CHAPTER 8

Demographic Decisions and Cascading Consequences

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8.1 Introduction

Global human population has been increasing rapidly in the last several decades from 2.5 billion in 1950 (U.S. Census Bureau, 2009) to more than 7.2 billion in 2014 (Population Reference Bureau, 2014). The vast majority of such population growth has taken place in developing countries. The global decline in mortality rate along with the high (although declining) fertility rates in developing countries may explain this rapid population growth (Bilsborrow et al., 2001, The World Bank, 2015). Such high population size and growth have directly or indirectly caused many socioeconomic and environmental problems across local to global scales (Cohen, 2003, de Sherbinin et al., 2007, Vitousek, 1994). These problems include biodiversity loss, ecosystem degradation, habitat fragmentation, hunger, and social unrest. They are prevalent in many parts of the world, even in "protected areas" (Curran et al., 2004, Liu et al., 2001). The population issue has gained attention at least as far back as the famous book *An Essay on the Principle of Population* (Malthus, 1798). Over the last several decades, many calls to curb the population explosion have been heard (e.g., Ehrlich, 1968, Ehrlich and Ehrlich, 2006, Meadows et al., 1972, O'Neill et al., 2010).

Many scholars have proposed models or theories regarding demographic dynamics (e.g., changes to birth and death rates; see Bilsborrow, 2002, Boserup, 2005) and their subsequent environmental consequences. For example, the vicious circle model (VCM; Brown, 2003, Marcoux, 1999) posits positive feedback loops among resource depletion, growing poverty, and high fertility. The widely cited IPAT model states that the environmental impacts (I) are the product of population (P), affluence (A), and technology (T) (Ehrlich and Holdren, 1972). Some scholars hold more optimistic views toward such acute human–environment crises in light of many mediating factors. Examples include agricultural intensification, technological advancement, institutional or cultural adaptation, and market substitution (Boserup, 1965, Simon, 1990).

There are many models and theories concerning population–environment relationships (e.g., Bilsborrow, 2002, Bilsborrow et al., 2001, Boserup, 1965, de Sherbinin et al., 2008, O'Neill et al., 2010). Many of these approaches rely on aggregated population measures (size, growth rate, fertility, etc.). Increasingly, other dimensions of demographics have been shown to deserve more attention. Examples include household numbers, demographic compositional measures (e.g., age and gender structure), and individual-level demographic decisions. For instance, Liu et al. (2003) found that in many parts of the world, even if population size declined, the number of households increased substantially. The resultant smaller households tended to have lower resource-use efficiency and posed serious threats to the environment. This thread of microlevel (primarily household) research in coupled human and natural systems (CHANS) is found in a large number of empirical studies (for a review on this topic, see de Sherbinin et al., 2007). Furthermore, it is considered essential to incorporate gender and age

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differences between individual household members and understand intrahousehold processes when conducting coupled systems research (de Sherbinin et al., 2008).

Addressing the above demographic dimensions poses substantial challenges to traditional approaches for coupled systems research. Such approaches tend to focus on either human systems or natural systems (An, 2012) while holding the other as "exogenous" context or as background. Inadequate attention to the complex reciprocal relationships between human and natural systems is rooted in the division between natural and social sciences. Such a shortcoming has hindered understanding of complexity in these systems.

To address this divide, the framework of CHANS has been developed (Liu et al., 2007a, b). It integrates knowledge and data across disciplines and across spatial, temporal, and organizational scales (see An, 2012, An et al., 2014, Liu et al., 2015). The framework emphasizes a range of complex features. Examples include reciprocal effects and feedback loops, heterogeneity, non-linearity and thresholds, legacy effects and time lags, surprises, and resilience (Liu et al., 2007a, b). These features were identified in the six sites examined by Liu et al. (2007a). Others have found these same features in other sites such as the Amazon (Malanson et al., 2006), Chitwan National Park in Nepal (Carter et al., 2014; Chapter 16), southern Yucatán in Mexico (Manson, 2005), and Northern Ecuador (Walsh et al., 2008).

Characterizing these complex features requires systems modeling approaches that can represent their characteristic structures and processes. Agent-based modeling (ABM) is a useful tool for coupled systems research largely because ABMs represent agents (decision-making entities such as individuals and households) and their environment in a computer model where agents interact with one another and with the environment. Models are typically dynamic: they run over multiple time steps, enabling agents to develop and interact with other agents as well as the environment. This agent-environment platform endows ABMs with a strong capacity to integrate data across spatial, temporal, and organizational scales, and to capture the decision-making processes of individual agents (An, 2012). Thus an ABM is capable of predicting or explaining "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). ABMs therefore offer great promise in CHANS research, as they can be parameterized with known information about individual agent behavior and interactions, and then general, emergent effects can be identified by studying outcomes. ABMs also show potential for scenario testing, as the effects of input rules and parameters can be evaluated. On the other hand, ABMs do not rule out the usefulness of traditional top-down approaches such as regression analysis, which actually may complement ABMs (e.g., through providing some decision rules for ABMs). In many instances, such traditional approaches even manifest greater effectiveness in capturing the corresponding human-nature relationships (An et al., 2005).

