Biodiversity and Conservation (2006) 15:2343–2363
DOI 10.1007/s10531-004-1064-6

Impacts of demographic and socioeconomic factors on spatio-temporal dynamics of panda habitat

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Received 22 September 2003; accepted in revised form 21 June 2004

Key words: Agent-based modeling, Giant panda conservation, Households, Human demography, Socioeconomics, Spatial dynamics

Abstract Demographic and socioeconomic factors of individual people and households may have significant impacts on their environment, which in turn may affect the spatio-temporal dynamics of wildlife habitat and local biodiversity. In the Wolong Nature Reserve (China) for giant panda conservation, local households live a rural lifestyle that has caused forest degradation by activities such as cutting fuelwood. Based on field data and a spatial agent-based model that integrates cross-scale data and cross-discipline models, we examine how panda habitat would respond to changes in a set of socioeconomic and demographic factors individually, and under a conservation scenario and a development scenario (setting factors to values that would benefit or degrade habitat, respectively). The model simulates each family member's life history (including needs, attitudes, and activities) and the household agents' interactions with each other and with the environment through their activities over 30 years. Our simulations show that among all the factors under consideration, providing cheaper electricity and changing the age structure through increasing marriage age or prolonging the interval between consecutive births could change habitat quantity significantly (at $\alpha = 0.05$ level); and the differences in panda habitat between the two scenarios escalate over time. In addition to benefiting local policy-making, this study provides a new approach to studying human–environment interactions from the perspectives of individual needs and decisions.

Introduction

Human activities have radically altered the earth's surface, oceans, and atmosphere, especially over the past 200 years (Turner 1990), which reminds the current generation of the warning by Malthus that unrestrained population growth would eventually be limited by fixed natural resources (Malthus 1798). To address this serious situation, many researchers have called for efforts to study effects of human activities upon the environment. In particular, changes in human demographic and socioeconomic factors (e.g., public policy) have exerted great impacts on the environment and need to be paid more attention (e.g., Pebley 1998; Liu et al. 1999a; Liu 2001; Lambin 2003). Pebley (1998) suggested that environmental issues (such as effects of demographic variables on environmental outcomes) become one of the mainstream topics in demography rather than peripheral topics as in the past.

An increasing number of researchers, including ecologists, geographers, sociologists, and demographers, have conducted studies to understand human–environment interactions (e.g., Liu et al. 1999a; Perz 2001; Axinn and Barber 2003). However, there are few studies of the impacts of socioeconomic and demographic factors on the environment at an individual or household level in a spatially explicit manner, partially due to the complexities of many social or individual choices in the coupled society-biodiversity systems (United States National Research Council 1999). Such systems usually have variant socio-economic, demographic, and/or biodiversity factors, coupled with many nonlinear relationships and heterogeneous spatial structures.

Drastic socioeconomic and demographic changes that have occurred in China over the last 2 decades may provide excellent opportunities (sometimes challenges) for researchers focusing on human–environment interactions. First, China has implemented an increasingly strict policy of family planning to curb its rapidly growing population. The 'later, longer, and fewer' (wan xi shao) campaign, implemented since the late 1970s, encouraged (required in some sense) couples to bear children at an older age (later), prolong the interval between two consecutive births if more than one child is allowed (longer), and have as fewer children as possible (fewer). This plan later developed into the more strict one-child policy (Feng and Hao 1992). As a result, China's total fertility rate (TFR) dropped greatly from 3.0 in 1979 (Hussain 2002) to 1.8 in the early 1990s, and could be as low as 1.6 in the near future (Wong 2001). Due to the big population base, China's total population reached 1.24 billion in 2000 (Liang and Ma in press) in spite of this decreasing fertility.

In addition to changes in population size, China's population structure has changed substantially, characterized by a decreased proportion of children (0–14) and an increased proportion of working-age (15–64 years old) groups over the past 3 decades (Hussain 2002). In parallel with this trend, another important phenomenon is the decline in household size, which has significant implications because smaller household size would cause higher per capita resource consumption (Liu et al. 2003a). Traditionally, Chinese people have been accustomed to a lifestyle of many generations under one roof (Liu et al. 1999a, 2001; An et al. 2003a), but this tradition has been increasingly challenged by the younger generation. In rural areas of China, the patrilineal extended family is still the prevailing order, and the majority of the elderly people tend to live with their children, with sons in particular (Cooney and Shi 1987). The research by An et al. (2003a), however, has shown that though the young adults care about the adverse effects associated with leaving their parental homes (such as housework and taking care of young children), many of them still prefer to live independently as long as resources (land and timber in particular) allow them to do so.

As the Chinese economy grows rapidly, cities continue to have a rising demand for migrant labor, resulting in a rapid rise of floating population (temporary migrants who stay at their places of destination over 6 months without permanent household registration status) that flows mostly from rural areas to coastal regions (Liang 2001). The floating population is estimated to be over 79 million in 2000, accounting for 6.34% of China's total population (Liang and Ma in press). On the one hand, this type of migration has provided a timely outlet for rural surplus labor and an opportunity for many farmers to earn much higher incomes than their original subsistence farming. On the other hand, it has led to a separation of temporary migrants' actual residence from their de jure residence (Yang 2000), which may affect both the destination and origin communities in many aspects such as environmental quality.

All the above-mentioned facts, to varying degrees, may have implications for biodiversity conservation. We are interested in how changes in some demographic features (e.g., age structure, fertility) and socioeconomic factors in a specific area could lead to changes in local biodiversity over time in a spatially explicit manner. A piecemeal treatment is obviously not effective because the underlying mechanisms and interrelationships among different subsystems are ignored or not paid sufficient attention. On the contrary, it is necessary to integrate various parts together and consider the interactions among various systems while developing policies or taking actions for conservation purposes. In this context, the questions of interest in this study include: (1) What demographic/socioeconomic factors would have significant impacts on the dynamics of local biodiversity? (2) Given changes in one factor or a combination of factors, how would local biodiversity respond accordingly over time and space?

