

# Long-term effects of family planning and other determinants of fertility on population and environment: agent-based modeling evidence from Wolong Nature Reserve, China

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**Abstract** The practice of family planning has a long history, but its environmental implications have not often been considered. Using data from Wolong Nature Reserve for the conservation of the world-famous giant pandas in China, we employ a spatially explicit agent-based model to simulate how family-planning and other fertility-related decisions may affect human population, household number, and panda habitat over time. Simulation results indicate that (1) population size has the shortest time lag in response to changes in family-planning decisions, and panda habitat has the longest time lag; (2) the amount of panda habitat is more sensitive to factors affecting number of households than those affecting population size; (3) although not large in quantity nor changing landscape fragmentation substantially, the associated changes in habitat are in good areas for the panda. This study offers a novel approach to studying long-term demographic and environmental effects of family-planning and fertility-related decisions across space.

**Keywords** Family planning · Agent-based modeling · Human population · Multiscale and multidisciplinary integration · Giant pandas · Habitat conservation

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## Introduction

A recent article in the Bulletin of the World Health Organization (WHO) argues that voluntary and rights-based family-planning programs are critical for developing countries to slow population growth and conserve the environment because rapid population growth and several other factors (e.g., climate change) may act cumulatively to deteriorate the environment and increase the vulnerability of humans to natural disasters (Bryant et al. 2009). Indeed, family planning has long been used to achieve the desired fertility levels, as well as to manage the timing and spacing of births (World Health Organization (WHO) 2009). However, the connection between family planning and environmental change remains little explored by the research community. This article provides a novel contribution that explores how individual family-planning decisions could affect long-term human dynamics and the associated environment through innovative application of spatial-temporally explicit modeling. We do so within an environmentally significant context—the Wolong Nature Reserve in rural China that was established to conserve the world-famous endangered giant panda. Both the substantive findings and the methodological approach yield advances in understanding the potential linkages between family planning, fertility decision-making, and environmental change.

## Background

### Population dynamics and land use

The world will soon be home to 7.0 billion people (Population Reference Bureau (PRB) 2009), compared to a global population size of 2.5 billion in 1950 (U.S. Census Bureau 2009). In regard to the effects of rapid population growth, debates have long revolved around the role of mediating factors such as agricultural intensification, technological advancement, cultural/institutional adaptation, and market substitution in the population–environment relationship. In line with such debates, empirical research has also been devoted to addressing questions such as “how much, and under what conditions, may such factors lessen the pressure of population growth on the environment?” (e.g., Boserup 1965; Simon 1990). Despite different opinions, many scholars believe rapid population growth, especially in a fragile environment, contributes to socioeconomic and environmental problems such as malnutrition, hunger, and ecosystem degradation (Vitousek 1994; Hempel 1997; Sinding 2000; Cohen 2003; Carr 2004; de Sherbinin et al. 2007). Some scholars even argue that there exist positive feedback loops among resource depletion, growing poverty, and high fertility, exemplifying what has been termed the vicious circle model (VCM) (Marcoux 1999; Brown 2003). In this context, calls to curb population growth, which can date back to Thomas Malthus’s *Essay on the Principle of Population* (Malthus 1798), have continued and risen sharply since 1960s (e.g., Ehrlich 1968; Meadows et al. 1972; Ehrlich and Ehrlich 2006). Correspondingly, the last several decades have witnessed an increasing amount of

scholarly inquiry into population–environment relationships (e.g., Vitousek 1994; Pebley 1998; Carr et al. 2006a).

Although demographic dynamics include many dimensions, population size has arguably received the most attention in population–environment research (e.g., Ehrlich and Holdren 1972; Bilsborrow and Dleargy 1991; Bongaarts 1996; Dietz and Rosa 1997). Indeed, given a certain level of economy and technology, population size could determine patterns and magnitudes of land cover and land use, biodiversity and vegetation abundance, and consumption of other natural resources (e.g., Cohen 1995, 329–355; Bongaarts 1996; for review see Hunter 2001). According to a review article by de Sherbinin et al. (2007), a few milestone works that look into the consequences of rapid population growth at the global scale are worthy of mention: the report *The Growth of World Population* (U.S. National Academy of Sciences 1963), the book *The Population Bomb* (Ehrlich 1968), and the *World Model* by the Club of Rome (Meadows et al. 1972). At national, sub-national, regional, or local levels, a large number of studies have been conducted to reveal population–environment relationships in different topic or geographic areas, and examples include the studies on food supply in developing countries (Bongaarts 1996), Brazilian Amazon deforestation (Wood and Skole 1998), and the effects of population and affluence on CO<sub>2</sub> emissions (Dietz and Rosa 1997) using the IPAT framework (Ehrlich and Holdren 1972). In contrast to scholarship on population size and its environmental effects, attention to the environmental effects of number of households has been relatively less although it has been increasing recently. There is empirical evidence showing that number of households may be more important than population size in affecting the environment (e.g., Entwisle 2001; Liu et al. 2003a; Walsh et al. 2005; Liu et al. 2007a, b; Yu and Liu 2007).

Aside from population quantities (i.e., population size and number of households) as shown earlier, demographic composition and its dynamics have received considerable attention in population–environment research. A vast amount of research has been devoted to how demographic composition may affect the environment, which may in turn affect demographic decisions and thus demographic composition (e.g., Rindfuss 1991; Liu et al. 1999a; Axinn and Ghimire 2007; VanWey et al. 2007). For instance, Liu et al. (1999a) argue that a higher proportion of young people may cause more habitat loss or fragmentation in Wolong Nature Reserve, China. Using data from Chitwan Valley, Nepal, Axinn and Ghimire (2007) show that neighborhood age structure (measured as the proportion of neighborhood population under age 15) has a significant inverse relationship with percent of agricultural land, but a positive relationship with percent of land for private buildings. The importance of demographic composition in affecting the environment could be, as argued by Rindfuss (1991), that younger age structures, corresponding to larger cohorts in the “demographically dense” period of life (about age 15–30), may stimulate changes in life-history events (e.g., marriage, childbearing, migration). Linking to environmental change, such demographic shifts are likely to translate into larger population size, construction of infrastructure and buildings, and conversion of forest into agricultural land (Moran et al. 2005).

Much of the research on population–environment relationships, no matter focusing on population quantity or population composition, has been conducted at

the macro level, including most of the studies mentioned earlier (e.g., Ehrlich and Holdren 1972; Meadows et al. 1972; Bongaarts 1996; Dietz and Rosa 1997; Wood and Skole 1998). To further population–environment research and complement such macro-level research, many recent studies have operated at micro-levels such as households or farms. Examples of micro-level research include the investigation of the links between household lifecycle variables (e.g., age of household head, duration of residence, and number of children) and environment in frontiers (Murphy 2001; McCracken et al. 2002), relationships between fertility and farm size/tenure (e.g., Stokes and Schutjer 1984; Clay and Johnson 1992; Carr et al. 2006b), and the role of local environment resources as a “safety net” or buffer in times of death or illness of a household member (e.g., McSweeney 2004; Hunter et al. 2007). Excellent reviews on micro-level population–environment research can be found in Sutherland et al. (2004) and de Sherbinin et al. (2008). Focusing specifically on land use, for instance, micro-level relationships and activities are found to be significant in affecting emergent land-use patterns. In the Amazon Basin, Moran et al. (2002) demonstrate that “trajectories of deforestation could be better understood knowing the age and gender structure of households through time, rather than just their aggregate number.” A more recent study also from the Amazon shows that changes in the number of children and women, rather than the number of adult men, exert most significant influences on local land use and land cover change (VanWey et al. 2007).

The above studies, conducted at macro- or micro-levels, undoubtedly shed important insights into population–environment relationships. In particular, the studies at the micro (primarily household)-level provide insights that may be very difficult, if not impossible, to obtain through macro-level studies alone. Clearly this is a significant advancement in understanding population–environment linkages and enriching the set of associated methodological approaches. However, the gender and age differences between household members may give rise to divergent preferences and decisions toward fertility, which may cause varying environmental consequences. There exists striking empirical evidence in this regard (e.g., Birdsall 1988; Wilk 1990; Strauss and Thomas 1995) showing that “the idea of a unitary household decision-making unit [can] be problematic” (de Sherbinin et al. 2008). Consequently, intra-household processes, an important topic not explicitly addressed in population–environment studies yet, should be examined to “link [linking] household demographics and environment” (de Sherbinin et al. 2008). Our research in this paper fills this gap by simulating intra-household processes and their interactions with the environment.

#### Spatially explicit and feedback-informed research on fertility–environment association

Intra-household processes, particularly those related to fertility decisions, obviously play a central role in shaping demographic dynamics, which is likely to modify household-level consumption and ultimately change the environment. A spectrum of research has been devoted to exploring determinants and environmental consequences of varying fertility decisions. As the focus of this paper is not on

fertility determinants, we refer readers with interest in this topic to excellent reviews on this topic by Carr et al. (2006b) and de Sherbinin et al. (2008). In terms of the environmental consequences of fertility decisions, the vicious circle model (VCM) is one of the most influential frameworks. This model hypothesizes that positive feedback loops exist among resource depletion/environmental degradation, growing poverty, and high fertility, contributing to a “downward spiral” (e.g., Marcoux 1999; Brown 2003). Empirical scholarship on fertility in relation to the environment includes fertility impacts on forest transitions (Carr et al. 2006b), consumption of resources such as vegetation (Fricke 1986), and the amount of land devoted to different land-use types (Ghimire and Hoelter 2007; Axinn and Ghimire 2007).