Many studies have focused on effects of demographic decisions on population size, but little attention has been paid to their cascading effects such as those on household number and the environment. In this chapter, we intend to fill this gap using interdisciplinary data from our model coupled system of Wolong Nature Reserve (Chapter 3). We set out to (1) illustrate demographic changes, (2) provide an overview of our ABM to understand detailed human–nature interactions, and (3) present simulation results using the ABM. Our simulations explore cascading effects of demographic decisions on complex features of coupled systems, including population size, household number, and panda habitat. In this chapter, we used the three-factor scheme approach (i.e., forest cover, elevation, and slope layers; see details in Chapter 7) to assess panda habitat.

8.2 Demographic dynamics

Demographic decisions, characterized by changes in fertility, marriage age, birth interval, migration, and a range of other factors (An et al., 2006, 2011, An and Liu, 2010) can translate into many demographic and environmental consequences. Examples include changes in population size, composition, number of households, household size, and panda habitat. In Wolong (as well as in many other parts of the world), fertility has declined in the past few decades. But given the large population base and relatively stable mortality rate, stable or even decreased fertility may still lead to considerable population increase (Figure 3.3).

The human population in Wolong increased from 3659 in 1982 to 4318 in 1997 and 4933 people in 2012 (Figure 3.3). Migration into Wolong is still strictly controlled due to Wolong's status as a nature reserve and via the *hukou* or household registration system implemented throughout China. In comparison, the number of households increased much faster than the population size over the same period. The number of households jumped from 631 in 1982 to 920 in 1996 to 1436 in 2012, representing an increase of 3.05% per year during 1982–1996 and 3.3% per year from 1996 to 2012 (Figure 3.3). Household size (number of people in a household) decreased from 5.8 in 1982 to 4.59 in 1997 to 3.44 in 2012 (Figure 8.1). There are several reasons for the rapid decrease in household size. First, young people prefer to leave parental homes at younger ages and establish their own homes. This tendency goes against the cultural tradition of having many generations under one roof. The choice to establish a new home is also made despite inconveniences associated with leaving the parental home, e.g., lack of child care and more household chores (Loucks et al., 2003). Second, the number of divorcees increased, while traditionally divorce was rare in Wolong (as in China

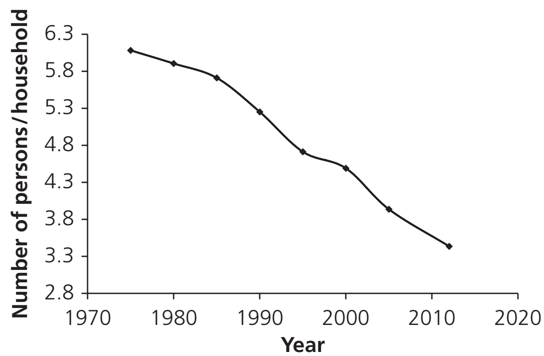

Figure 8.1 Dynamics of household size in Wolong Nature Reserve.

in general). Increasing divorces may lead to more households, even though the population size does not increase (Yu and Liu, 2007). Third, many people live longer than before due to improvements in living standards and medical care (see Figure 8.2). After a household member passes away, the number of people in the house decreases but the household still remains. Fourth, government policies also contribute to dwindling household size over time. For example, in 2001, government subsidies for the Natural Forest Conservation Program were distributed on a household basis. This arrangement provided a strong financial incentive for local households to split into smaller ones (Liu et al., 2005). Household dynamics in Wolong are similar to global patterns that also show faster

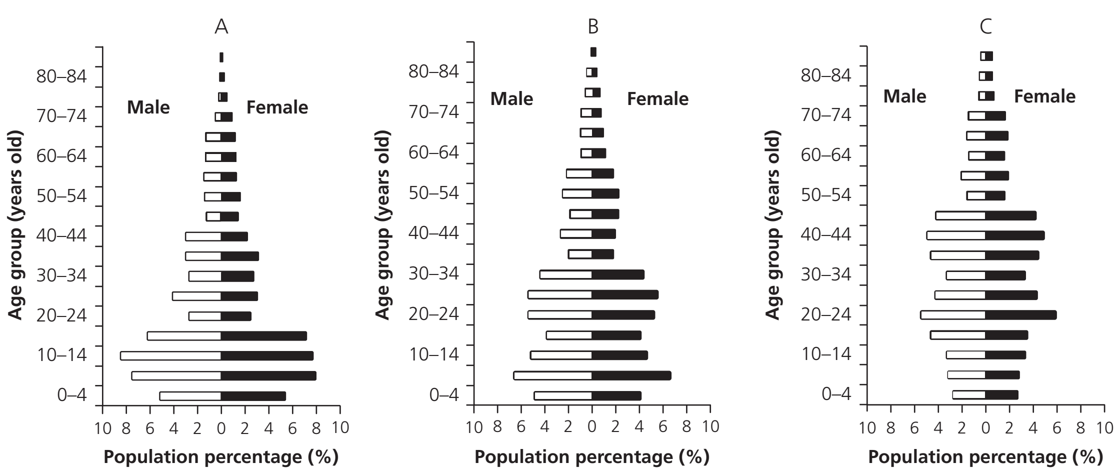

Figure 8.2 Population age/sex structure in (A) 1982, (B) 1996, and (C) 2006 in Wolong Nature Reserve.