Methods

Study site

An excellent site for studying these issues is the Wolong Nature Reserve (Figure 1). Designated in 1963 with an area of 200 km^2 and expanded to approximately 2,000 km^2 in 1975, Wolong Nature Reserve has a human settlement comprised primarily (approximately 75%) of Tibetan residents. The giant panda (*Ailuropoda melanoleuca*) has declined substantially in the reserve from 145 animals in 1974 (Schaller et al. 1985) to 72 in 1986 (China's Ministry of Forestry and World Wildlife Fund 1989) partly due to serious habitat degradation resulting from human deforestation. In addition to dislodging pandas from human residence areas, local inhabitants cut wood from surrounding forests for cooking and heating their households, while pandas depend on most of these forests as cover, shelter, and their understory bamboo as staple food (Liu et al. 2001). The past two decades have witnessed a continued

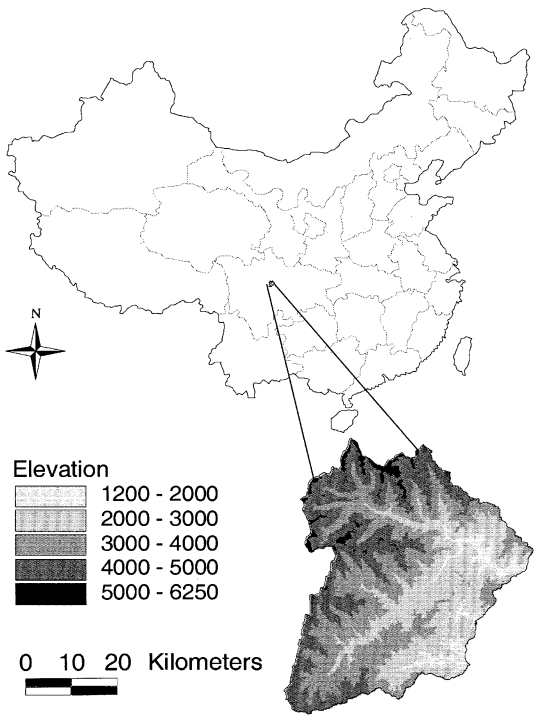

Figure 1. The location and elevation of Wolong Nature Reserve in China. The unit of elevation is meter.

increase in annual fuelwood consumption (from 4,000 to 10,000 m^3), which has caused a reduction of over 20,000 ha of panda habitat (Liu et al. 1999a). Panda habitat is used as an indicator of local biodiversity because over 2,200 animal/insect species and 4,000 plant species cohabit with the giant pandas in the reserve (Wolong Nature Reserve 1987).

The human population has increased at a rapid rate of 69% (from 2560 people in 1975 to 4320 people in 1998) despite the nationwide 'wan, xi, shao' campaign and the later one-child policy. Wolong Nature Reserve, as a rural area mostly composed of minority groups and a 'flagship' reserve in China, enjoys some special policies. For instance, it allowed three children per couple, especially in some remote areas in the reserve. Its fertility was 2.5 between 1975 and 1999 (Liu et al. 1999a). However, recent years have seen a draconian policy of two children per couple, even for minority groups in remote areas. Paralleling the increase in population, the number of households has escalated at an even higher rate (124%, from 421 households in 1975 to 942 households in 1998). The population age structure in Wolong, as in the entire country, has been characterized by an increased proportion of working-age (Figure 2a and b). It is reported that the more young adults live in Wolong, the more forest may be cut down and more habitat may be degraded (Liu et al. 1999a).

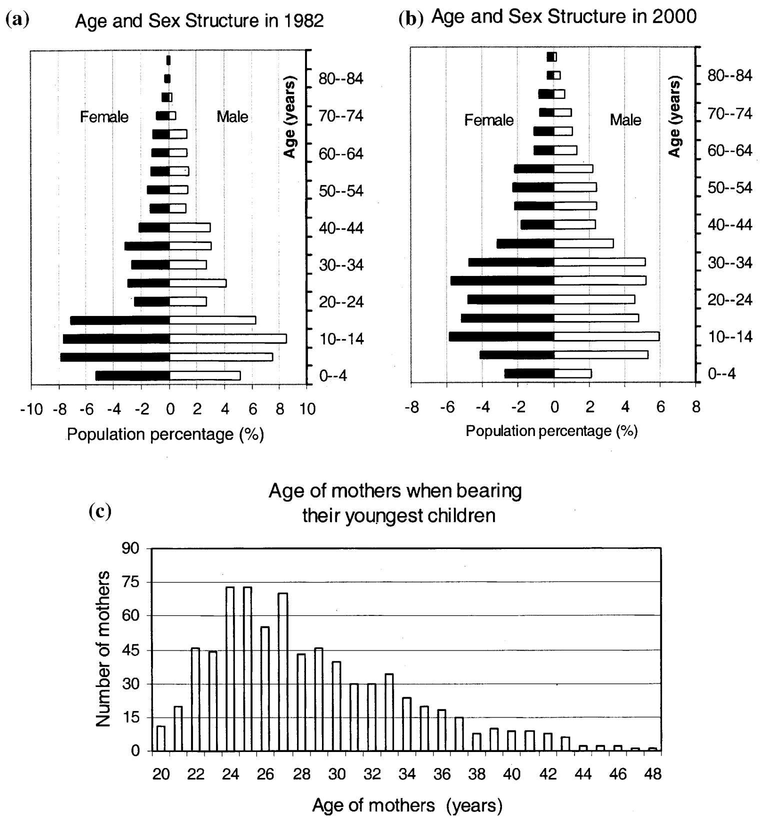

Figure 2. (a) Age and sex structure in 1982. (b) Age and sex structure in 2000. (c) Number of mothers who give birth to their youngest children at varying ages.