However, little work has examined the micro-level fertility–environment relationships in a spatially explicit manner although fertility processes vary among specific places. Such places have spatially and temporally changing biophysical and socioeconomic conditions, which in turn may affect intra-household processes. Empirical analysis without spatial data would miss the influences of spatial heterogeneity exerted on human decision-making, long-term population dynamics, and the proximate natural environment (Billari and Prskawetz 2003; An et al. 2005; Messina and Walsh 2005). For instance, in the household-level simulations of land cover change in the US Midwest, Evans and Kelly (2004) found that heterogeneous data at fine spatial resolutions were critical in calibrating the model and producing land cover patterns to match observed data. Furthermore, it is found that significant relationships between household demographic patterns (e.g., fertility, morbidity and mortality) and the natural environment are usually mediated through natural resource extraction and other activities at specific locations (An et al. 2005; McSweeney 2005). Thus, considering such activities in a spatially explicit manner should facilitate better understanding of the connection between fertility and the environment. This need for spatially explicit population–environment research is echoed by a recent call to “put people into place” in which human behavior and outcomes are recommended to be explained in a potentially changing local context (Entwisle 2007).

Equally important, if not more important, may be consideration of feedback and interactions between individuals or between individuals and their environment (e.g., Entwisle 2007) in population–environment research. Indeed, much work in mathematical demography (including, but not limited to, research on family planning) has focused on mathematical methods such as using life tables, establishing statistical models, and fitting curves and equations based on aggregated samples or census data (Keyfitz 1976, 1993; Hobcraft et al. 1982; Preston 1993). Much less attention has been paid to how individual people may adjust their fertility or resource utilization decisions (e.g., use of fuelwood) in response to changes in other individuals or in the local environment. Consequently, some complex phenomena such as “emergence” may not be well understood. Emergence arises when local-level characteristics and interactions between actors cause some higher-level or emergent outcomes. Such outcomes may not be explained by low-level information or tracking the activities of local actors alone (Manson 2001; Liu et al. 2007b). We use the popular World Wide Web example to explain emergence. Without central control over how individual people (local actors) make links to

other websites (actions of these actors), the number of links pointing to each web page follows a power law: a small number of web pages are linked to many times and most pages are seldom linked to (a type of emergence that arises “naturally”). Put more generally, the power law emergence reflects the fact that frequency of an item or event is inversely proportional to its frequency rank (Barabasi et al. 1999).

This paper presents several innovations in methods. We advance the micro-level human–environment analysis to intra-household level without making the sometimes problematic “assumption of a unitary household” (de Sherbinin et al. 2008). We further examine the spatial-temporally explicit relationships among population, fertility, and the local environment with consideration of spatial heterogeneity and feedback effects. A spatial agent-based model<sup>1</sup> was developed to simulate the effects of family-planning decisions on human population size, numbers of households, and changes in the local environment within a coupled human and natural system (Liu et al. 2007a, b) in rural China. Specifically, we address the following questions: how does fertility-related behavior of each person affect demographic features (e.g., household size and composition) of his/her household and community over time? Given the spatiality of each household (e.g., varying topography and access to resources), how do its evolving demographic changes translate to changes in the environment through resource use? How do changes in the environment feed back into the corresponding household’s resource use decisions? To the best of our knowledge, little effort has been devoted to simultaneous consideration of all these questions to date, even though recognition of its importance has been noted (e.g., Entwisle 2007; Gaffikin 2007; Spiedel et al. 2007).

Although fertility can be determined or affected by many factors, we consider family planning as a major approach to changing fertility due to its popularity and effectiveness<sup>2</sup> in our study site. Family planning generally refers to the process of planning births as well as the means to implement that process. In this article, family planning means the planning decisions and outcomes of such decisions related to the number, timing, and spacing of births. We structure the paper in the following way: we first provide a short profile of family planning in China, followed by a description of the study site and computer simulation model. Then, we present simulation results with regard to the response of population size, number of

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<sup>1</sup> An agent-based model “predicts or explains emergent higher-level phenomena by tracking the actions of multiple low-level ‘agents’ that constitute, or at least impact, the system behaviors” (An et al. 2005). Agents are objects (e.g., individual people, households, animals) with some degree of self-awareness, intelligence, and knowledge of the environment and other agents. Agents can adjust their own goals or actions in response to changes in other agents or the environment.

<sup>2</sup> In light of frameworks for analysis, research efforts about family planning have been devoted, but not limited, to (1) the effects of family-planning programs (e.g., laws or policies, media, service quality) on contraceptive use, fertility preferences, and realized fertility (e.g., Ross and Issacs 1988); Freedman 1997; Hong et al. 2006; Hutchinson and Wheeler 2006; Demographic and Health Surveys 2009; (2) various clinic-based contraceptive services, their effectiveness on reducing pregnancies and fertility, and people’s opinions or attitudes about them (e.g., Eryilmaz 2006; Foster et al. 2006; Population Council 1998; Steiner et al. 2006); and (3) demographic and socioeconomic characteristics of family-planning participants or non-participants and the psychosocial factors associated with use of family-planning services (e.g., Clarke et al. 2006; Sable et al. 2006).

households, and the environment to changes in family-planning and other fertility-related factors. Finally, we discuss the broader implications of our approach to studying human demographic processes related to family planning and human–environment interactions.

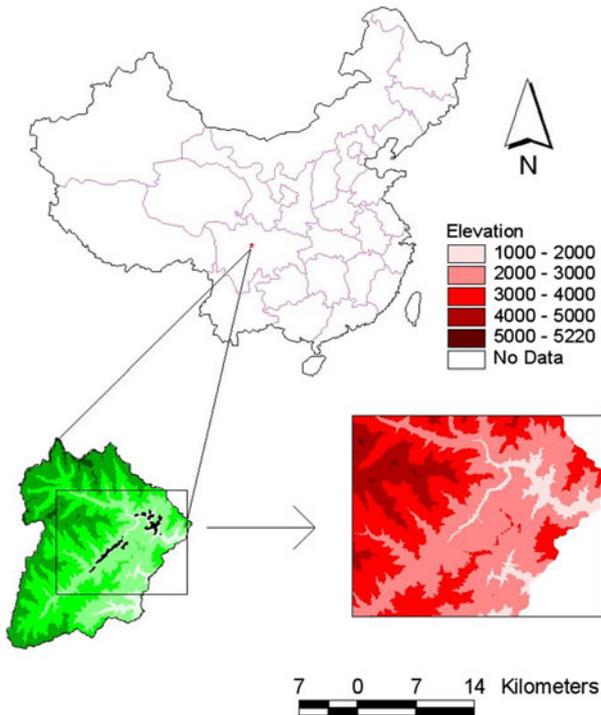
### A profile of family planning in China

China's official family-planning policy began with a “later, longer, and fewer” (*Wan-Xi-Shao* in Chinese) campaign in the 1970s (Feeney and Feng 1993). This campaign encouraged couples to bear children at an older age (later), prolong the interval between consecutive births (longer), and have as few children as possible (fewer). The approach later developed into a more strict one-child policy (with the slogan of “one child per couple”) in cities and many rural regions (Feng and Hao 1992; Lee and Feng 1999). As a result, China's total fertility rate declined from 3.0 in 1979 (Hussain 2002) to 1.8 in the early 1990s (Wong 2001) and has stabilized at approximately 1.7 since 1995 (Liu and Zhang 2009). Even with this fertility decline, however, the country's total population reached 1.24 billion in 2000 due to population momentum (Liang and Ma 2004). China's overall population is projected to be over 1.35 billion in 2010 (United Nations Population Division (UNPD) 2009). The Chinese government still considers family planning an effective way to reduce maternal and child mortality and curb its increasing population size (National Population and Family Planning Commission of China (NPFPC) 2008). Even so, little research has been devoted to examining how family planning, especially when intertwined with other demographic, socioeconomic, and environmental factors, could shape local population and environmental conditions in the long run.

## Methods

### Study site

Wolong Nature Reserve (102°52'–103°24'E, 30°45'–31°25'N), located in Sichuan Province of southwestern China (Fig. 1), was designated in 1975 to conserve the world-famous endangered giant panda (*Ailuropoda melanoleuca*). Based on the 2000 panda census, there were approximately 140 pandas residing in the reserve (Yin 2005), which constitute around 10% of the entire wild panda population (Zhang et al. 1997; World Wildlife Fund (WWF) 2010). With elevations ranging from approximately 1,000–6,250 m, the reserve is home to more than 6,000 species of plants, insects, and animals—and it is within one of the 25 global biodiversity hotspots identified by Myers et al. (2000). One prominent social characteristic is that approximately 4,500 people from four ethnic groups—Tibetan, Han, Qiang, and Hui—live within the reserve's boundaries (Wenchuan County 2006). These local residents, living in more than 1,000 households, mostly depend on growing crops and raising animals for self-consumption. They collect fuelwood for cooking and heating in the long winter (most settlements are in areas with elevations from 1,500



**Fig. 1** The location of Wolong Nature Reserve in China. The region within the rectangle is our study site, and the *black dots* indicate approximate locations of households within the reserve

to 2,000 m), although electricity was available but subject to problems such as relatively high costs, unstable voltage levels, and frequent outages (An et al. 2002).

The same forests from which fuelwood is collected serve as an important panda habitat. Forest cover, slope, altitude, and the availability of bamboo are the important determinants of such habitat (Schaller et al. 1985). The staple food of pandas includes arrow bamboo (*Bashania fangiana*) and umbrella bamboo (*Fargesia rebusta*), both of which grow as understory of broadleaf, conifer, or mixed forests. As large-scale bamboo distribution data are often unavailable in mapping panda habitat, previous research shows that areas with canopy forests, low to moderate elevation (between 1,700 and 3,250 m), and shallow slope (less than 30°) are potential panda habitat (Liu et al. 1999b)—and these proxies are used here when we classify different landscape pixels into habitat or non-habitat.