increase in the number of households than population size, and continued decrease in household size (Bradbury et al., 2014, Liu et al., 2003).

The population structure in Wolong also changed dramatically between 1982 and 2006 (Figure 8.2). The large proportions of people in age groups 5–9, 10–14, and 15–19 as well as the decreased proportion of people in age group 0–4 (as compared to those in 1982) largely reflect the outcomes of the national family planning policy. This policy, introduced in 1978 and started in 1980, was initially known as a suggestion for "*wan* (later marriage), *xi* (prolonged time interval between births), and *shao* (fewer children)." The policy later developed into the stricter nationwide one-child policy. At the national level, China has witnessed curbed population growth due to its strict family planning policy. As a result, China has experienced drastic changes in its population composition. There has been an increase in the proportion of people of working age (15–64 years) and a decrease in the proportion of children (0–14 years) (Hussain, 2002). In Wolong, there was less control over family planning due to the large proportion of minority ethnic groups (e.g., Tibetan and Qiang). Minority ethnic groups enjoy special exemptions. Two to three children per couple were allowed for the 76% of people who belong to ethnic minorities (An et al., 2006, 2011).

The environmental implication of demographic dynamics could be substantial. The proportions and numbers of adults, particularly males, experienced steady increases in Wolong from 1996 to 2006, which expanded the available labor force that could be devoted to fuelwood collection and farming. According to a survey by Liu et al. in 1997 (Liu et al., 1999, 2005), there was a positive relationship between a local person's age and the number of days he or she spent collecting fuelwood. This relationship was non-linear with its peak in the age group of 25–59, followed by a sharp decrease after age 60.

To understand complex long-term human–nature interactions such as effects of demographic decisions, we developed multiple systems modeling approaches. In Section 8.3 we provide an overview of an ABM to characterize human–nature interactions in Wolong. Then, in Section 8.4, we use our model to simulate how demographic decisions affect long-term dynamics of population size, household number, and the environment (panda habitat in our context).

8.3 Agent-based systems model

The conceptual framework of our ABM "Integrative Model for Simulating Household and Ecosystem Dynamics" (IMSHED) is illustrated in Figure 8.3 (An et al., 2005). The left panel (T1) represents a symbolic snapshot of the households (represented by two households), the household members inside, and the forests on the landscape. The right panel (T2) represents all the households and forests at a later time. During the time between these two snapshots, many human and environmental processes take place. All local people (Person agents) go through individual life-history events (e.g., childbearing, in- or out-migration, or death). Person agents are heterogeneous in many dimensions such as demographic features (e.g., age or education), household locations, and fuelwood demand. For instance, Person A (female, the parent of B, C, D, and E) at the upper household dies. Persons C and D (both male, the children of A) move out of the household during this time interval for various reasons. Examples include going to college (i.e., education out-migration) or out-migrating to a spouse's home outside the reserve (i.e., marriage out-migration). Person E (female, the child of A) marries Person F (male, the child of J) at the lower household. They establish their own household. Person B (male, the child of A) remains in the parent's household. He marries a woman (Person K) who moves into the reserve through marriage (i.e., marriage in-migration). From T1 to T2, the lower household experiences structural changes but the household size remains stable. One Person (F) moves out as described above, and one Person (a baby) is born into the household.

The primary data sources for parameterizing and testing IMSHED are the 1996 Wolong agricultural census (Wolong Administration, 1996), the 2000 population census (Wolong Administration, 2000), and in-person surveys of 220 households that were conducted in 1999 (An et al., 2002, 2005). The forests (F1–F3, Figure 8.3) are modeled based on geographic information systems, remote sensing data, and literature (at two spatial resolutions of 90 m