Temporary migration has occurred in Wolong as in other rural areas, characterized by the following facts. First, there are much fewer local residents (compared to other regions) who have temporary jobs in cities, which may arise from its special standing as a nature reserve. For instance, local people enjoy some special benefits (subsidies and lower taxes) and have less motivation to migrate to cities. Second, the rapidly growing local eco-tourism (centered on watching pandas in the reserve's breeding center) has provided some job opportunities for local residents. For instance, some young people work in local restaurants, some sell tourism souvenirs, and some collect Chinese medicine herbs and sell them to tourists. Last, most of the temporary workers with jobs in cities come back for the Chinese new year (spring festival), and some to help in agriculturally busy months. Therefore, these types of people are still considered as local population in this study because our major concern is the use of resources (land and forest in particular), and these people are still entitled to land and participate in most of the local resource use activities such as fuelwood collection and farming.

Some people (including a portion of these temporary workers) marry people in cities or other rural areas and move out permanently. This is the major form of out-migration in Wolong. Another form of out-migration is through young people's education: when young people who go to colleges or technical schools find jobs in cities after graduation, they settle down elsewhere (Liu et al. 1999a). According to Liu et al. (2001), elder people in Wolong do not want to relocate due to various reasons such as lack of skills to make a living in other areas and an inability to adapt to the outside environment. However, they encourage their children or grandchildren to emigrate through obtaining higher education. On the other hand, a small number of outside people move into the reserve each year and obtain permanent residence through marriage.

The local residents follow a rural lifestyle, characterized by satisfying their subsistence needs directly from, forests and cropland. They grow potatoes and corn primarily for pig fodders, and raise pigs for consumption and sale to tourists. Because of their belief that pig fodder should be well cooked prior to feeding pigs, they use a large portion of their fuelwood to cook pig fodder each year. Electricity, the likely substitute for fuelwood, is subject to problems such as relatively high price, unstable quality, and some degree of safety concerns. Our study of switch probabilities under different socioeconomic conditions shows that lowering price, increasing voltage, and decreasing outage frequency can encourage local residents to use electricity as a substitute for fuelwood, thus reducing forest degradation (An et al. 2002).

Model

With an excellent study site and a wealth of data (see Section 'Data preparation and integration'), we have developed an Integrative Model for Simulating

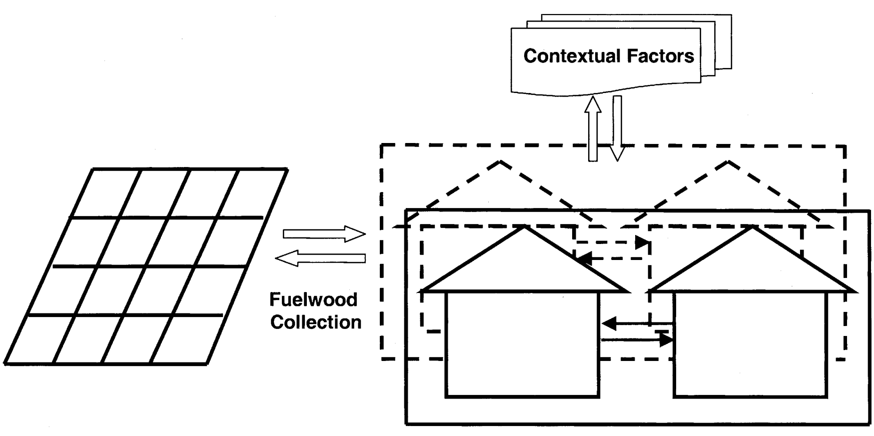

Figure 3. Model structure of IMSHED (modified from An et al. 2003b).

Household and Ecosystem Dynamics (IMSHED; see An et al. 2003b), which studies many complexities in the coupled human–environment system of Wolong by integrating agent-based modeling (ABM), traditional equation-based models, and geographic information systems (GIS). ABM is a methodology that predicts or explains emergent phenomena by tracking multiple microlevel 'agents' that constitute or at least impact the system behavior observed at higher levels (Jiang and Gimblett 2002). Agents, usually with some degree of self-awareness, intelligence, autonomous behavior, and knowledge of the environment and other agents, adjust their own actions in response to changes in the environmental or other agents' behavior (Lim et al. 2002).

The model structure is illustrated in Figure 3. IMSHED views individual persons, households, and land pixels as discrete agents or objects. The layer of dashed households in the dashed box represents households in the Wolong landscape at a past time, while the layer of solid ones represents households in the same landscape but at a later time (our introduction focuses on this layer). All the existing households come from the past and will move into the future, and many events (listed below) could happen during this process.

Birth and death

Based on the current family planning policy (2.0 children/couple) and our field observations (e.g., many couples prefer more than 2 children, but usually not more than 5), we set the average fertility to be 2.5 children/woman, while allowing couples to have 0, 1, 2, 3, 4, and 5 children with varying probabilities (for details see An et al. 2003b). When a specific female under consideration reaches a certain age (22, the average age at first marriage; see Hussain 2002) and finds a spouse (see Marriage below), she can give birth to a number of children (the number set by fertility as mentioned above) at appropriate times: the birth time of her first child is set by a parameter first kid interval, and the birth time of her other children (if possible) is set by a parameter birth interval (the time between two consecutive children).

People in Wolong at different age groups face different mortality rates (An et al. 2001). If the random number generator creates a number smaller than mortality rate corresponding to the age group that the person belongs to, he/she dies; otherwise the person survives and moves to the next year.

Marriage

Marriages occur when people reach 22 or above with a decreasing probability as they become older. When a female or male chooses to marry a person within the reserve, the resultant household location differs, and the specific rules are explained later in 'Household dynamics'. On a yearly basis, all the people are categorized into four groups: (1) young group for those under 22 years old and unmarried people (males and females), (2) single male group for all single males over 22 years old, (3) single female group for all single females over 22 years old, and (4) married group for all females and males who have spouses with them.