Factors affecting panda habitat include two types of human resource extraction activities<sup>3</sup>: small-scale tree removal primarily for fuelwood<sup>4</sup> and for house

<sup>3</sup> Other legal activities (e.g., farming) exert much less direct impact on panda habitat. China has a land system in which land is owned by governments and people have usufruct only. Converting forested land to farmland is subject to a very strict approval process, which is even more difficult in Wolong due to its status as a nature reserve.

<sup>4</sup> Fuelwood collection is legal in some parts of the reserve although use of electricity is encouraged.

construction. As fuelwood is the main source of energy for cooking human food, cooking fodder for pigs (a major livestock in the reserve), and heating, fuelwood collection is a major threat to panda habitat in the reserve (Liu et al. 1999b). House construction may also affect panda habitat through wood harvest and residential land allocation. Panda habitat may recover as the forest regenerates, but research suggests such recovery may require nearly 40 years (Bearer et al. 2008). As lower elevation forests are lost, pandas may move to places at higher elevations.

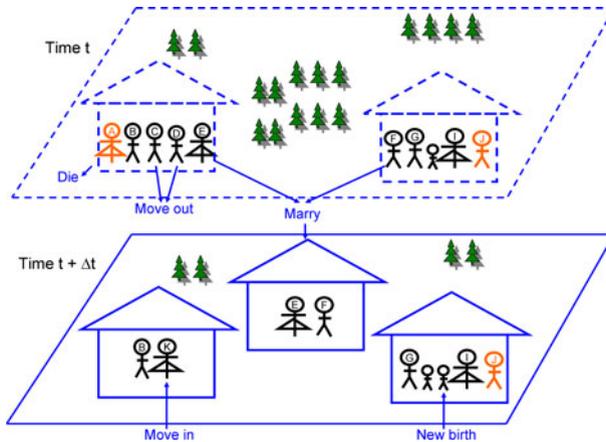
Wolong Nature Reserve has some unique characteristics compared to cities but shares many common features with other rural areas in China. First, the nationwide family-planning policy is still enforced in rural areas. A couple is now allowed to have only two children, and penalties are charged for excess childbearing.<sup>5</sup> Second, the local community still retains a large proportion of young people adhering to the above family-planning policy. This relatively young population is connected to an active local panda-related tourism and business market, where young people find off-farm job opportunities such as selling their products including herbs from the mountains to tourists. Third and last, as the reserve is a relatively isolated place and preserves traditional Chinese culture, local residents live a subsistence lifestyle. This lifestyle, usually labor intensive, is sensitive to any family-planning programs. Such programs usually aim to limit or postpone births, which will translate to a future reduction in local labor force. All these factors make the reserve an excellent place to examine the micro-level relationships among population, fertility, and the environment in consideration of spatial heterogeneity and feedback under different family-planning decisions or policies.

### Model and data description

We have developed an agent-based model to simulate human demographic dynamics and their connections with potential habitat dynamics in a spatially explicit manner. The model has passed a set of tests (e.g., verification, validation, and sensitivity analysis) in terms of population size, number and location of households, and panda habitat amount and spatial distribution over time (An et al. 2005). The following data have been collected to calibrate and verify the model: (1) Social survey data. This dataset includes in-person interviews of 220 households, a spatially stratified (based on villages) random sample from a total of approximately 1,000 households. During the surveys, we asked where and when new households had been/would be established. Other information collected includes annual household fuelwood consumption, the conditions under which local people would be willing to switch from using fuelwood to electricity, etc. (An et al. 2002). (2) Government archival data. This dataset is mainly comprised of 1996 Agricultural Census data (Wolong Nature Reserve 1997) and 2000 census data (Wolong Nature Reserve 2000). Information for the approximately 1,000 households (e.g., farmland area, household composition) and 4,500 individuals (e.g., age, gender, education) is available. (3) Geospatial and remote-sensing data. This dataset includes digital

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<sup>5</sup> The one-child policy is implemented in urban areas. Two children are allowed in many rural areas of China.



**Fig. 2** Conceptual framework of our agent-based model. It highlights the major components and processes while excluding much detail. The *upper dashed part* is for an earlier time and the *lower solid part* is for a later time. Modified from Fig. 4 in An et al. (2005)

elevation models at 30- and 360-m resolutions, a land-cover classification map (Linderman et al. 2004), and geographic coordinates of all the households in Wolong (An et al. 2005). More details about these data are provided below.

The conceptual model is illustrated in Fig. 2. The dashed upper part is for time  $t$ , where the two symbolic households (including all individuals within each household) represent all households on the landscape within the reserve. The solid lower part is for time  $t + \Delta t$ , where the households evolve from those at time  $t$ . During the time interval  $\Delta t$ , Person A (female, parent of B, C, D, and E) dies, Person B remains in the same household and marries Person K, who moves into the household from outside the reserve. Persons C and D (males) move out of the reserve (e.g., through marrying people outside the reserve or going to college), and Person E (female) marries Person F (male) from a different household and establishes a new household (in the middle; lower panel, Fig. 2). Except for Person F, who marries and moves out, all individuals in the right household at time  $t$  survive and remain in the same household with a new baby born into the family.

On the environmental dimensions, within our conceptual model, forests are cut for house construction or fuelwood. In addition to natural growth or regeneration processes, the local forests at the earlier time (upper panel, Fig. 2) may experience different human interferences due to varying local topography and accessibility conditions. The forest on the left of the lower panel (Fig. 2) exists without an obvious reduction in volume; the one on the right still exists with a reduced volume, and the one in the middle is destroyed due to house construction or fuelwood collection. These and other changes in forests would affect panda habitat amount, location, and quality that are determined by the criteria set by Liu et al. (1999b; also see “Study site”).

## Mapping and modeling the heterogeneous biophysical environment

The biophysical environment is represented as 360-m  $\times$  360-m pixels—a tradeoff between a fine resolution to capture as much environmental heterogeneity as possible and a coarse resolution to maintain computation efficiency. To map panda habitat, we used the criteria of Liu et al. (1999b) in relation to elevation, slope, and canopy forest, as mentioned earlier. We do not include bamboo information in habitat identification because information about bamboo dynamics over time across large spatial extents is not available (Liu et al. 2001).

Each pixel is assigned a range of characteristics, including elevation, slope, aspect (estimation based on a digital elevation model of 360-m resolution), and the primary land-cover type derived from a supervised land-cover classification (Linderman et al. 2004). There are ten classes of land cover, including deciduous forests, coniferous forests, mixed deciduous and coniferous forests, and several non-forest types (Linderman et al. 2004). We find that previous research on local vegetation (Yang and Li 1992) can be used to parameterize the three forest types in terms of forest volume, age, and growth rate (An et al. 2005). For instance, a cell of deciduous forest is randomly assigned an age between 50 and 100 years and a volume between 60 and 100 m<sup>3</sup>/ha. The growth rates can be simplified to 0.8 or 1.0 m<sup>3</sup>/ha/year if the age is between 50 and 80 years or between 80 and 100 years, respectively. If the age goes above 100 years or the volume above 100 m<sup>3</sup>/ha, the growth may stop, i.e., the rate = 0.

## Modeling life-history events

A number of life-history events in this research are modeled based on empirical data. The model simulates the real life histories of local residents, which is important in the context of this research because we explore the effects of family-planning decisions (e.g., time spacing between two consecutive children) and other fertility-related factors (e.g., age at the first marriage; Table 1) on the dynamics of population, number of households, and ultimately, panda habitat.

*Marriage.* Based on age and marital status, a person is assigned to one of four groups: (1) young group (unmarried and less than 22 years old), (2) single male group (single males equal to or over 22 years old), (3) single female group (single females equal to or over 22 years old), and (4) married group. When a person reaches the age at first marriage (a parameter, i.e., *MarryAge* in Table 1), he/she will move from the young group to either single male or single female group. The people in these two groups, qualified to marry one another (except for people with the same household ID) or people from outside the reserve, will get married at empirical probabilities each year and move to the married group. Based on traditions and our observations in Wolong, we assume that local people get married prior to starting a family (not vice versa). A married person will be moved back to the single male or single female group if his/her spouse dies (see below for simulation of deaths). Divorce is not modeled because it is a rare occurrence in Wolong.

*Birth.* The time of first childbearing after marriage is set as a parameter (*FirstKidInterval* in Table 1), randomly taking values of 1 or 2 years based on our

**Table 1** Simulation experiment design

Variables	Definition	Baseline	Values for individual experiments	Demographic contraction scenario	Demographic expansion scenario
<i>MarryAge</i>	Age at first marriage (years old)	22	22, 26, 30, 34, 38	38	18
<i>FirstKidInterval</i>	Time between the first marriage and the first birth (years)	1	1, 3, 5, 7, 9, 11	Any number <sup>a</sup>	1
<i>BirthInterval</i>	Time spacing between consecutive births (years)	3	1, 3, 5, 7, 9, 11	Any number	1
<i>NumOfKids</i>	Fertility rate (number of children a woman plans to have)	2	1, 2, 3, 4, 5, 6	Any number	6
<i>UpperBirthAge</i>	Upper child-bearing age (years old)	50	30, 35, 40, 45, 50, 55	30	55

<sup>a</sup> See text in section “Comprehensive experiments” for the reason

field observations. As locals in Wolong still hold a traditional attitude toward marriage and birth, children born out of marriage are very rare and thus not considered in the model. The intended number of children a female may bear during her lifetime is termed as her birth plan (i.e., *NumOfKids* in Table 1). This plan may take integer values of 0–5 with varying empirically based probabilities, resulting in 2.5 children per woman (average parity) as reported by Liu et al. (1999a). Birth interval is the time interval between births of two consecutive children (*BirthInterval* in Table 1), assumed to take integer values from 1 to 6 years with even probabilities and the average equal to the empirically based time (3.5 years; Wolong Nature Reserve 2000). The upper childbearing age (*UpperBirthAge* in Table 1) is defined as the age beyond which a woman will not bear any additional children. Its default value (50) is derived from 2000 census data (Wolong Nature Reserve 2000).