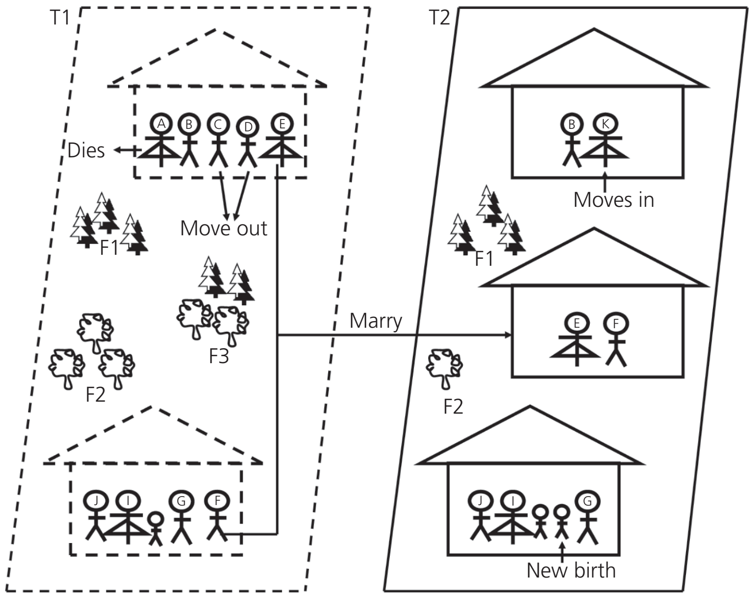

Figure 8.3 Conceptual framework of the Integrative Model for Simulating Household and Ecosystem Dynamics (IMSHED). Reprinted with permission from Springer Science and Business Media (originally printed in An and Liu 2010).

and 360 m). Land cover (vegetation type, volume, age, and growth rate), topography, and households are spatially explicitly represented in the ABM (An et al., 2005).

The ABM can simulate human–nature interactions over time. For example, the model simulates how individual decisions (e.g., about the age of marriage) made at a local site and a specific time affect dynamics of population size, household number, and panda habitat. The model captures the heterogeneous features of the individual persons (e.g., age and sex), households (e.g., location), and their local environment (e.g., available fuelwood collection sites). The impacts of these heterogeneous features are reflected in when (depending on the person's age and sex) and where (depending on the original household) a new household will be established. Once the new household is established, the model calculates the household's fuelwood demand in relation to the distance from the nearest fuelwood site according to the regression results from An et al. (2002).

After robust model verification and validation (An et al., 2005), we conducted a set of experiments concerning the effects of demographic decisions (An et al., 2006, 2011, An and Liu, 2010). For example, the model has been used to simulate fuelwood collection, a major interaction between the human and natural systems in Wolong. Effects include deforestation (e.g., F3, Figure 8.3) or volume reduction (e.g., F2, Figure 8.3) and habitat loss or degradation. Agents visit available forests within 1080 m, between 1080 and 2160 m, and over 2160 m from their households to collect fuelwood. There, they participate in fuelwood collection at observed probabilities of 0.48, 0.27, and 0.25, respectively (An et al., 2005). Using terrain data, all Person agents who collect fuelwood choose the path that has the least cost-distance between a household and its nearby forests so as to minimize energy consumption. All such agents choose the available forests with shortest cost-distance for fuelwood collection. Household agents may reduce their fuelwood demand as the remaining forests become less available and farther away (An et al., 2005). In this manner, the magnitude and location of household environmental impact due to fuelwood use may be modeled.

8.4 Effects of demographic decisions

In this section, we highlight several features of coupled systems that result from demographic decisions through running the ABM described above. Multiple relationships or feedback loops in coupled systems may sometimes strengthen or weaken (or even cancel out) one another. Due to complexities such as feedbacks, the system may feature emergent outcomes that cannot be explained or predicted by exploring individual system components alone.

8.4.1 Non-linearity and thresholds

Non-linearities are prevalent in Wolong, such as the non-linearity between population size and age at first marriage (MarryAge in Figure 8.4; An and Liu, 2010). When people postpone their marriages (MarryAge changes from 18 to 26, to 34, and finally to 38 years old), population sizes drop and show non-linear changes over time. The difference in population size over time becomes increasingly large. When people get married at 26 or later, population sizes start to decline at some time point (e.g., year 27 when MarryAge = 38; Figure 8.4A). This population inflection is a threshold (transition point between alternate states; Liu et al., 2007a).

The number of households also manifests complex non-linear relationships (Figure 8.4B). Even when population sizes decline, the numbers of households still increase. Also, the two curves for MarryAge = 34 and 38 resemble each other and display an "S"-shaped increase. This pattern shows that over the long term, the numbers of households would almost converge at the end of 50-year simulations despite the differences in age at first