Migration

Based on the migration situation as mentioned in Section 'Study site', we consider three types of migrations: (1) local people marry people outside the reserve (usually people in richer areas) and move out permanently, (2) people outside the reserve marry local people and move into the reserve, and (3) young people go to college and reside elsewhere after graduation. Other types of migrations into Wolong are not allowed by law and local policy to conserve the giant panda. We use stochastic processes to control the number of out-migrants and in-migrants: if the random number generator produces a number smaller than any of the rates below in a given year, then the associated event would occur for that specific person under consideration.

The following rates control migrations in the model. (1) College attendance rate: the ratio between the number of people who go to college and the total number of people between 16 and 22 years of age in a given year. (2) Female marry-out rate: the ratio between the number of females between 22 and 30 years old who move outside the reserve through marriage and the total number of females between 22 and 30 years old in a given year. We use 22 as the lower limit because it is the average marriage age, and 30 as the upper limit because most of the people who migrate through marriage are young people not older than 30 years old (An, field observations). Some females marry people outside the reserve through a social network as mentioned above, e.g., introduction by relatives who migrated earlier. This is also true for other migration types as follows. (3) Male marry-out rate: the ratio between the number of males between 22 and 30 years old who move outside the reserve through marriage and the total number of males between 22 and 30 years old in a given year. (4) Female marry-in rate: the ratio between the number of males of 22 and 30 years old who bring outside females into the reserve through marriage and the total number of males of 22–30 years old in a given year. (5) Male marry-in rate: the ratio between the number of females of 22 and 30 years old who bring outside males into the reserve through marriage and the total number of males of 22–30 years old people in a given year.

Household dynamics

A parameter leave-home intention controls whether a 'parental-home dweller' establishes a new household after marriage. The parental-home dweller may be (1) a male who has no siblings, (2) a male who has only female siblings, (3) a male who is the youngest male sibling among brothers, (4) a female who has no siblings, or (5) a female who has only female siblings and is the youngest among these female siblings. We do not consider such situations as single-mothers or divorces because they are not that common in Wolong (An, field observations). Leave-home intention is determined or influenced by a set of psychosocial factors, including resource availability (primarily land and timber) and demographic structure of the parental household (An et al. 2003a). If a person is not a parental-home dweller, he/she leaves the parental home and establishes his/her own household after marriage; if he/she is, he/she does so with the probability specified by the parameter leave-home intention (with the default of 0.42 based on our field data). The new household is located in the vicinity of the parental household (the distance between the two households is controlled by a parameter with the default of 800 m) with appropriate elevation and slope (not over 2610 m and 37°, respectively, based on our field data).

The model updates the household dynamics (size and structure) at a yearly basis. Household size increases or decreases when people move into or out of the household under consideration through processes as described above (e.g., birth, death, move-in or move-out through marriage). When the number of people in a household becomes zero (for reasons like death and out-migration), the corresponding household becomes dissolved and removed from the model.

Resource demand

Given household structure and dynamics thus determined at each time step, the model predicts its fuelwood demand and probability to switch from fuelwood to electricity by a number of socioeconomic and demographic factors (An et al. 2001, 2002). The fuelwood demand for a household consists of three components: (1) fuelwood for cooking, which is a function of household size and calculated annually, (2) fuelwood for heating, which depends on if there is a senior person (60+ years old) in the household because a household with a senior person has to heat for a longer period of time in winter, and (3) fuelwood for cooking pig fodder, which is a function of land area for corn. This dependence on the area of corn land arises from the local lifestyle: local people use as much land as possible to grow corn (usually intercropped with potato), and cook the corn and potato using fuelwood to feed pigs and sell the extra pork or bacon (besides their own consumption) to tourists and local restaurants.

The probability of switching from fuelwood to electricity is determined by age, gender, and education of the household head, household annual income, current and hypothetical electricity prices, outage frequency levels, voltage levels, and so on (An et al. 2002). These variables are either updated yearly (e.g., age), remain unchanged (e.g., gender), or act as parameters subject to changes (e.g., outage frequency levels) in model tests or simulations.

Human–environment interactions

The interactions between humans and the environment are realized through fuelwood collection, as shown by the two horizontal block arrows in Figure 3. On the one hand, the trees on the landscape, given no human interference, grow and die by themselves. On the other hand, a household, given a certain amount of fuelwood demand, goes to a certain pixel to cut fuelwood. Because of ineffective enforcement of the habitat restriction policy (e.g., caused by the difficulty in monitoring due to the complex topographic conditions) and the common property nature of the forests, the model only considers geography of the forests in determining fuelwood collection sites. Specifically, it calculates the cost-distances (geographical distances corrected by slope) of all the locations within a certain buffer distance, and chooses the one with the smallest cost-distance.

Contextual factors

Government policies (e.g., fertility and migration regulations in the reserve) and environmental factors (e.g., tree species, volume, and growth rate in each pixel) play an important role in affecting the above human–environment system. Based on our goal in this study, we only focus on how policies in relation to the socioeconomic and demographic factors (Table 1) could be used to affect panda habitat through processes such as household formation and demand for electricity. Later in Section 'Simulations' we will show how we simulate the panda habitat dynamics by changing these factors.

Table 1. Two-sample paired t-test ($\alpha = 0.95$) results in population size, number of households and panda habitat in response to changes in the socioeconomic and demographic factors (the numbers are values of t statistic; double asterisks stand for significance at 0.95 level, and single asterisk at 0.90 level).