When assigning values to these four parameters, we do not consider their potential correlations due to lack of empirical data. However, our agent-based model “mimics” marriage/childbearing behaviors on an individual basis, which should rule out some unrealistic combinations. For instance, a woman who has a late marriage age (e.g., 35) will not accomplish her birth plan (e.g., 5 children) if she has a relatively low upper childbearing age (e.g., 45 years old) and long birth interval (e.g., 5 years). When she reaches her *UpperBirthAge*, she will stop bearing children in the model, regardless of whether her birth plan has been fulfilled.

*Death and migration.* According to empirical yearly mortality rates<sup>6</sup> for age groups 0–5, 6–12, 13–15, 16–20, 21–60, and over 60 (An et al. 2005), a person may die if the random number generated by the model is less than the mortality rate corresponding to the age group to which s/he belongs. Males and females may move out of the reserve through marriage (between 22 and 30 years old) or going to college and settling down elsewhere (between 16 and 20 years old). Individuals

<sup>6</sup> These rates incorporate deaths caused by all possible factors, such as maternal mortality.

from outside may migrate into the reserve for marriage. The probabilities for such in-migrations or out-migrations are derived from 1996 Agricultural Census data (Wolong Nature Reserve 1997) and 2000 census data (Wolong Nature Reserve 2000; for detail see An et al. 2005). We consider in-migration through marriage only because the *hukou* system of permanent residence permits (Liu 2005) does not allow other types of migration into the reserve.

### Modeling household dynamics

As in other rural regions across the globe, rural China has a household-based farming system, thereby making households the basic units of many consumption and production processes. Household information, including household size and composition (e.g., the number of people, the age and gender of each household member) and cropland area, is derived from 1996 Agricultural Census data (Wolong Nature Reserve 1997). The households are mapped based on the coordinates obtained through a global positioning system (Trimble<sup>®</sup>) and GIS mapping tools (Environmental Systems Research Institute (ESRI) 2007). As life-history processes take place, households may evolve in size and composition, e.g., a baby is born into the lower-right household (Fig. 2). While existing households may be dissolved if all members move out or die, new households may be established (such as the middle household in the lower panel of Fig. 2). With land from the parental household (the areas are proportional to the sizes of the two households), the new household may be established at a location near the parental household (usually  $\leq 800$  m away based on our field observations) and at less than  $37^\circ$  in slope and less than 2,610 m in elevation (G. He, personal communication). New houses, usually in rectangular shape with an average area of  $118 \text{ m}^2$  (not including yards), are built for those people who decide to leave parental homes at the time a new family is formed (Wolong Nature Reserve 2000).

A number of married people may establish their own new households as Persons E and F do, while others may remain in their original households (e.g., Person B in Fig. 2). This decision is determined by several factors such as gender, as well as gender and order of siblings, if any (An et al. 2003, 2005). We use a probability to represent this decision, which may take different values depending on the above conditions. For instance, a local female may remain in her parental household with her husband at a probability of 0.58 after marriage if she (1) has no siblings or (2) is the youngest among siblings and all of them are females. Taking the above processes into account, the model simulates the dynamics of all local households. They may grow, decline, or remain unchanged in size. Some households may dissolve or be established, depending on the life events and demographic features of all individuals in these households.

Large-scale commercial timber harvesting has been prohibited since 1975, when the Wolong Nature Reserve was established (Liu et al. 2003); the conversion of forested land to farmland was limited due to its status as a reserve (see “Study site” section). The major connection of the human and environmental systems is realized through fuelwood collection. We link the household demographic and

socioeconomic data with their energy decisions based on our in-person interview results. The model calculates the amount of actual fuelwood demand as

$$Fwd\_actual = fwd \times (1 - Elec\_prob) \quad (1)$$

where *Fwd\_actual* is the actual household annual fuelwood demand, *fwd* is the household annual fuelwood demand without considering an electricity subsidy, and *Elec\_prob* is the probability that a household will switch from using fuelwood to electricity (the only feasible alternative energy source in the reserve). The variable *fwd*, comprised of fuelwood for heating and cooking, can be calculated as a function of household size, whether a household has a senior person (age 60+), and cropland area cultivated for growing corn and potatoes (An et al. 2001). This function establishes a link between household fuelwood demand and its demographic and socioeconomic features. The variable *Elec\_prob* is modeled as a function of a set of socioeconomic and demographic variables based on data we collected about them through government archives (e.g., Wolong Nature Reserve 2000) and our in-person interviews (An et al. 2002). Such variables include electricity price, voltage levels, outage frequency, and several non-electricity variables such as age of the household head, geographic location of the household, and perceived fuelwood transportation distance.

#### Human–environment interaction

Although less influential than fuelwood collection, house construction also plays a certain role in affecting the environment. We model this process by removing the forest (if any) for household construction within a certain radius from the corresponding household (a parameter defaults to 90 m based on our field observations). Other activities such as farming are not included in the model (An et al. 2001, 2005). Demand for fuelwood is calculated in Eq. 1. People visit available forests that are within 1,080 m, between 1,080 and 2,160 m, and over 2,160 m from their households to collect fuelwood at the observed probabilities of 0.48, 0.27, and 0.25, respectively (G. He, unpublished data). A household is set to collect fuelwood in one of the above distance intervals at these empirical probabilities. Among the sites within the distance interval thus determined, one site is chosen that has the smallest cost distance. Using pixel elevation and slope data, the model calculates cost distances between a household and its nearby forests in consideration of minimizing energy consumption: A person carrying fuelwood on his/her shoulders chooses a downhill first, then flat road, and an uphill last. The household chooses the conceivably “best” fuelwood collection place<sup>7</sup> using rules of

<sup>7</sup> Between the household and the forest, a buffered area is constructed along the straight line connecting them. This buffered area, controlled by a parameter for its size, would help the fuelwood collector stray as little as possible to save energy cost. The collector chooses the cell that has a lower elevation (or the cell with the smallest elevation increase) largely in the direction of the household within the buffer area. To save energy cost, we assume the collector would not turn back once he/she moves to a new cell. He/she will keep searching the cells in front until the target household cell is reached. Calculating the Euclidean distance between each pair of adjacent cells that he/she passes, the model readjusts the distance by dividing the cotangent of the slope angle between the two cells. The sum of all such adjusted distances is defined as the cost distance between the household and the forest. Using the same algorithm, the distances

bounded rationality (the decision maker, given limited information and computation capacity, makes decisions of incomplete rationality; see Cho 2005 for more detail).

People affect changes in the environment, and these changes, in turn, shape future human decisions. The model incorporates such feedbacks in two ways. First, the model endows individual households with “intelligence” to search for fuelwood collection sites using the same algorithm mentioned earlier. Second, when the collection distance becomes larger, local households’ probability to use electricity will increase, and thus decrease the fuelwood demand (see the explanation on *Elec\_prob* for Eq. 1; An et al. 2002). Here, the estimated distance is the cost distance (see footnote 7) between households and fuelwood collection sites during the previous year.

### Simulations and data analysis

The overarching goal of this study was to examine how family-planning decisions could affect long-term demographic dynamics and the associated environmental changes in a spatially explicit manner. Simulation experiments are designed to explore how population size, numbers of households, and panda habitat may respond to changes in individual parameters (individual experiments) or in a set of parameters (comprehensive experiments).

Most local households are in clusters near the major road (Fig. 1), and production- and consumption-related activities (e.g., farming, collecting fuelwood) have rarely occurred in remote areas that are topographically difficult for local residents to access (J. Yang and S. Zhou, personal communications). Therefore, we restricted our study site to a rectangular area of approximately 1,178 km<sup>2</sup> (Fig. 1) to facilitate faster simulations. We focused on long-term patterns of three dependent variables (population size, number of households, and panda habitat) in response to changes in the five family-planning variables. These variables are (1) age at the first marriage (*MarryAge* in Table 1), (2) time spacing between two consecutive births (*BirthInterval*), (3) time between the first marriage and the first-born child (*FirstKidInterval*), (4) birth plan (*NumOfKids*), and (5) upper childbearing age (*UpperBirthAge*, Table 1). Except for age at the first marriage<sup>8</sup> that was considered by Bongaarts (1978) as a “proximate determinant” of fertility, the other variables are outcomes of family-planning practices, services, or programs aimed at changing fertility rate as well as timing and spacing.<sup>9</sup> For instance, reduced fertility may arise from use of contraceptives or post-partum abstinence, longer spacing of births from improved clinic service or health counseling, and an increase in age at marriage from education or employment enhancement.

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Footnote 7 continued

between the household and other potential forest cells can be calculated. The forest cell with the smallest cost distance from the household will be chosen as the fuelwood collection site.

<sup>8</sup> This variable has been shown to have a negative association with fertility (e.g., Jones 2007).

<sup>9</sup> Spacing and timing of births have also received considerable attention as they affect completed fertility (e.g., Kohler and Ortega 2002).