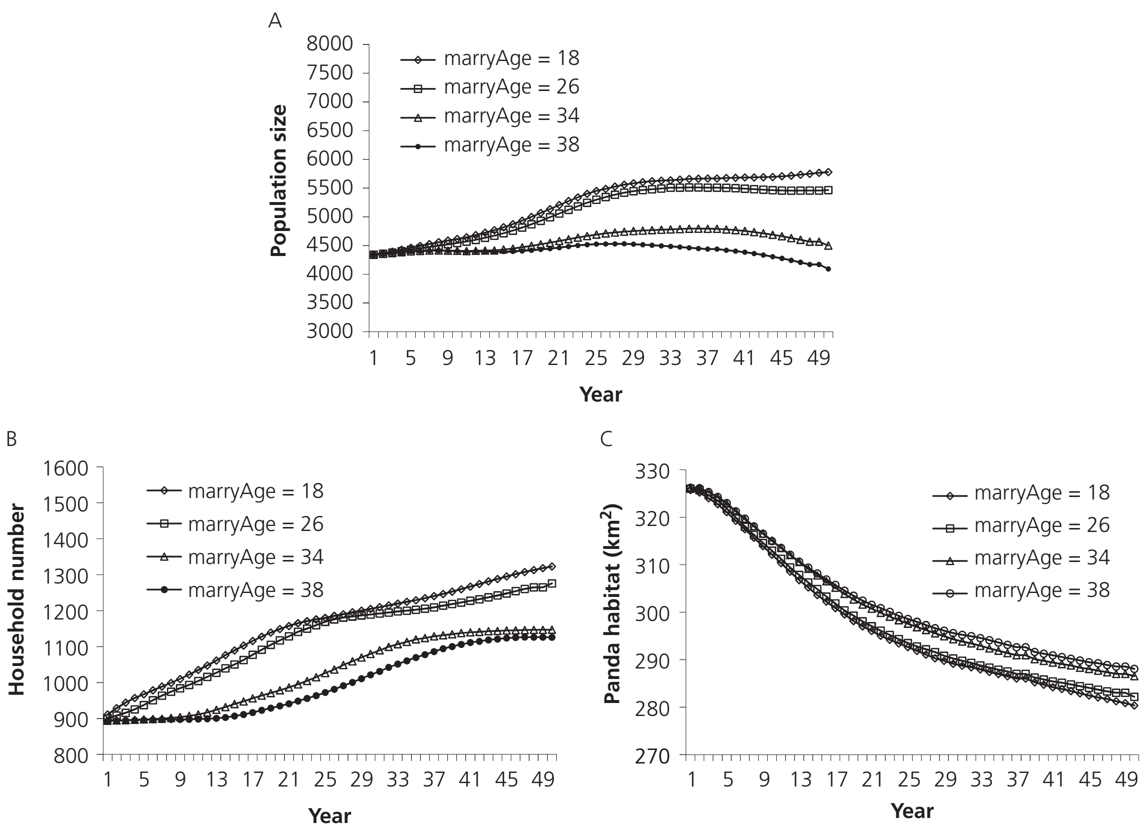

Figure 8.4 Responses of (A) population size, (B) number of households, and (C) amount of panda habitat to changes in age of first marriage (MarryAge). Reprinted with permission from Springer Science and Business Media (originally printed in An and Liu 2010).

marriage. Once the young people of this generation reach 34, they will begin to marry and most likely set up their new households and, therefore, the number of households will go up. However before their children (the next generation) grow up, the number of households will increase at a decreasing rate and finally level off. By that time, most people of this generation will have married and already established their households.

8.4.2 Time lags

Time lags commonly occur when key processes like population size, number of households, and panda habitat respond to changes in demographic decisions, e.g., age at first marriage, fertility, and the maximum age for childbearing (An and Liu, 2010). Consider the time interval between marriage and the first birth (BirthInterval in Figure 8.5) as an example. When this interval increases from one year to 11 years, population size responds quickly in about 3–5 years. But it takes nearly 20–25 years to see the corresponding change in the number of households, and 40–50 years for panda habitat to respond (Figure 8.5). Clearly when this interval is prolonged, children will be born later, which explains the nearly immediate response in population size. However only at the time that these birth-postponed babies grow up and establish their own households can the change in the number of households be observed. Panda habitat is the slowest to respond for many reasons, for example, forest volume may assimilate the increased demand for fuelwood associated with the incoming "new" households.

Another example is related to the time lags between the number of households and panda habitat (Figure 8.6). When fertility (numOfKids in Figure 8.6) changes from 1 to 6, the number of households and amount of panda habitat take about 17 years and 27 years to respond, respectively. Why does this average ten-year difference (over multiple simulation runs) in response time