	Scenario	Variable	Value	Population size	Number of households	Panda habitat (km^2)
Status quo	1		Baseline	–	–	–
Socioeconomic	S2	Electricity price	0.05 Yuan decline	−0.02	−1.5	−30.29**
	S3	Electricity voltage level	One level increase	0.20	−1.86	−1.06
	S4	Electricity outage level	One level decrease	−0.33	−0.08	−18.38**
	S5	Leaving parental home intention	0.42 → 0.63	−0.20	−10.50**	6.17**
Demographic	D2	Fertility	2.5 → 3.5	−24.48**	−1.40**	0.57
	D3	Marriage age (year)	22 → 28	9.80**	3.69**	−2.76*
	D4	Birth interval (year)	3.5 → 5.5	1.55	−1.51	−5.05**
	D5	Upper birth age (year)	55 → 35	4.15**	−1.39	−0.96
	D6	College attendence rate (%)	1.92% → 5.76% (16–20 youth)	30.36**	9.49**	−1.73
	D7	Female marry-out rate (%)	0.28% → 20%	9.72**	9.97**	−1.49

Data preparation and integration

Our data used for model construction consist of the 1996 agricultural census data (Wolong Nature Reserve 1996) and 2000 population census data (Wolong Nature Reserve 2000). All these individual-based data are arranged by household, covering all rural people in the reserve, including name, ID of the household a resident belongs to, gender, age, education, kinship relation to the household head, and so on. But the 1996 data do not have interpersonal relations relative to the household head as the 2000 data do; we derive these relations based on the data in 2000, as shown below.

Based on the relations between individuals in the 2000 data, we derive the relations for the 1996 data. For example, household A had four individuals in 2000, and they were the household head, his wife, a child of 3 years old, and the household head's father. In 1996, there were also four individuals – but a woman 3 years younger than the household head with the same family name, not the child, was in the household. So we assume that the child was not born yet, and the woman was the sister of the household head who moved out of the household (or died) between 1996 and 2000. We are also interested in the reason why she was no longer in the household any more. It could be that she (1) moved out of the household and was relocated in another household in the reserve through marriage; (2) moved out of the reserve through marriage; (3) died; or (4) went to college. Only situation (1) can be determined based on our available population data of Wolong because the same person should be still registered in the reserve even though she was in another household. Situations (2), (3), and (4) are more difficult to address, though. We put all the people similar to this situation together (e.g., 30 people in total), and then used the age-based mortality rates to determine how many of them may have died, and used the rate of going to college to determine how many may have gone to college. The remaining number should be the number of people who went outside the reserve through marriage.

In this manner, we calculate the annual probabilities that a male would migrate into Wolong through marriage, that a female would migrate into Wolong through marriage, that a male would migrate to the outside of Wolong, and that a female would migrate outside Wolong between 1996 and 2000. The four rates thus derived, 0.043, 0.19, 0.043, and 0.28%, respectively, are used later in simulation.

Model test

We test our model by structural verification and empirical validation. For easiness of explanation, we still follow the traditional terms of verification and validation regardless of the debate about whether models (especially in complex systems) can be truly verified or validated (e.g., Oreskes et al. 1994; Rykiel 1996). Simply put, a verified and validated model is the one we fail to falsify using our available data and methods. Because the model has a number of stochastic processes, we run the model 30 times and compute the averages for each test or simulation. The length of demographic tests or simulations is normally 30 years for one run, though we run some simulations for 50 years to allow for some demographic factors' impacts to be demonstrated. For the socioeconomic simulations, we run the model over 20 years because such a time span is sufficient for the factors to exhibit their impacts on panda habitat.

The structural verification refers to the following processes: (1) the model passes both extreme tests (individual parameters taking maximal and minimal values) and combined extreme tests (a set of parameters taking maximal or minimal values simultaneously; these parameters are the most sensitive ones based on our sensitivity analysis, see details in An et al. 2003b); (2) the model gives expected spatial patterns of households and panda habitat over time under different scenarios; (3) the model gives stable but slowly increasing standard deviations in predicted panda habitat, number of households, and population size, and forms confidence envelops ($\alpha = 95\%$) with increasingly wider opening. This phenomenon is reasonable because uncertainties in demographic, socioeconomic, and ecological subsystems normally increase with time.

The empirical validation refers to: (1) our predicted rate of habitat loss is 1.45 km^2/year, very close to the rate of 123 km^2/year derived from findings of other researchers (Laurie and Pan 1991); (2) the paired two-sample *t*-test ($\alpha = 95\%$) between the predicted and observed population size from 1997 to 2003 gives a *p*-value of 0.88; and (3) the paired *t*-test between the predicted and observed household number from 1997 to 2000 gives a *p*-value of 0.89. The last two *t*-tests fail to reject the null hypothesis that the difference between the predicated and observed population sizes (or household number) is zero. In summary, the model works well and gives us reasonable confidence for later simulation and analysis.

Simulations

We simulate the impacts of socioeconomic factors for 20 years, and those for demographic factors for 30 years (Table 1). Two reasons account for doing so: (1) we have found that changes in many demographic factors require a longer time to impact panda habitat (An et al. 2003b). (2) Theoretically, 30 years could allow the young children (e.g., under 5 years old) to grow up and experience nearly all the important events, such as going; to college and getting married. In some situations where two generations are theoretically needed to examine the associated effects, we conduct the simulations for 50 years. For instance, if we increase the time (years) between births of two consecutive siblings, it lakes time for the birth-delayed sibling to experience all the possible events (e.g., going to college, deciding to leave parental household) and affect changes in habitat through increased/decreased fuelwood demand over time.

Electricity factors (price, outage level, and voltage level) are found to be significant in affecting fuelwood demand, and the default values for each household are set to be equal to the current values of these variables based on our survey data in 1999 (An et al. 2002). To test how changes in these three variables would impact panda habitat, we set a 0.05 Yuan (it represents a moderate change based on current electricity price) decrease for electricity price, a one level increase for voltage level (no more than level 2, the highest level in our study), and a one-level decrease for outage level (no less than 0; 0 for low, 1 for medium, and 2 for high for both voltage and outage levels). Also significant is the variable leave-home intention: the default value is set to be 0.42 based on our data, indicating that 42% of the 'parental-home dwellers' (See Section 'Model' under 'Household dynamics') would prefer to live separately. As a consequence of the decline in fertility, the proportion of elderly people will grow (Zimmer and Kwong 2003). Together with an increasing preference for initiating their own households, the pattern of an aging population (Figure 2a, b) may offset the decreasing trend in the number of households induced by the lowered fertility. We set the value of this parameter to be 0.63 (a 50% increase from the default value of 0.42) and test how the number of households and panda habitat would respond to this change.