### Individual simulation experiments

We conduct individual experiments by varying the value of each of the above five independent variables, running the model under each parameter setting for 30 replicates, and recording the values of the three dependent variables over 50 years. The decision to run 30 replicates comes from the need to capture the effects of stochastic processes (see “[Model and data description](#)” section) on simulation results without greatly sacrificing efficiency. This decision is also based on understanding drawn from prior simulations, in which relatively small variations exist in the simulation outcomes and can be captured by 30 replicates. In similar agent-based modeling contexts, many researchers run 20–30 replicates to account for stochastic processes in the associated models (e.g., Lustick 2000; Deadman et al. 2004; Castella et al. 2005; Robinson and Brown 2009).

Depending on the default value of the variable under consideration, i.e., the observed value or the value designated by the law or local policy, we choose six discrete values that satisfy the following criteria: (1) the default value is included, (2) all values are theoretically possible, and (3) the increment is large enough to cause observable changes in at least one of the three dependent variables at a later time (e.g., year 10). For example, the default value for the age at first marriage is 22 (years old). We use an increment of 4 and choose the ages of 18, 22 (the default value), 26, 30, 34, and 38 years old to conduct experiments. To simplify presentation, we show only the results for four of the values. The same considerations apply to the other four independent variables (see Table 1).

### Comprehensive experiments

By varying the values of all five variables simultaneously (see Table 1), we develop two comprehensive scenarios. One is the demographic contraction scenario, in which the five family-planning variables are set at values that would decrease human population size and sometimes number of households as well in the long term in favor of panda habitat conservation. Specifically, we set *MarryAge* at a value (e.g., 38) greater than *UpperBirthAge* (e.g., 30; or any other numbers less than or equal to *MarryAge*), which guarantees zero new births regardless of the values of other variables. In doing so, we aim to give an extreme (rather than realistic) scenario. The other scenario represents demographic expansion, in which the five variables are set at values that would favor increases in human population size and number of households. We set these five independent variables to very low or very high values to show how the population size, number of households, and panda habitat could be affected by different family planning and other fertility-related variables. Specifically, *MarryAge* = 18, *BirthInterval* = 1, *FirstKidInterval* = 1, *NumOfKids* = 6, and *UpperBirthAge* = 55. This best enables identification of possible long-term effects.

### Spatial habitat analysis

In addition to providing insights into overall human population size, number of households, and amount of panda habitat, our spatially explicit approach allows for

**Table 2** Results of habitat pattern analysis using Fragstats

	# Of patches	Mean patch area (ha)	Cohesion	Contagion	Shannon evenness
Habitat at year 0	83	393.17	97.05	17.58	0.90
Baseline scenario at year 50	89	313.22	96.27	24.25	0.84
Demographic contraction scenario at year 50	90	322.27	96.36	22.50	0.86
Demographic expansion scenario at year 50	85	320.34	96.25	25.24	0.83

*Note:* Results are calculated based on the average of 30 replicates. # Of patches is the number of patches in the landscape of patch type (class) I (here panda habitat). Mean patch area is the average area (ha) of habitat patches. Cohesion is a measure of the physical connectedness of the corresponding patch type (here panda habitat); it ranges from 0 (very poor connectedness) to 100 (perfect connectedness). Contagion is a measure of aggregation of patch types where 100 means the landscape consists of a single patch and 0 the landscape is well interspersed by all patch types. Shannon evenness measures the evenness of proportions of the landscape occupied by all relevant patch types, where 0 stands for that the landscape contains only 1 patch, and 1 for perfectly even distribution of area among all patch types (see Fragstats documentation)

inclusion of geographic locations with different biophysical, socioeconomic, and human–environment processes. We first map the habitat in different scenarios representing habitat outcomes as a result of different natural (e.g., forest growth) and human (e.g., demographic changes) processes.<sup>10</sup> Based on these maps, we then calculate several landscape metrics (Table 2) to quantify the overall changes in habitat connectivity and/or fragmentation at the landscape level using Fragstats 3.3 (McGarigal et al. 2002).<sup>11</sup> For the purpose of map overlay in ArcGIS (Environmental Systems Research Institute (ESRI) 2007), we produce three binary maps based on maps 2–4 (see footnote 10). Pixels with a probability of being habitat equal to or greater than a cut-off probability (here 0.5)<sup>12</sup> are assigned “habitat” (1), and those with a probability less than the cut-off probability are “non-habitat” (0).

### Linking family planning, demographic changes, and shifts in panda habitat

Finally, we quantify and map the changes in probable panda habitat for three scenarios: (1) Lost habitat at year 50 under the baseline scenario (the difference between maps 1 and 2); (2) Saved habitat under the demographic contraction

<sup>10</sup> We produce (1) a map of habitat at year 0 (1996); (2) a probability map of habitat in the baseline scenario at year 50 (2046; the same hereafter); (3) a probability map of habitat in the demographic contraction scenario at year 50; and (4) a probability map of habitat in the demographic expansion scenario at year 50. Maps 2–4 are calculated as the averages of the 30 replicates at year 50 and expressed as a probability gradient of 0 (non-habitat) to 1 (habitat).

<sup>11</sup> We measure number of habitat patches, patch cohesion index (a measure of habitat connectivity), mean patch area, contagion (a measure of spatial clumpedness), and Shannon evenness index (for detail see Chap. 5 in Turner et al. 2001).

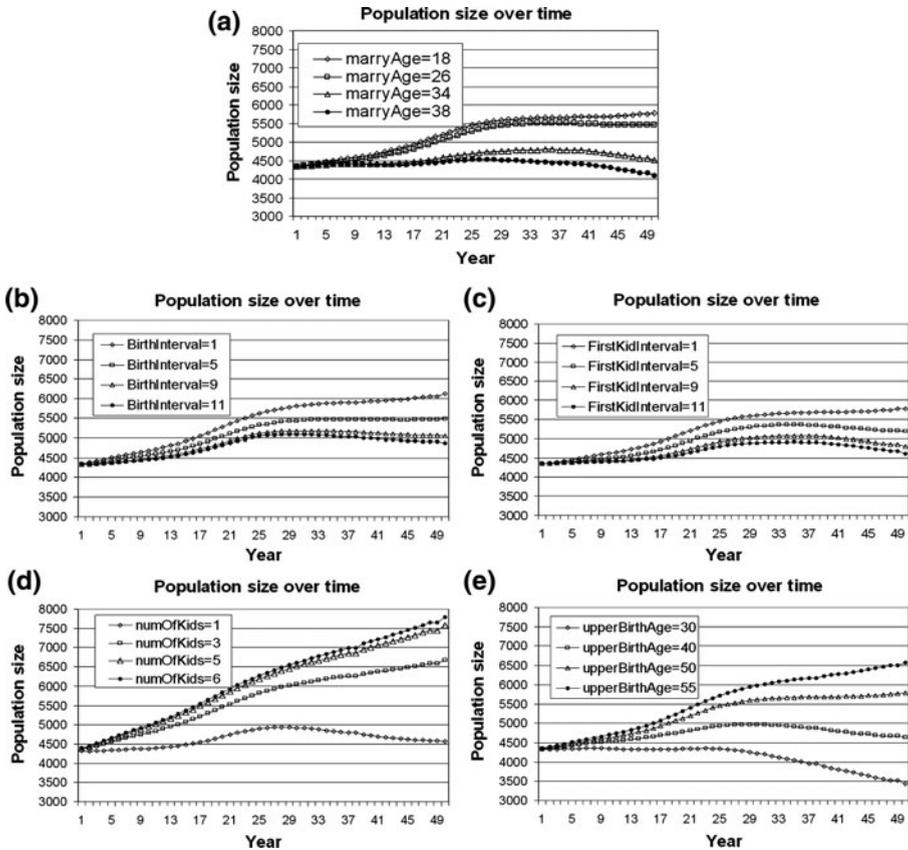
<sup>12</sup> We calculate the amount of saved or lost habitat at the probabilities of 0.20, 0.25, ..., 0.90, resulting in a near-linear relationship between amount of saved or lost habitat and threshold probabilities. So we choose 0.5 (i.e., 50%) as the threshold value: When a cell has 0.5 or higher likelihood to be habitat, it will be counted as a “habitat” cell; otherwise it will be “non-habitat”.

scenario at year 50 (the difference between maps 2 and 3); and (3) Habitat loss under the demographic expansion scenario at year 50 (the difference between maps 2 and 4).