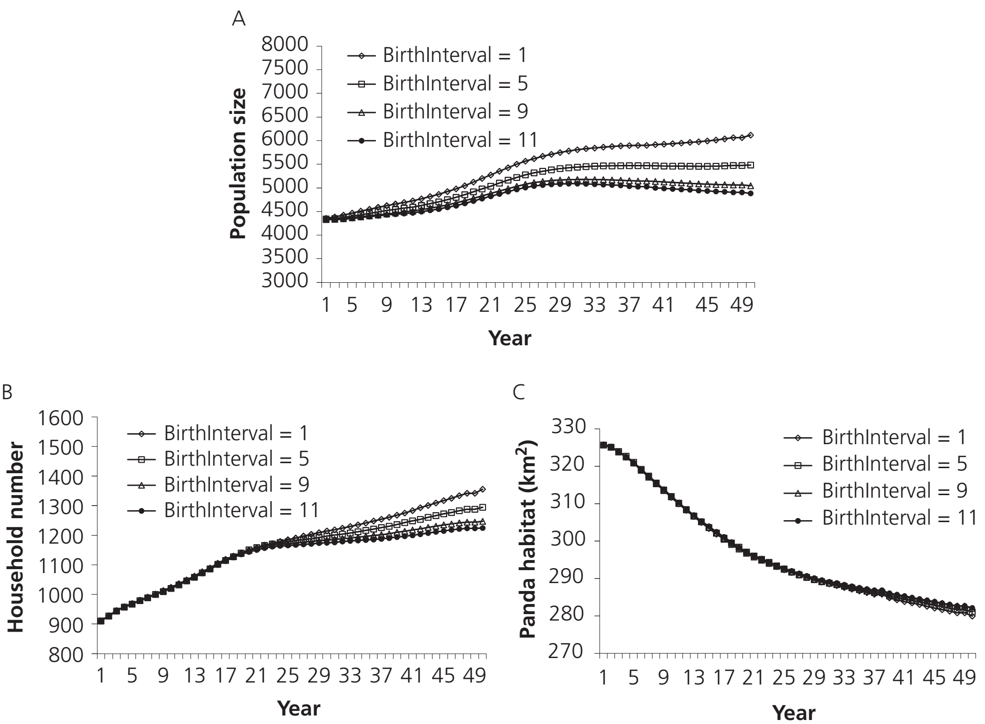

Figure 8.5 Responses of (A) population size, (B) number of households, and (C) amount of panda habitat to changes in the interval between marriage and first birth (BirthInterval). Reprinted with permission from Springer Science and Business Media (originally printed in An and Liu 2010).

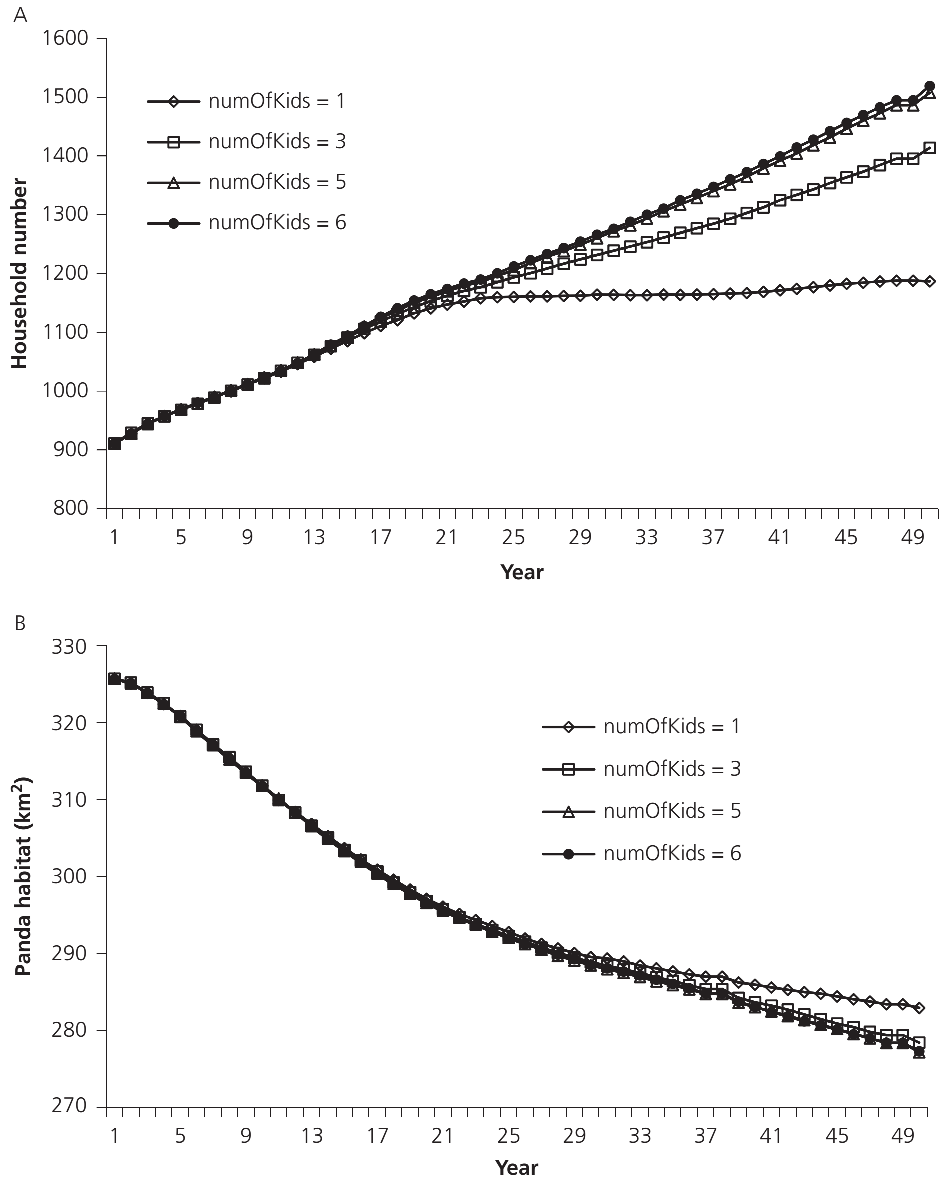

Figure 8.6 Responses of (A) number of households and (B) amount of panda habitat to changes in fertility (numOfKids). Reprinted with permission from Springer Science and Business Media (originally printed in An and Liu 2010).