A few demographic factors are worth testing for their potential impacts on panda habitat. One of them is total fertility rate (TFR) because controlling fertility is a major policy in China to control population. The default value is set to be 2.5 children per couple (Liu et al. 1999a). We change it to 3.5 for a lesser control, which could be caused by an ineffective government implementation of the policy. The motivation for more children lies in the fact that the more children a couple has, the more financial and instrumental (e.g., assistance to conduct daily house chore) support they may obtain from their children when they become old because there is no insurance or pension system for farmers in China (Zimmer and Kwong 2003).

In addition to fertility, a few other factors could affect population dynamics and panda habitat accordingly. (1) Marriage age: the higher the marriage age, the fewer births within a certain period of time given the same fertility rates. We change its value from the default (i.e., 22) to 28 years old, which is consistent with the 'later' component of the 'later, longer, and fewer' campaign. Some other developing countries (such as India; see Sushama 1996) have used this approach to curb population increase. (2) Birth interval (time interval between births of two consecutive siblings): the longer this interval, the fewer births within a certain period of time given the same fertility rates. This conforms to the 'longer' component of the 'later, longer, and fewer' campaign. We set its default to be 3.5 based on our data, and change it to 5.5 years as a policy test. (3) Upper birth age: as indicated by Figure 2c, the majority of the females have given birth to their last children prior to 50, so 50 is the default value for the maximal age to give births. However, as economic incentives and technical supports (such as contraceptives) are implemented, this number may undergo great decline. As such, we change it from 50 to 40.

Table 2. Definition of desirable and undesirable scenarios.

Factors	Variable	Desirable scenario	Undesirable scenario
Socioeconomic	Electricity price	0.05 Yuan decline	0.05 Yuan increase
	Outage levels	One level decrease	One level increase
	Voltage levels	One level increase	One level decrease
	Leaving parental home intention (probability)	0.42 → 0.21	0.42 → 0.95
Demographic	College attendance rate (%)	1.92 → 30% (16–20 years old youth)	1.92 → 0.0%
	Female marry-out rate (%)	0.28 → 20%	0.28 → 0.0%
	Fertility	2.5 → 1.5	2.5 → 5
	Birth interval (year)	3.5 → 5.5	3.5 → 1.5
	Marriage age (year)	22 → 28	22

The first numbers in the spaces below are the default values in the model, and the second values are those used in the associated scenarios.

Migration could also affect local population dynamics and household dynamics. First, we consider college attendance rate by changing it from 0.0192 to 0.05 to reflect a policy of more investment on local education in the hope of relocating more young people in the future. Second, we consider female marry-out rate (Table 1): we change it from 0.0028 to 0.20 to represent a possible social change that more local females would be attracted to marry people outside the reserve for purposes such as higher education opportunities and living standards.

In addition to studying the impacts of individual factors described above, we examine two scenarios, considering all of the above factors simultaneously: a desirable scenario with the factors taking values that would benefit panda habitat, and an undesirable scenario with the factors taking values that would degrade panda habitat. Table 2 summarizes what these two scenarios include. Doing so may provide some insight into the range of possible trajectories of panda habitat change.

Results

With changes in five socioeconomic factors (Table 1), the predicted population sizes do not have significant changes (Figure 4a). However, scenario S5 (an increase of leaving parental home intention) has a significant impact on the number of households (Figure 4b). Regarding panda habitat, only scenario S3 (a one level increase in electricity voltage level) does not cause significant changes (Figure 4c). Changes of demographic factors, except scenario D4 (an increase in birth interval from 3.5 to 5.5 years), have significant

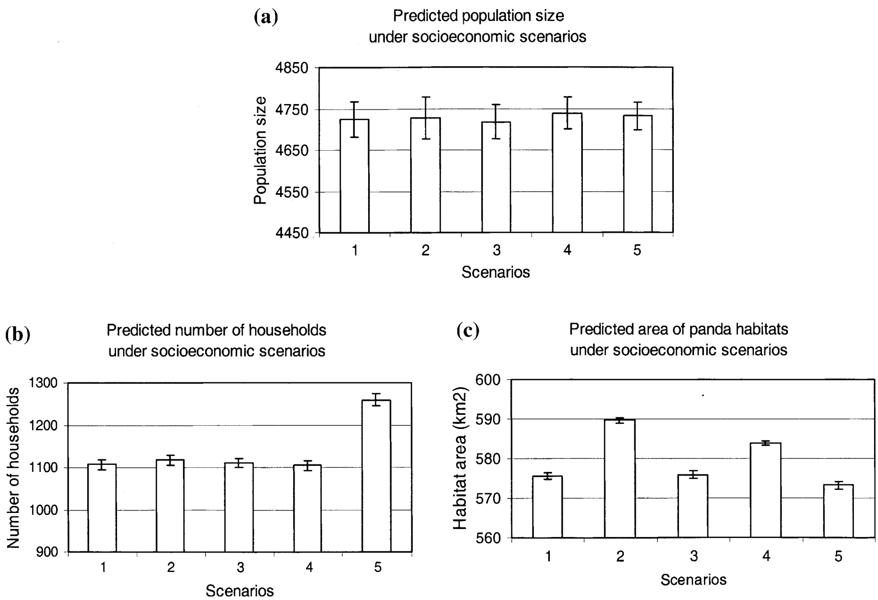

Figure 4. (a) Predicted population size, (b) number of households, and (c) the total amount of panda habitat under five socioeconomic scenarios (see Table 1 for definition of these scenarios).

