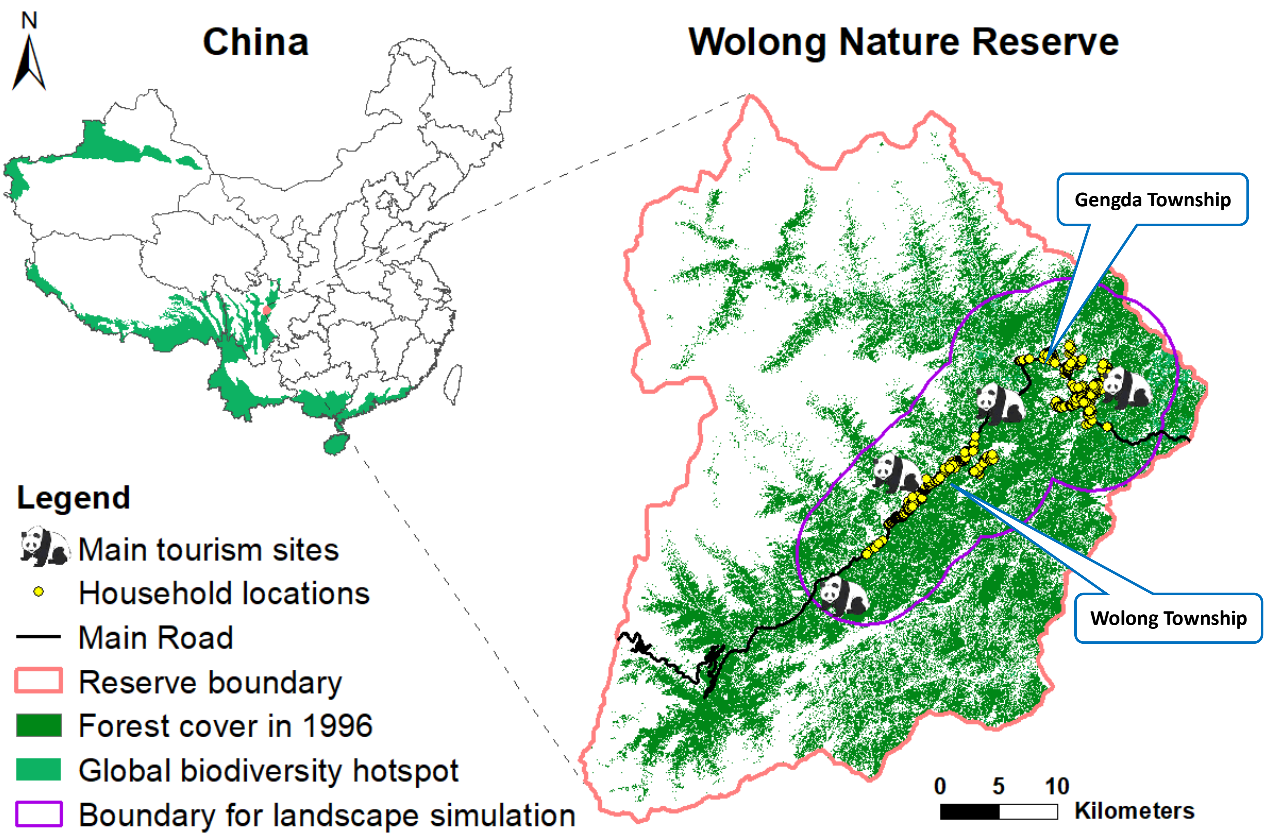

Figure 1 Wolong Nature Reserve in Southwest China.