occur? The increase in fuelwood demand that accounts for habitat loss is related more to the increase in number of households than to the number of people, and so human impact on habitat is most pronounced when young adults form their own households.

8.4.3 Resilience

Resilience is the ability of a system to maintain similar structure and functioning after disturbances (Folke et al., 2002, Liu et al., 2007a). It is prevalent in Wolong. For example, out-migration can be considered a disturbance to the coupled system. Wolong parents often take pride in their children's out-migration through education. They encourage their children to go to college and find permanent jobs outside Wolong, even though they are not personally willing to emigrate due to many reasons, such as lack of skills for working and living in cities (Liu et al., 2005). To understand the impact of this form of out-migration, we set the education out-migration rates (Edu Mig Rate in Figure 8.7; the probability that a person between 16 and 20 years old would go to college or technical school and migrate out) from 0.02 (baseline) to 0.05, 0.15, and 0.30. Surprisingly, this "good" disturbance does not cause an increase in the amount of panda habitat until 10–15 years later. In other words, the amount of panda habitat is resilient to out-migration for the first 10–15 years and only starts to respond after a time lag (Figure 8.7). The reason may be that when these young people move out, their original households still remain in Wolong and continue to use fuelwood, although a slightly lower amount. Only at the marriage of these young out-migrants can we see a substantial reduction in the number of households because out-migrants do not establish new households inside the reserve.

8.4.4 Heterogeneity

Coupled systems are characterized by multiple heterogeneous features. Under Wolong's specific spatial distribution of existing forests and households, demographic changes will not cause evenly distributed degradation or restoration among all forest or habitat types. We sought to analyze the

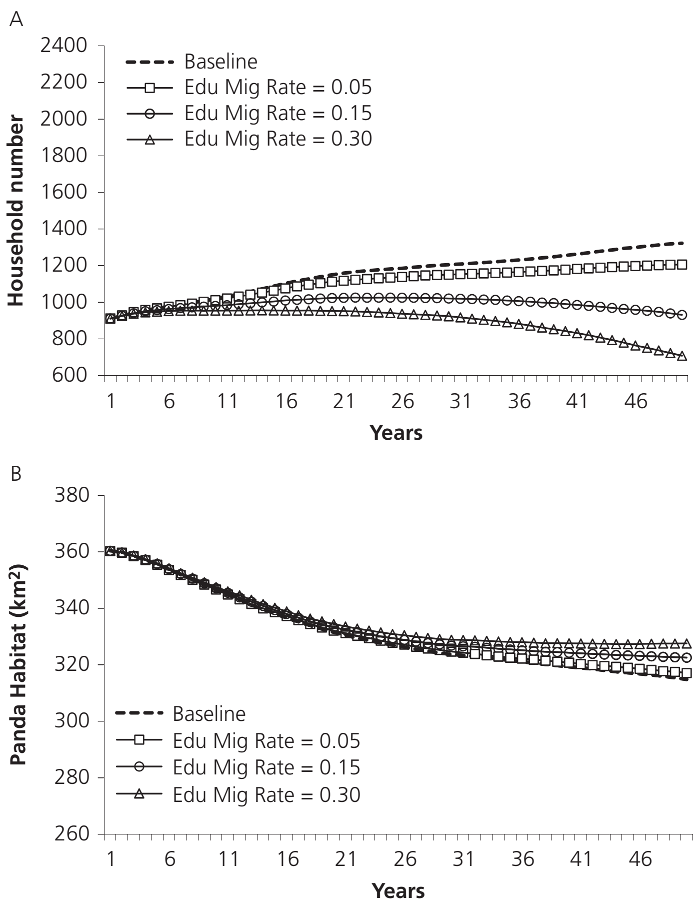

Figure 8.7 Responses of (A) number of households and (B) amount of panda habitat to changes in education out-migration rate (Edu Mig Rate).

effects of demographic expansion and contraction (due to factors that encourage or discourage population growth, respectively; see An and Liu, 2010). To do so, we mapped how panda habitat may respond to different policies in a spatially explicit manner. The simulation results show that, in year 50 (the end of the simulation), most of the saved habitat due to the demographic contraction policy is located in areas with coniferous forests. On the other hand, most of the lost habitat due to the demographic expansion is in areas with deciduous forests. These emergent phenomena may arise from the fact that in the demographic contraction scenario, people reduce or cease to collect fuelwood from places dominated by coniferous forests. Many such regions are at higher elevations and far from residential areas. In the demographic expansion scenario, these new households are often located in areas near their parental households. They collect fuelwood first in deciduous forests, which are at lower elevations and near residential areas. By explicitly modeling the spatial locations of new households and the least-cost fuelwood harvest sites, important differences in scenario outcomes can be identified.