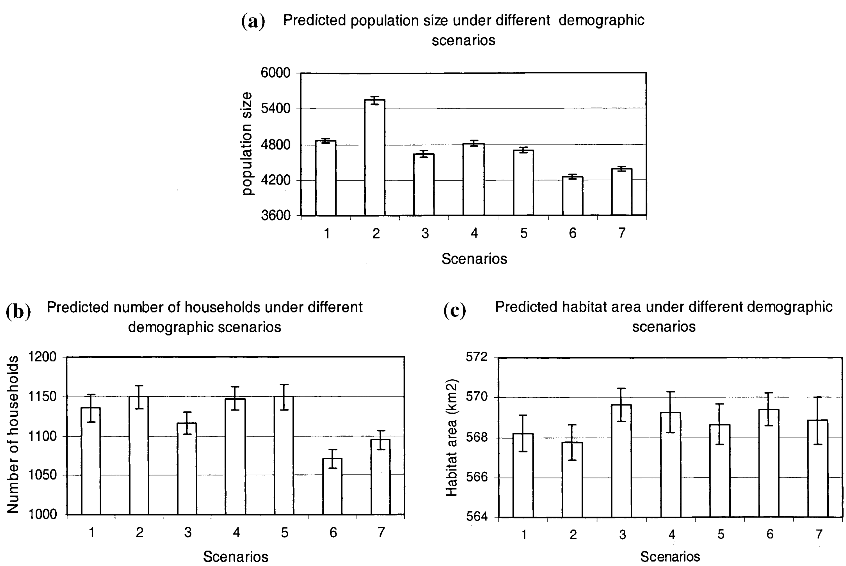

Figure 5. (a) Predicted population size, (b) the number of households, and (c) the total amount of panda habitat under seven demographic scenarios (see Table 1 for the definition of these scenarios).

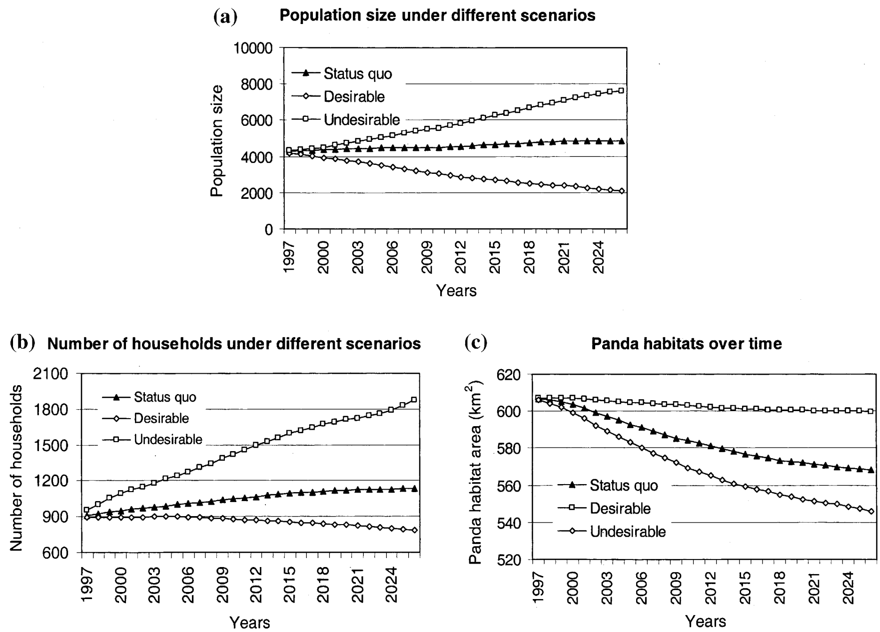

Figure 6. Predicted (a) population size, (b) number of households, and (c) amount of panda habitat over time under status quo scenario, desirable scenario, and undesirable scenario. For definition of desirable and undesirable scenarios, see text in Section 'Simulations'.

impacts on human population size (Figure 5a). Scenarios D4 and D5 (an increase in upper birth age from 55 to 35; (Figure 5b), however, do not have significant impacts on the number of households. Regarding impacts on habitat, only scenarios D3 (an increase of marriage age from 22 to 28 years old) and D4 are significant at the 90 and 95% significance levels, respectively, though the absolute magnitudes are relatively small, ranging from 1.0 to 2.0 km^2 . The other four scenarios have not significantly changed the amount of panda habitat (Figure 5c).

The desirable and undesirable scenarios show that (1) the differences between the impacts on population size, number of households, and panda habitat between these two scenarios become increasingly large with time (Figure 6), and (2) At the end of 2026, there could be a difference of approximately 5550 people, 1100 households, and 54 km^2 panda habitat between these two scenarios. When the spatial distributions of panda habitat and households are considered (Figure 7), it is clearer to see the impacts caused by demographic and socioeconornic factors. Figure 7 shows that with outward expansion of households, the habitat is lost and fragmented over time. In addition, the spatio-temporal dynamics of panda habitat could differ substantially due to different values of the socioeconomic and demographic parameters in the two scenarios.

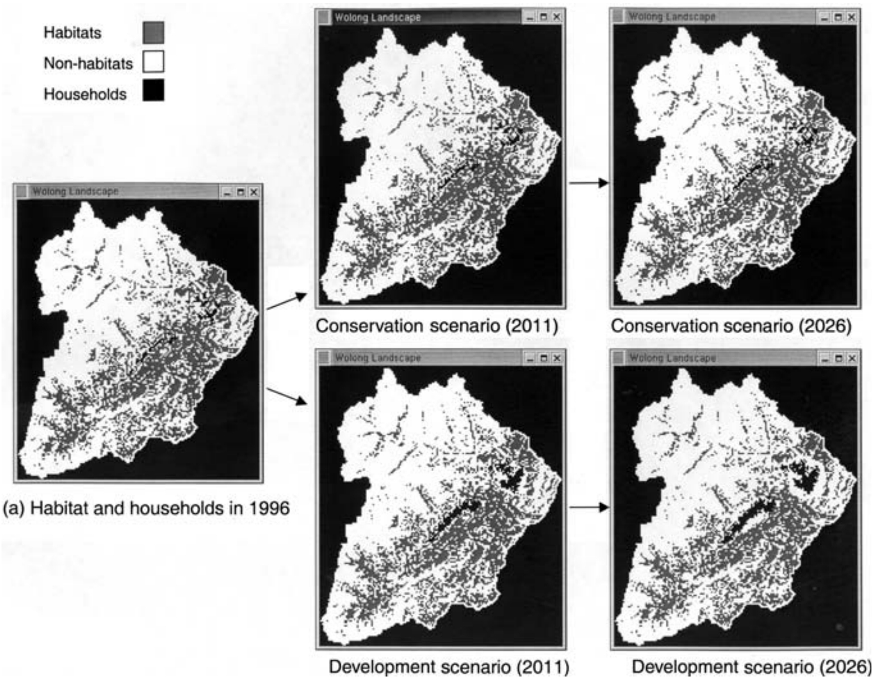

Figure 7. Snapshots of the spatio-temporal dynamics of panda habitat and households in 1996, 2011, and 2026 under conservation and development scenarios.