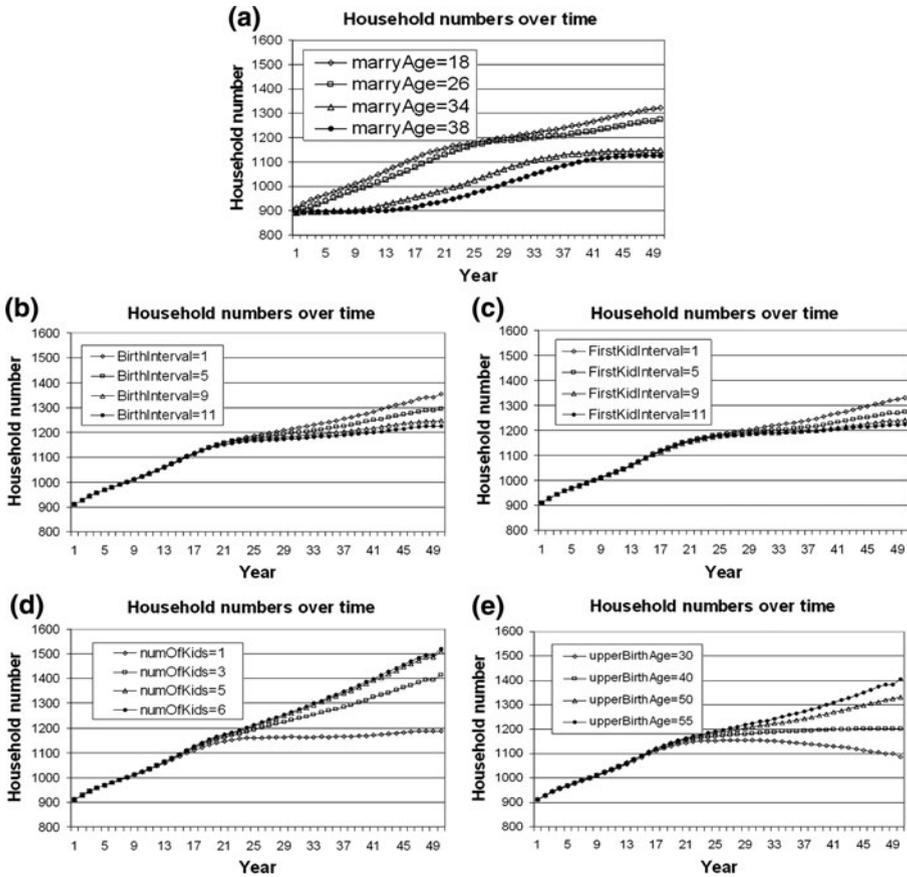
Further, we calculate several descriptive statistics of the saved or lost habitat related to its elevation, slope, and vegetation type. We perform all map overlays and calculations in ArcGIS 9.2 (Environmental Systems Research Institute (ESRI) 2007).

### Results

We first report changes in population size, number of households, and amount of panda habitat as related to each of the five individual family-planning factors (Figs. 3, 4, 5, the results of individual experiments) and the two comprehensive scenarios (Figs. 7, 8, 9). Next, results of spatial habitat analysis are presented.



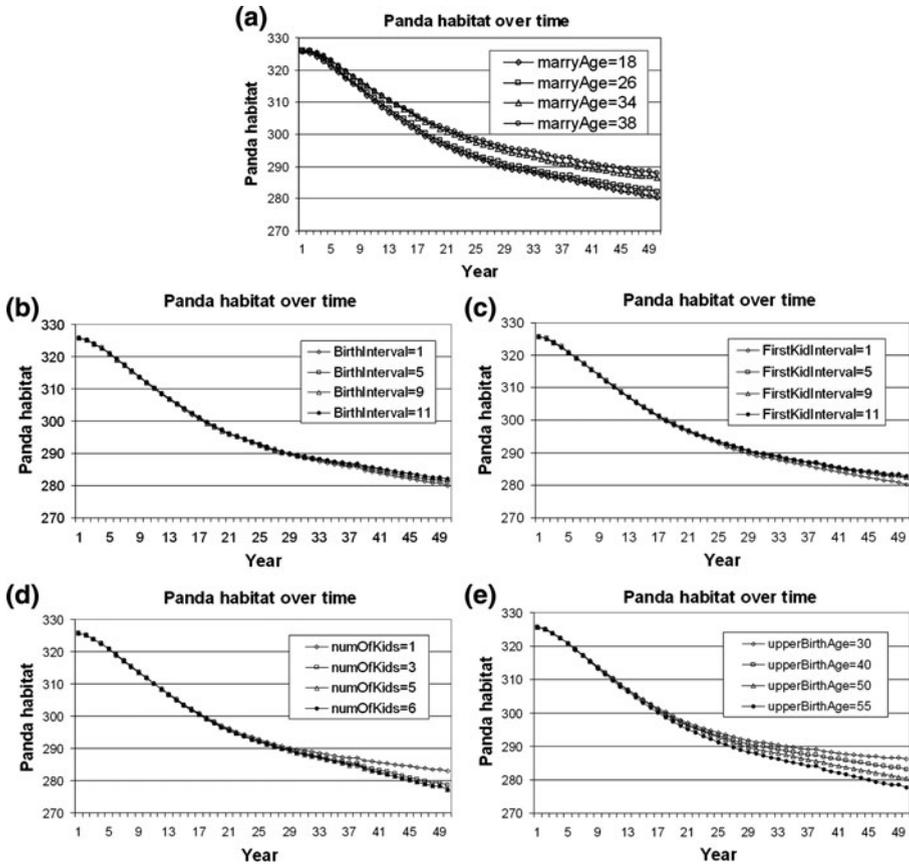
**Fig. 3** Population dynamics over 50 years when different values are taken in **a** *MarryAge*, **b** *BirthInterval*, **c** *FirstKidInterval*, **d** *NumOfKids*, and **e** *UpperBirthAge*. For a clearer figure, the curves for four of the values taken by each variable are shown



**Fig. 4** Household dynamics over 50 years when different values are taken in **a** *MarryAge*, **b** *BirthInterval*, **c** *FirstKidInterval*, **d** *NumOfKids*, and **e** *UpperBirthAge*. For a clearer figure, the curves for four of the values taken by each variable are shown

Effects of family-planning scenarios on population size and number of households

When people postpone their marriages (*MarryAge* changes from 22 to 38 years old), the difference in overall population size over time becomes increasingly large. By year 50, there are 1,700 fewer people (Fig. 3a). When people get married at 30 or older (i.e., age at first marriage  $\geq 30$ ), population size starts to decline at some time point (e.g., year 35 when *MarryAge* = 30). When the time between marriage and bearing first children (*FirstKidInterval*) or the time between two consecutive births (*BirthInterval*) is considered (Fig. 3b, c), the population trend is similar to the trend in response to changes in *MarryAge*. When the values of these two variables are large enough (e.g., *BirthInterval*  $\geq 7$  or *FirstKidInterval*  $\geq 5$ ), the overall population size begins to slowly decline from approximately year 39. When locals



**Fig. 5** Panda habitat dynamics (unit: km<sup>2</sup>) over 50 years when different values are taken in **a** *MarryAge*, **b** *BirthInterval*, **c** *FirstKidInterval*, **d** *NumOfKids*, and **e** *UpperBirthAge*. For a clearer figure, the curves for four of the values taken by each variable are shown

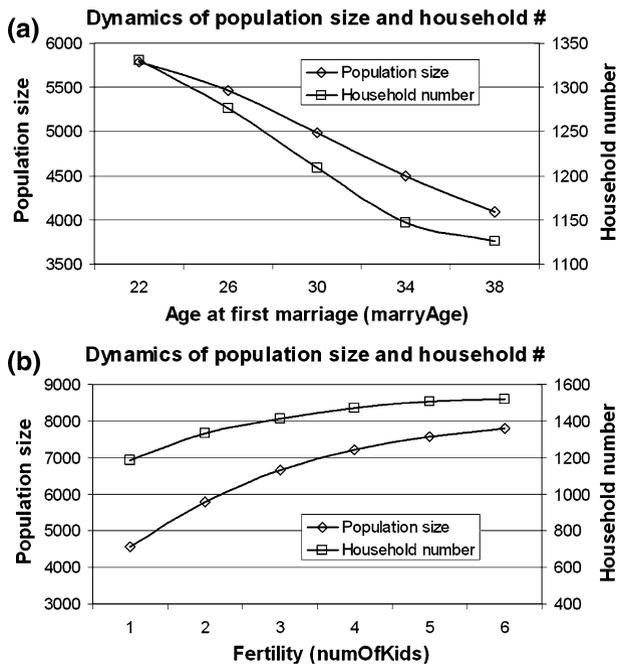
increase fertility (*NumOfKids*) or choose to bear children at older ages (*UpperBirthAge* becomes larger), the difference in human population size between two scenarios (e.g., *NumOfKids* = 1 vs. *NumOfKids* = 6) turns to increase rapidly over time (Fig. 3d, e).

The number of households under different parameter values (Fig. 4) changes very differently than population dynamics do (Fig. 3). First, except for changes made in the upper childbearing age (*UpperBirthAge*; Fig. 4e), number of households *increases* continuously in all situations (Fig. 4a–d). Second, except for age at first marriage (*MarryAge*; Fig. 4a), numbers of households among different parameter values are quite close with each other until fairly late. For instance, when fertility increases from 1 to 6, the number of households remains nearly unchanged until year 20. From that point on, the difference in the number of households becomes increasingly large and reach 260 till the end year of simulation (i.e., between *NumOfKids* = 1 and 6; Fig. 4d). However, the same increase in

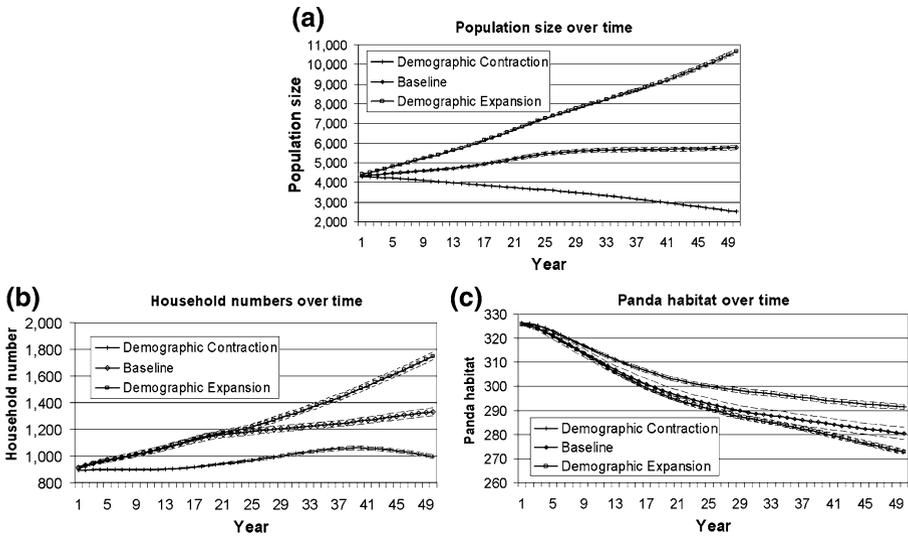
fertility from 1 to 6 brings fairly big differences in population size even at early times, and such differences become larger with time (Fig. 3d).