8.5 Discussion and concluding remarks

CHANS researchers have paid much attention to data collection and analysis at the household level but many lack understanding of "intrahousehold processes" at the household member (individual) level (de Sherbinin et al., 2007). This chapter introduces an ABM that simulates individual-level demographic decisions and environmental interactions. The model can translate these dynamic household processes to explore emergent outcomes in populations and the environment. It has generated unique insights that could not be otherwise obtained. For example, we can see that the numbers of households evolve differently compared with population size. Population size already starts to decline or become stable while the number of households still keeps increasing (Figure 8.5). This difference can be attributed to reduced household size. Household sizes become smaller due to reasons such as reduction in multigenerational households, increase in divorce, increase in longevity, and division of households to receive more conservation subsidies. These and other simulation results (e.g., Figures 8.4 through 8.7) can be better understood from utilizing knowledge about individual decisions (such as fertility, time of marriage) and the associated driving forces. Demographic decisions play an essential role in affecting dynamics of coupled systems.

The ABM becomes more useful when there are a large number of links among the many demographic decisions, socioeconomic factors, and the environment (see also Chapter 14). For instance, the forest is affected by location-specific fuelwood demand. This demand is in turn a function of household age structure (consequence of earlier demographic decisions), distance from household to collection sites, and other factors (An et al., 2005). In the future, using the above socioeconomic, demographic, and environmental covariates to predict these demographic decisions (An et al., 2014, Zvoleff and An, 2014) could help researchers better understand complex relationships in coupled systems.

Coupled systems possess many complex features that deserve more attention, including those discussed in Section 8.4. Our research shows that the VCM (Brown, 2003, Marcoux, 1999) is not necessarily applicable in all instances. We provide an example in a small community surrounded by dense forests with high volume and fast forest growth. Here, increases in population size and number of households may not cause serious environmental degradation if the forest volume and regrowth surpass the demand from the community and elsewhere.

Spatial and temporal scales adopted in research affect what we observe and conclude. For instance, an increase in fertility is projected to cause observable changes in panda habitat after 30 years (Figure 8.6). If we only had data for a shorter period (e.g., 10–20 years), the conclusion would be that increasing fertility has no impact on panda habitat. However, this would be a misleading conclusion due to the time lag of impacts resulting from changes in fertility.

Our research in this chapter also has management and policy implications for promoting sustainability of coupled systems. For example, as shown in Section 8.4, different demographic decisions may cause major habitat change in either deciduous or coniferous forests. Coniferous forests, located in higher elevations compared to deciduous forests, are closer to the upper elevational boundary of panda habitat. If resources are limited, less priority can be placed on conserving habitat areas of coniferous forests due to their longer distances from residential areas and relative inaccessibility for local residents. Also worthy of mention is that individual-level demographic decisions, especially those less researched, such as marriage timing and birth interval, deserve more attention as they have long-term significant impacts on population and environmental dynamics. In addition, the complexity features in coupled systems may warrant data collection and analysis over long time frames (to account for time lags and feedback loops) and large geographic extents (to include spatial heterogeneity). Empirical research over several decades or larger spatial extents would in most instances be difficult, but modeling would be feasible.

8.6 Summary

Human populations in many places are undergoing demographic transitions involving complex shifts in marriage timing, fertility, mortality, and migration. But the interactions between individual characteristics (e.g., age and demographic decisions such as marriage) and the natural environment are not well understood. To fill this knowledge gap, we used an agent-based model to simulate interactions between demographic properties of individual households and environmental change in Wolong Nature Reserve in China, which has undergone profound shifts in demographics. Demographic characteristics such as time interval between marriage and age at first birth were shown to affect population size, household number, and fuelwood collection behaviors, which in turn impacted forests and panda habitat. Complex patterns arose from these demographic parameters such as non-linearities and thresholds, feedbacks, legacy effects, time lags, heterogeneity, and resilience. For example, when the time interval between marriage and first birth increased from one year to 11 years, population size responded quickly in about 3–5 years. But it took nearly 40–50 years for panda habitat to show less degradation with the increase in time interval between marriage and first birth. An example of heterogeneity can be seen in our simulation results showing improvements in coniferous forests far from households 50 years after population reduction. In contrast, declines were seen in deciduous forests closer to households after population expansion. Our work demonstrates the importance of considering and modeling individual-level differences and demographic decisions in coupled human and natural systems over long-term time frames.

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