Conclusion and discussions

The above analyses show that socioeconomic factors play a very important role in affecting the spatio-temporal patterns of panda habitat, while some demographic factors do not have significant impacts on the panda habitat over 30 years. This phenomenon may arise from the cumulative effects of some demographic changes because the longer the time frame, the more differences will be made in human population size or number of households, and thus the more differences are likely to occur in panda habitat. From Figure 6(c), we can see an increasing difference in the impact of human factors between the two scenarios. This escalating-impact trend should be true for the four insignificant factors (D2, D5, D6, and D7) individually as time moves on. For instance, we run the model over a span of 40 years by setting upper birth age (D5) at 35 years old. It turns out that the average amount of panda habitat is 565.10 km^2, and the increase is significant at the 5% level compared to the baseline situation (564.15 km^2). On the other hand, the magnitude of habitat changes (approximately 1 km^2 over 40 years) in relation to the baseline situation may seem insubstantial when the distribution of panda habitat is not considered. Pandas usually prefer those areas that humans also tend to visit for fuelwood collection. So this decrease in habitat may occur in the panda's preferable habitat, which may considerably threaten panda survival.

In this study, we treat many demographic factors as exogenous factors (i.e., not explained or predicted by other factors). An example is fertility, which could be affected by many other socioeconomic and demographic factors as well. For instance, female education, economic equity (e.g., job opportunities) between males and females, household income, and financial equality between rich and poor households could affect fertility rates to varying extent (Daily 1996). In microeconomics where the concept of household production function is introduced and used, the incomes and time value of household members are combined to produce an array of commodities that yield utilities and welfare. As economy grows and the value of human time rises, households tend to have fewer but 'higher-quality' children who receive better health care and higher education (e.g., Schultz 1981). Household income, though a parameter included in the model, is not used in our simulations due to lack of household income data, though it is reported to be an important factor in determining many household decisions regarding fertility (e.g., Klawon and Tiefenthaler 2001) and land use (Perz 2001). In the future, inclusion of this factor may improve the analyses. However, as Wolong is a nature reserve where the primary goal is to protect giant pandas, other endangered species, and the associated ecosystems, economic growth should be encouraged elsewhere.

Our findings in this research are consistent with those of other researchers. First, as indicated by Liu et al. (1999a), human demographic factors (age structures in particular) play an important role in affecting biodiversity conservation in the long term. In our case, a decline in fertility or an increase in marriage age would save panda habitat in the long run. Second, migration (especially through higher education) is an ecologically effective, economically efficient, and socially acceptable approach to conserving wildlife habitat or biodiversity in a broader sense (Liu et al. 1999a). Our results show that an increase in college attendance rate would make substantial differences in panda habitat over 30 years. In the long run, it is worth considering other types of out-migrations aside from what have been included in this research (i.e., migration through marriage and education) because more young people may join the floating population in cities. As the economy in urban areas further grows, more migrants (including local residents in Wolong) may be attracted for higher incomes. Last, non-family organizations or services (electricity subsidy and assistance in our case) can reduce direct consumption of natural resources and could be integrated into programs in environmental protection and biodiversity conservation (Axinn and Barber 2003). We have shown that in the short run, providing subsidies for the use of electricity and increasing the quality of electricity would work well in conserving panda habitat.

Additionally, our findings suggest that family planning (e.g., controls in marriage age and birth time between consecutive children) is very important in conserving natural resources and thus has critical significance in human–

environment studies. This finding also has great policy implications in a developing rural setting such as Wolong, where people still follow a subsistence-oriented lifestyle and need more children as labor force. It may encounter social resistance if a policy of strict birth control (e.g., one child per couple) is implemented. However, policies encouraging later marriage and longer birth interval between children should have more public acceptance, especially when economic incentives (such as electricity subsidy or tax reduction) are tied to such a family planning program.

Based on the findings from our research and other studies, we recommend that a program for providing electricity subsidy and assistance and a policy of out-migration through higher education be implemented and initiated for panda conservation while the existing family planning policy continues to be monitored and implemented. While our research is in progress, the reserve government has built a new hydropower plant, and we hope cheaper electricity could be provided for local people. Aside from such practical purposes, this research is also oriented towards using an integrated approach to explore the impacts of socioeconomic and demographic factors on the environment. As is often the case in many other places or for other purposes such as protection of other species, complexities in many coupled society–biodiversity systems have kept some socioeconomic and demographic factors (often intertwined) and their interactions from being explicitly studied. Though socioeconomic and demographic factors and their specific interactions may differ from place to place, the perspectives and methods used in this research could still be useful. For more effective and efficient biodiversity conservation, it is crucially important, thus highly recommended, that socioeconomic and demographic factors, along with more individual-level information if possible, be integrated into more research and conservation activities.

Acknowledgements

We thank Hemin Zhang and Shiqiang Zhou for their assistance in data acquirement, and the two anonymous reviewers for their comments and suggestions. We are also indebted to financial support from the National Science Foundation (CAREER Award and Biocomplexity Grant), National Institute of Child Health and Human Development (R01 HD39789), American Association for Advancement of Sciences, the John D. and Catherine T. MacArthur Foundation, and Michigan State University.

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