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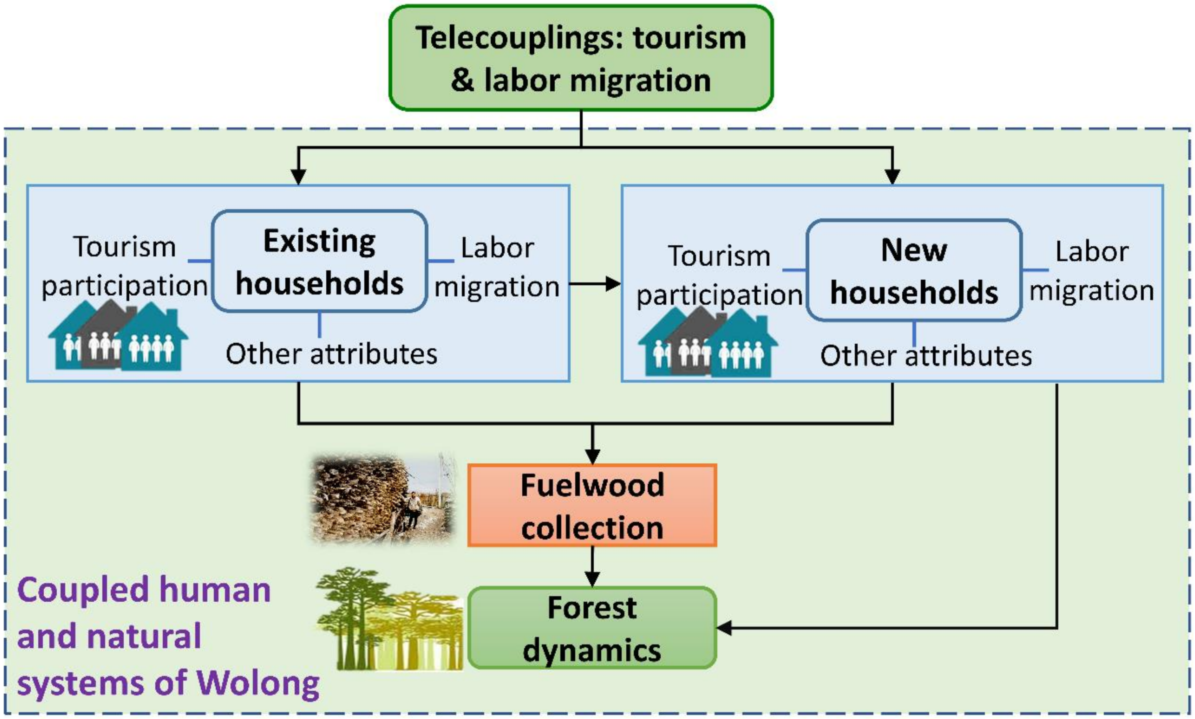

Figure 2 Conceptual framework of the model for simulating the effects of tourism and labor migration on forest dynamics in the coupled human and natural systems of Wolong.

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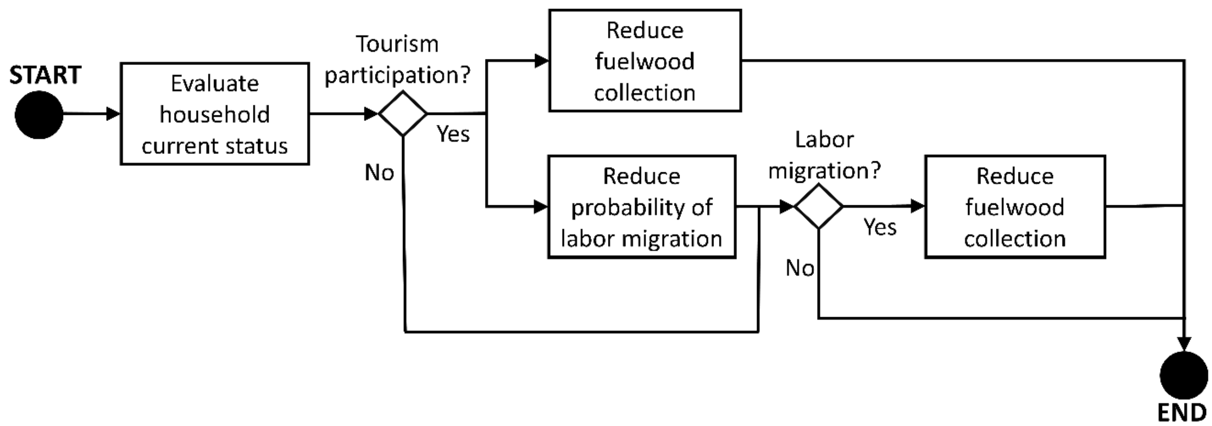

Figure 3 Decision process regarding each household's status of being a tourism or a labor migration household at each simulation step and their effects on fuelwood collection.