Worthy of mention are the non-linear effects of these family-planning factors. Take age at first marriage (*MarryAge*) and fertility (*NumOfKids*) as an example. When age at first marriage changes from 22 to 38 (Fig. 6a), the population size at year 50 declines in a nearly linear manner. Interestingly, number of households starts to level off at year 34 (Fig. 6a). When varying fertility (*NumOfKids*) from 1 to 6, population size and number of households increase at reduced rates over time (Fig. 6b). For instance, when fertility increases from 1 to 2, there is a net increase of nearly 1,200 people and 150 households at year 50. However, when fertility increases from 5 to 6, the increases in population size and number of households are only 200 and 12, respectively. This could arise from the fact that other family-planning factors such as time spacing between births (*BirthInterval*), time between marriage and first birth (*FirstKidInterval*), and the upper child-bearing age (*UpperBirthAge*) play a role in determining the number, timing, and spacing of births. Due to many stochastic processes existing in marriage and childbearing (see “[Modeling life-history events](#)” section), a woman with four or five children may have reached her upper child-bearing age and would be unable to bear more children despite her birth plan of, e.g., six children.

At year 50, a total of approximately 420 more households, corresponding to 4,800 more people, would be added to Wolong Nature Reserve if the demographic



**Fig. 6** Changes in population size and number of households (at year 50) caused by different values in **a** *MarryAge*, and **b** *NumOfKids*



**Fig. 7** a Population dynamics, b household dynamics, and c panda habitat dynamics in demographic contraction, baseline, and demographic expansion scenarios

expansion scenario replaces the baseline scenario (Fig. 7a, b). If the demographic contraction scenario is implemented, a total of 3,300 people and 335 households would be taken away from the baseline scenario at year 50. At year 38, the number of households begins to decline in the demographic contraction scenario (Fig. 7b), and the differences between the demographic expansion and contraction scenarios become increasingly large over time.

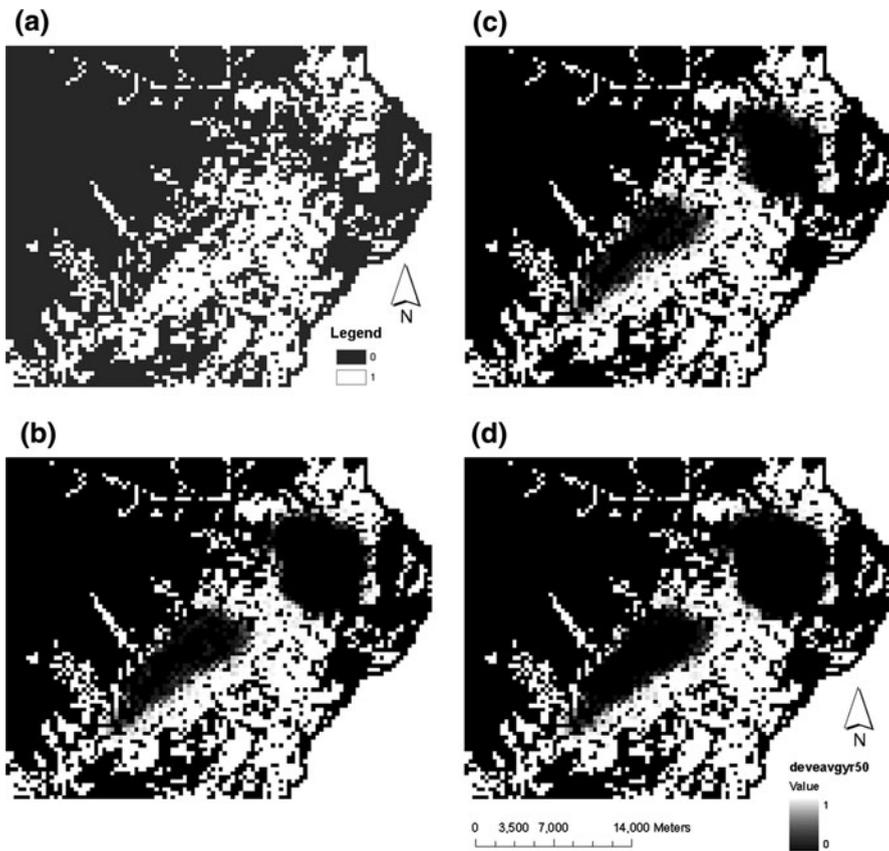
Effects of family-planning scenarios on panda habitat

Considering the habitat changes caused by individual factors, age at first marriage (*MarryAge*) and upper child-bearing age (*UpperBirthAge*) yield the two largest values, i.e., 8 km<sup>2</sup> between *MarryAge* = 38 and 18 (Fig. 5a) and 10 km<sup>2</sup> between *UpperBirthAge* = 30 and 55 (Fig. 5e). Fertility (*NumOfKids*), when taking 1 and 6, gives a difference of 5.6 km<sup>2</sup> in habitat at year 50 (Fig. 5d), while time spacing between births (*BirthInterval*) and time between marriage and first birth (*FirstKidInterval*) lead to the smallest difference in panda habitat, both at 2.5–2.6 km<sup>2</sup> (Fig. 5b, c). In terms of the timing when a relatively large difference in habitat (e.g., 3 km<sup>2</sup>) takes place, age of first marriage, upper child-bearing age, and fertility make this happen between years 10 and 11, years 24 and 25, and years 40 and 41, respectively. In terms of total differences in panda habitat caused by the two comprehensive scenarios, there is a difference of around 20 km<sup>2</sup> at year 50 (Fig. 7c).

The habitat becomes slightly more fragmented over time, in parallel with a slightly higher clumpedness for the overall landscape, suggesting that non-habitat becomes more clumped. The number of patches does not change much among

different scenarios, but habitat patch size decreases from year 0 (393.17 ha) to year 50 in all three scenarios (around 313–322 ha; Table 2). Habitat connectivity measured by cohesion does not change much (all around 96). The Shannon evenness index has a moderate decrease from 0.90 at year 0 to around 0.85 at year 50, and again does not differ much between the three scenarios. We will discuss the possible reason(s) and implications of such results in the next section.

Further spatial analysis focusing on local habitat changes shows that the areas near existing human settlements (Fig. 1) are deforested with varying probabilities in the baseline scenario (Fig. 8b). In the demographic contraction scenario, the saved habitat has an average elevation of 2,430 m and slope of 20°, which are moderate in the elevation and slope ranges for pandas (Table 3; see habitat definition in “Study site” section). A large proportion of such saved habitat is in deciduous or coniferous areas (Table 3). On the other hand, the demographic expansion scenario would expose many near-settlement areas of habitat to destruction with varying probabilities (Fig. 8d and Fig. 9c). The lost habitat areas, averaging 2,475 m in

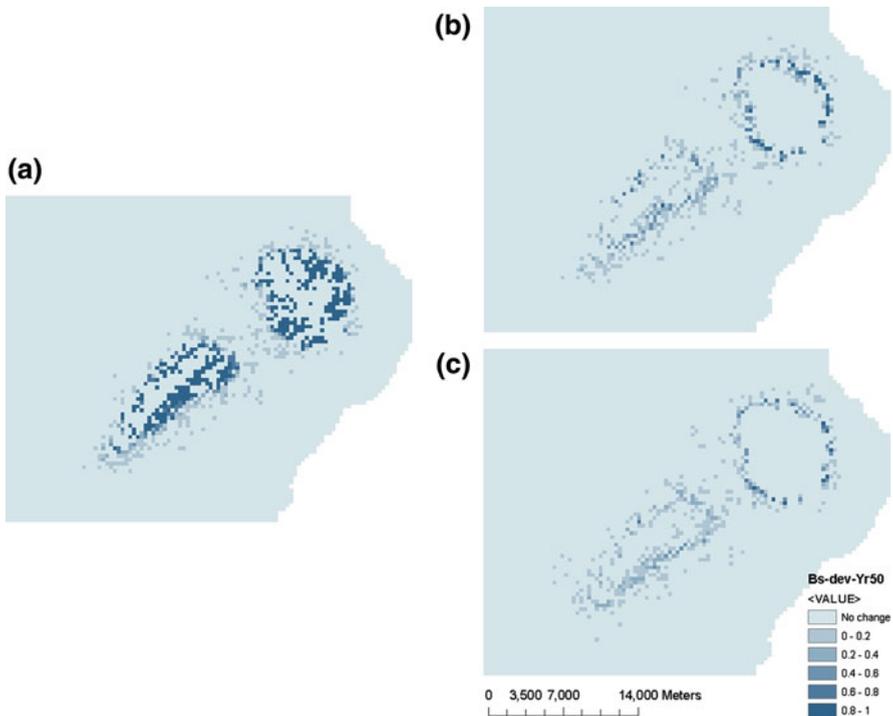


**Fig. 8** Spatial distribution of habitat **a** at year 0 (1996), **b** at year 50 in the baseline scenario, **c** at year 50 in the demographic contraction scenario, and **d** at year 50 in the demographic expansion scenario. In the gradient between 0 and 1, 0 stands for completely non-habitat, and 1 completely habitat

**Table 3** Descriptive statistics of lost or saved habitat

Habitat <sup>a</sup>		Average	Max.	Min.	SD	Area of panda habitat under each vegetation type (km <sup>2</sup> )		
						Deciduous	Conifer	Mixed
Lost habitat in demographic expansion scenario	Elevation (m)	2,475	2,991	2,062	283	1.81	1.43	0.39
	Slope (degree)	22	29	5	6	Total: 3.63		
Saved habitat in demographic contraction scenario	Elevation (m)	2,430	3,020	1,703	304	2.98	3.11	1.56
	Slope (degree)	20	29	2	7	Total: 7.65		

<sup>a</sup> The lost habitat is the difference of habitat between the baseline and demographic expansion scenarios at year 50. We calculate the habitat of baseline and demographic expansion scenarios using the criteria mentioned in “Study site” The habitat in each scenario is comprised of cells with probability  $\geq 0.50$  (see footnote 12) out of the 30 replicates. Similar explanations apply to the saved habitat in the demographic contraction scenario



**Fig. 9** Locations of **a** lost habitat at year 50 (2046, compared to year 0 or year 1996) in the baseline scenario, **b** saved habitat in the demographic contraction scenario, **c** lost habitat in the demographic expansion scenario; b and c are compared with baseline at year 50

elevation and  $22^\circ$  in slope, are located mostly in deciduous or coniferous areas (Table 3).