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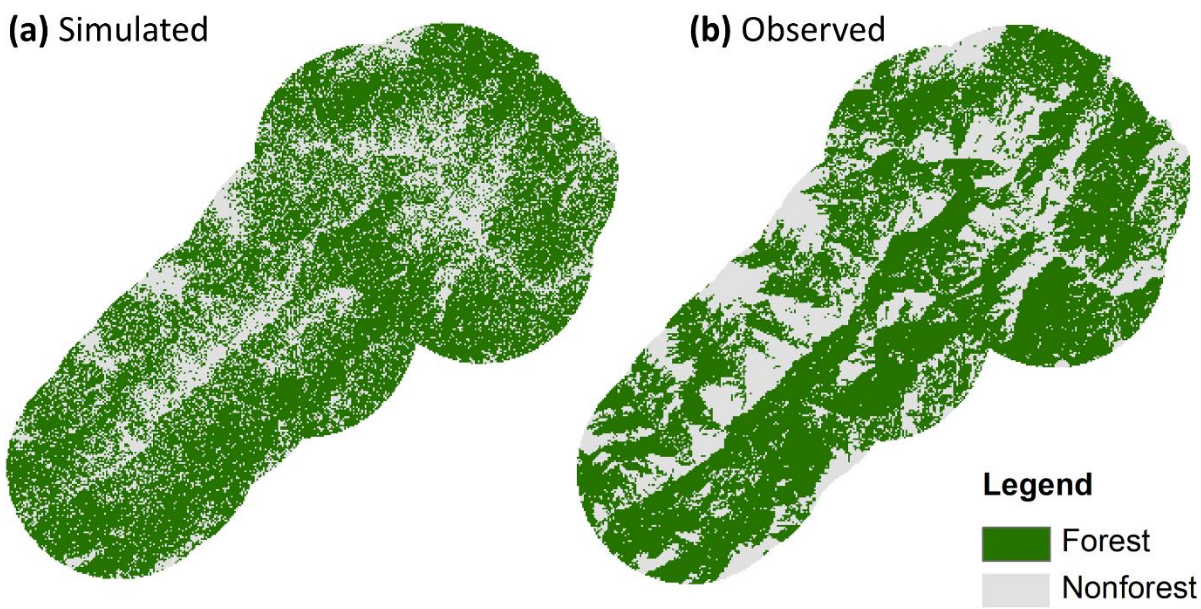

(c) Confusion matrix

Observed \ Simulated	Non-forest	Forest	Accuracy
Non-forest	971	609	0.62
Forest	784	2636	0.77
Accuracy	0.55	0.81	

Figure 4 Comparison of simulated and observed forest distribution in 2007. (a) Simulated forest cover in 2007; (b) Observed forest cover in 2007 derived from classification of Landsat imagery; (3) Confusion matrix that shows the consistency between the simulated and observed forest cover based on results of 5000 random pixels. The overall accuracy value is 0.72.

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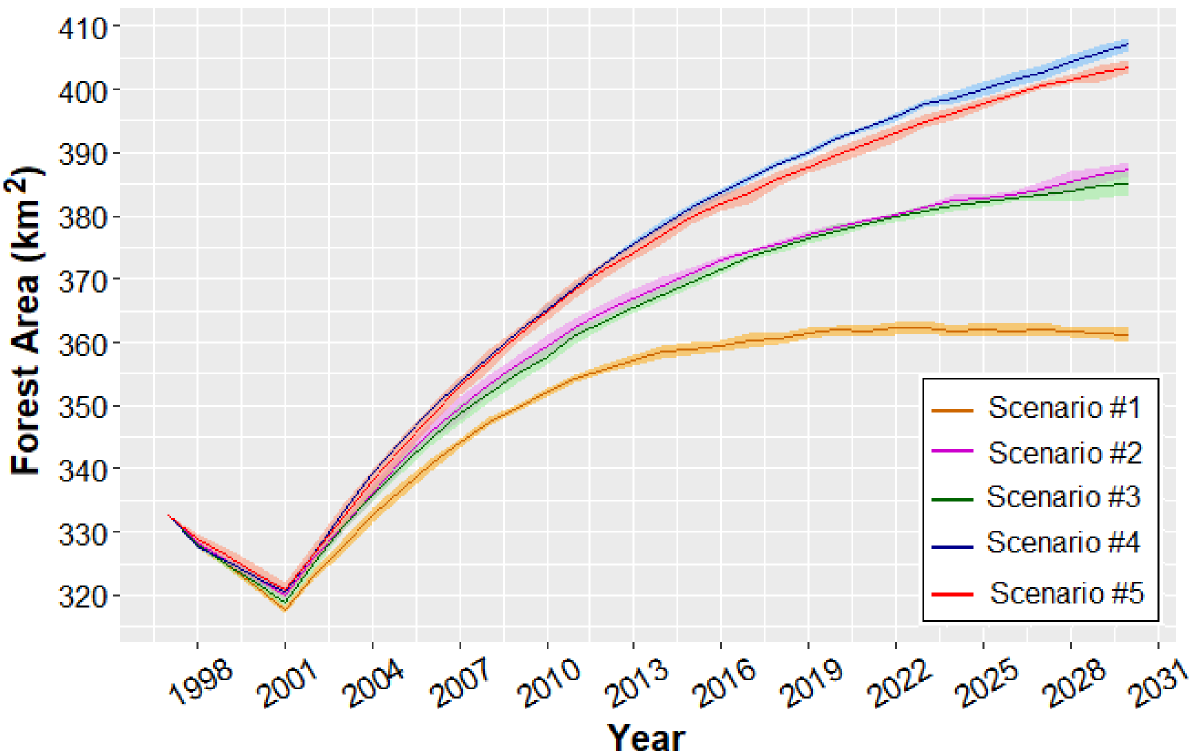