## Discussion

The simulation experiments presented here yield important insights into the hypothetical demographic and environmental implications of changes in family-planning factors in the Wolong Nature Reserve. Incorporating individual-level age and gender information, a few intra-household processes are simulated to take place in and modify a spatially explicit environment with various biophysical and geographic features (e.g., amount and type of vegetation, access to fuelwood), and changes of these features may feed back into the intra-household processes. When all the above processes or factors are simultaneously considered in our agent-based model, several key insights emerge. First, family-planning and other fertility-related factors (such as fertility rate, time spacing between births, and upper child-bearing age) yield almost immediate changes in population size (Fig. 3). In particular, decreases in upper child-bearing age could result in substantial changes in population dynamics over time: the population difference arising from a decrease in upper child-bearing age from 55 to 30 is nearly equal to that arising from a decrease of fertility from 6 to 1.

Second, all the factors considered in this paper (except time at first marriage) exhibit important time lags in their impacts on number of households at broader scales. The variable that mostly quickly alters projected numbers of households is age at first marriage: A decrease from 38 to 18 could give rise to a difference of 90 households at year 5. More interestingly, this difference increases over time (e.g., 150 households at year 10), maximizes at year 20 (around 220), then decreases from year 20 to 40, and finally increases. This phenomenon may be largely explained by the household lifecycle: delayed marriages directly postpone the establishment of new households and births of babies who may establish their households in a similar or even longer time frame (Fig. 4a). It takes more time for other variables to take effect in reducing number of households. For instance, when fertility rate (*NumOfKids*) increases by 1, the added children still remain in their parental households until they grow up and establish their own households, which explains the 20+ years of time lag (Fig. 4d). These findings have important policy implications, and corroborate findings and thoughts regarding temporal lags inherent in population–environment linkages (e.g., Carr et al. 2006a). As shown earlier, if the goal is more focused on curbing unsustainable increases in population size, then reducing fertility rate or upper child-bearing age should be more effective, particularly when we look at the timing of such changes (Fig. 3d, e). On the other hand, if reducing number of households as soon as possible is of more concern, a focus on promoting an older age at first marriage (*MarryAge*) might be more effective (Fig. 4a), which is the “later” part of the *Wan-Xi-Shao* policy.

Third, we discuss the effects of family-planning factors on panda habitat. Here, we simply present our simulation results regarding how population size, number of households, and panda habitat may respond to changes in those family-planning or

fertility-related factors. These simulations do not represent our own attitudes or preferences of family-planning or fertility-related factors. In terms of ultimate influences on panda habitat, increasing the upper age to bear children (*UpperBirthAge*), through sterilization at earlier ages for instance, makes the biggest difference (approximately 10 km<sup>2</sup>; Fig. 5e) in the long run. A reduced upper childbearing age (*UpperBirthAge*) from 50 to 30 can bring down population size from approximately 5,785 to 3,400 people and number of households from 1,331 to 1,087 at year 50. Changes in other variables do not reduce population size (Fig. 3a–d) and number of households (Fig. 4a–d) at such magnitudes. In terms of the earliest time to cause a larger habitat difference, changes in age at first marriage (*MarryAge*) make the biggest difference. By postponing this age, young people remain at their parental homes longer, and the growth in number of households substantially slows, which can be seen from the bottom curve (*MarryAge* = 38) in Fig. 4a. The change of potential panda habitat depends more on number of households than on population size, which is consistent with what has been found at the global scale (Liu et al. 2003a). This may arise from the way fuelwood is consumed. A large proportion of fuelwood is used for heating in winter, which changes little when a new person is added to or removed from the existing household. In consideration of cooking, the extra fuelwood caused by adding one person or the fuelwood saved by removing one person would be small (An et al. 2001).

Last, the methods and findings in this study are important for panda habitat conservation. As shown earlier, a decision of postponing marriages (an increase in *MarryAge*) or stopping childbearing at earlier ages (a decrease in *UpperBirthAge*) might result in saving panda habitat in the long run (Fig. 5a, e). However, if the goal is to save habitat as *early* as possible, then an increase in upper childbearing age might be more effective than a decrease in fertility rate. A reduction in fertility rate (*NumOfKids*) does not save habitat as much as the above two options in the short run (compare d with a and e in Fig. 5) and may be subject to more social resistance. However, a reduction in fertility rate might still be effective over a longer term (e.g., over 100 years), which goes beyond our simulation time frame.

The spatial habitat patterns (Table 2) do not vary much over different family-planning and fertility-related scenarios at early times, but such small changes may be cumulative over a longer time period (e.g., 100 years). Second, even these numbers can show us some useful information. For instance, the demographic contraction scenario gives an increase of 9 ha in patch size compared with the baseline scenario. This *increasing trend* is meaningful for panda conservation in the long run (e.g., >50 years), especially when we consider the giant panda's home range of 200+ ha per animal (Schaller et al. 1985). Patches smaller than 200 ha and with poor connectivity with other habitat patches are not likely used by pandas. Fortunately, most of the habitat patches are still well connected in light of the high cohesion index values (96 out of 100; Table 2). Last, the overall landscape indices alone do not reveal where habitat is saved or lost or the characteristics of such habitat, which may be equally (if not more) important for pandas.

Our analyses disclose not only the spatial distribution of panda habitat in the baseline (Fig. 8b), demographic contraction (Fig. 8c), and demographic expansion (Fig. 8d) scenarios, but also the locations and characteristics of net habitat lost or

saved in these scenarios. We have shown that the lost or saved habitat is of moderate elevation and slope and in areas of deciduous or coniferous forests. This may play a very important role in affecting panda activities because areas with such characteristics are more preferred by pandas (see “[Study site](#)” section for habitat definition). Such information would be more valuable in combination with other ecological or biological data. For instance, if the lost areas break existing corridors connecting separate habitat patches, panda metapopulations may suffer from lack of dispersal, inadequacy of genetic flow, and high likelihood of local extinction (Drechsler et al. [2003](#)).

## Conclusions

Our bottom-up approach simulates micro-level (intra-household) population processes and the corresponding environmental responses in a spatially explicit manner, incorporating many individual- or household-level decisions, environmental heterogeneity, and feedbacks. This approach thus has the potential to integrate multidisciplinary data and continuous processes operating across varying commensurate spatial and temporal scales (An et al. [2005](#)). This potential helps to address many issues inherent in many population–environment studies, such as choosing the appropriate spatial/temporal scales or handling “spatial and temporal discontinuities” in data or analysis (Carr et al. [2006a](#)). As a result, we have observed what researchers in complexity theory call “emergence” (see “[Background](#)” section). For instance, the non-linear relationships between changes in number of households and the increases in age at first marriage are not easily detected (Fig. [4a](#)) unless we take into account the many relevant individual-level data or decisions as discussed earlier. Another example of observed emergence is how population size and number of households respond differently to changes in age at first marriage (Fig. [6a](#)): population size has a near-linear decline as the age goes up, while number of households decreases at a reduced rate when the age is greater than 34 (earlier we have briefly discussed possible reasons). This bottom-up approach may also explain the different responses of number of households and population size when fertility (*NumOfKids*) changes (Fig. [6b](#)).

However, like many other models, our model is a simplified representation of the real-world patterns and processes under investigation, although it has been calibrated using empirical data and has passed a series of model testing procedures (An et al. [2005](#)). Thus, we use the model more as a laboratory of the coupled human–nature system to answer what-if questions than as a tool to accurately predict population, households, and habitat. More experiments could be conducted using such a laboratory, answering questions that were not addressed in this study, such as “How would population size, number of households, and panda habitat dynamics respond to varying initial population age structure caused by different types of migrations?” Also worthy of mention is the model’s capacity to link various types of data/findings and mimic different processes over time. For example, although we treat fertility as an exogenous variable for the goals of this paper, we can endogenize fertility and link it to other variables such as farm size and

tenure (Coomes et al. 2001), distance to market (Carr et al. 2006b), and resource dependency (Dasgupta 2000) in other instances.

We hope that all such efforts could introduce new perspectives into studies of human demography, especially household and family demography that was considered “a recent and relatively underdeveloped branch of population studies” (Bongaarts 2001). These new perspectives, the agent-based bottom-up approach in particular, may help to form more scientifically grounded policy and yield a more sustainable future for both humans and the natural environment.

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