Figure 5 Dynamics of the forest areas simulated under five different scenarios: (1) without tourism and labor migration; (2) with tourism only; (3) with labor migration only; (4) with both tourism and labor migration but without considering their interaction; and (5) with both tourism and labor migration and with considering their interactions. Lines and corresponding ribbons represent the means and standard deviations of the results from 20 runs, respectively.

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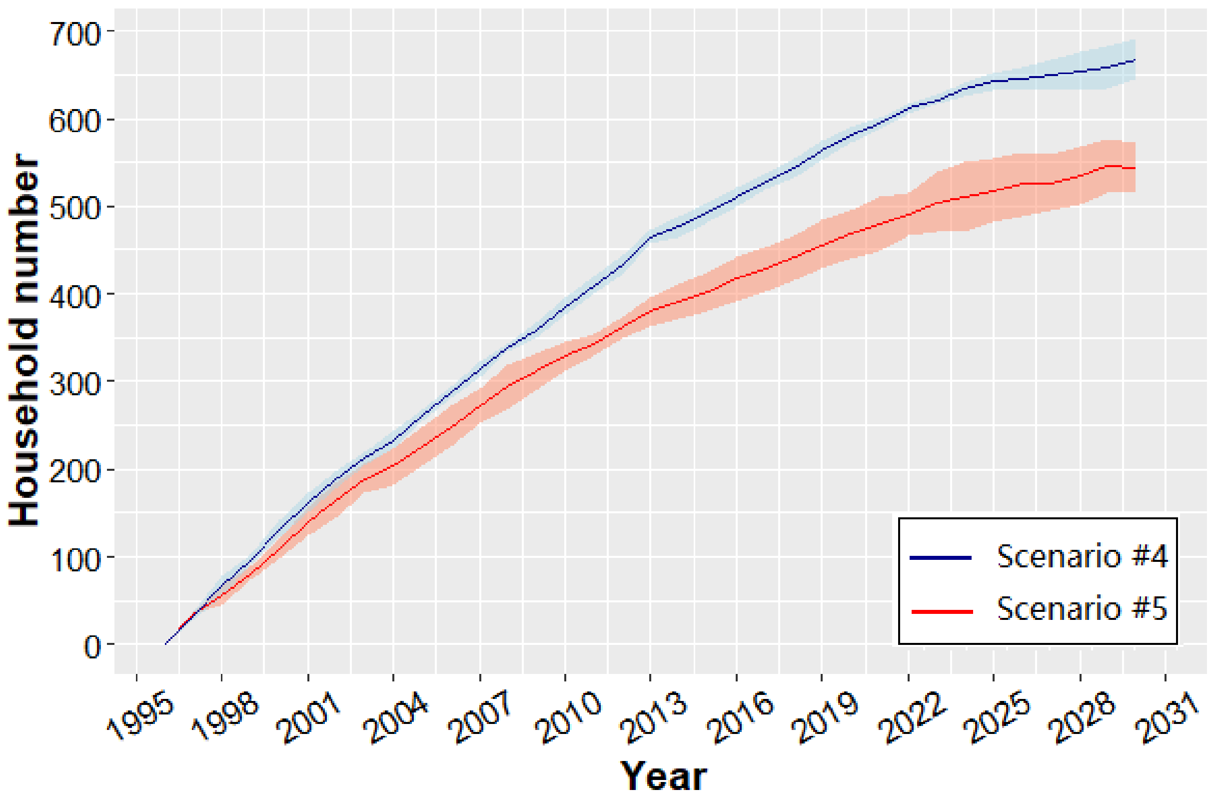

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800 Figure 6 Simulated dynamics of the numbers of labor migration households from 1996 to 2030 under scenarios with (Scenario #5) and without (Scenario #4) considering the negative impact of tourism participation on the probability of labor migration. Lines and corresponding ribbons represent the means and standard deviations of the results from 20 runs, respectively.

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