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Ecological Modelling 140 (2001) 31–49

ECOLOGICAL MODELLING

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Simulating demographic and socioeconomic processes on household level and implications for giant panda habitats

Li An [a,*], Jianguo Liu [a], Zhiyun Ouyang [b], Marc Linderman [a], Shiqiang Zhou [c], Hemin Zhang [c]

[a] *Department of Fisheries and Wildlife, 13 Natural Resources Building, Michigan State University, East Lansing, MI 48824, USA*

[b] *Department of Systems Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, PR China*

[c] *Giant Panda Research Center of China, Wolong Nature Reserve, Wenchuan County, Sichuan Province, PR China*

Abstract

Human activities have significantly affected wildlife habitats. Although the ecological effects of human impacts have been demonstrated in many studies, the socioeconomic drivers underlying these human impacts have seldom been studied. We developed a household-based, stochastic, and dynamic model that simulates the impacts of household demographic and socioeconomic interactions on fuelwood use, a key factor affecting the quantity and quality of habitats for the giant pandas (*Ailuropoda melanoleuca*). Using Wolong Nature Reserve (China) as a case study, this model mimics household production and consumption processes and integrates various demographic and socioeconomic factors. Household interviews conducted in 1998 within the Reserve provided the data for parameterization. The simulation results fit well with both the data used in constructing the model and with a set of independent data. Age structure and cropland area were found to be the most sensitive factors in terms of fuelwood consumption, and thus deserve more attention in panda habitat conservation. This model could help reserve managers to understand the interrelationships among local economy, local cultural traditions, and habitat degradation, facilitating more scientific and economically efficient policymaking.

Keywords: Household; Fuelwood consumption; Modeling; Simulation; Giant Panda; Habitat; Wolong Nature Reserve; Population; Environment; Natural resources; China

1. Introduction

Human activities have caused serious disturbances to wildlife populations and their habitats (e.g. Wilson, 1988; Ehrlich, 1995). Previous research has mostly focused on the ecological effects of human activities, such as the effects of agricultural land development on wildlife population abundance (Freemark and Csizy, 1993; Sietman et al., 1994; Warner, 1994), as well as the influences of timber logging on biomass (Hollifield and Dimmick, 1995; Norwood et al., 1995), animal home range change (Ims et al., 1993; Chang et al., 1995; Linnell and Andersen, 1995), and species distribu-

* Corresponding author. Tel.: +1-517-3535468; fax: +1-517-4321699.

E-mail address: anli@perm3.fw.msu.edu (L. An).

PII: S0304-3800(01)00267-8

tion and composition (Lyon, 1979; Geier-Hayes 1989; Skovlin et al. 1989; Nelson et al. 1996).

In addition to the understanding of these ecological effects, conservation biologists have also observed that human population size, economic activities, and attitudes (e.g. attitudes towards childbirth) interact with each other and ultimately result in ecological effects (Liu et al., 1999a). These interactions and the underlying mechanisms, though only intuitively understood (Dompka, 1996; Liu, 1997), have been demonstrated to be critically important in terms of conservation applications (e.g. effective wildlife management, Liu et al., 1999a,b). Additionally, exploration of these issues has triggered integration of ecology, economics, and modeling techniques (e.g. establishment of spatially explicit models, Liu, 1993; Liu et al., 1995).

Quantitative computer modeling has been an effective method for integrating ecological and socioeconomic factors (Costanza and Daly, 1991; Liu, 1993). It helps to understand the dynamics of the processes of interest by 'mimicking the actual but simplified forces that are assumed to result in a system's behavior' (Hannon and Ruth, 1994). For instance, quantitative computer modeling has been successfully used in studying wildlife population dynamics (Liu, 1993; Conroy et al., 1995), comparing alternative management strategies (Liu et al., 1994, 1995; Turner et al., 1995), and interpreting the spatial connectivity of processes within a specific habitat (Hanson et al., 1988). All these studies were largely conducted on region or landscape scales, seldom on the household level, which is actually the basic unit of human production and consumption in rural areas and thus deserves more attention for wildlife conservation. In addition to this scale issue, literature on using modeling to integrate both attitudes and economic incentives into household level decision processes for wildlife conservation is not, to our knowledge, available.

We developed a household-based and stochastic dynamic model, named 'Panda habitat_Demographic, Ecological and Economic Model' ('PANDA_DEEM' hereafter), to simulate household level consumption and production processes, demographic and socioeconomic dynamics, and their interactive effects on habitats for the giant pandas (*Ailuropoda melanoleuca*). By integrating economic, demographic and ecological data into a systems model, PANDA_DEEM is designed to disclose the underlying mechanisms for habitat fragmentation and loss. Because forests are an important component of panda habitats (Hu et al., 1980; Schaller et al., 1985), PANDA_DEEM takes *fuelwood use quantity* as an indicator of the giant panda habitat disturbances caused by human activities. The more fuelwood is used, the more trees need to be cut and forests destroyed. Previous research shows that fuelwood consumption has contributed most to the loss of panda habitats (Liu et al., 1999a, 2001).

In this paper, we begin with an introduction to the study area and the model structure. We then focus on methods for model parameterization and model testing (including model verification, model validation, sensitivity analysis, and uncertainty analysis). Finally, we present the results of model testing and discuss the implications of the model.

2. Methods

2.1. Study area

Wolong Nature Reserve (102°52′–103°24′E, 30°45′–31°25′N, Fig. 1) is located in Sichuan (one of the most populated provinces in China) with an area of approximately 2000 km^2. Four major ethnic groups, i.e. Han, Tibetan, Chang, and Hui, constitute the total rural population of 4320 people in 1998, corresponding to a total number of 942 households. These households mainly rely on growing corn, potato, and vegetables for subsistence and use fuelwood as their main energy source for cooking and heating in winter. Pig raising, collection of Chinese medicinal herbs, timber harvesting, transportation, construction of local roads and hydropower stations, as well as house building are also their main activities besides farming. The famous 'one child policy', which is strictly implemented in urban areas, does not apply to this area populated by minority groups (Tibetan, Chang and Hui) due to loose governmental control in rural areas with minority groups. The average number of children per couple in Wolong is 2.5 (Liu et al., 1999b).

As the largest of China's 25 giant panda reserves, Wolong Nature Reserve was designated in 1962 with an area of 200 km^2 and expanded to approximately 2000 km^2 in 1975. The years since 1975 have witnessed a drastic decline in the giant panda population — from 145 animals in 1974 (Schaller et al., 1985) to 72 animals in 1986 (China's Ministry of Forestry and World Wildlife Fund, 1989), paralleled with a fast human population increase (an increase of approximately 70% from 1975 to present). As a national treasure of China as well as a precious natural heritage of concern to people around the world, this most endangered species, the giant panda, has been attracting increasing national and international attention. For instance, the World Wildlife Fund (WWF) has adopted the giant panda as its logo.

2.2. Conceptual model and data sources

PANDA_DEEM consists of three submodels and their interrelationships are demonstrated in Fig. 2: (1) submodel *DEMOGRAPHY* includes the number of people per household, age structure, and educational level. Local residents' attitudes towards birth and education are key factors influencing the demographic features of the household — specifically, the number of children, and the educational level; (2) submodel *ECON*-

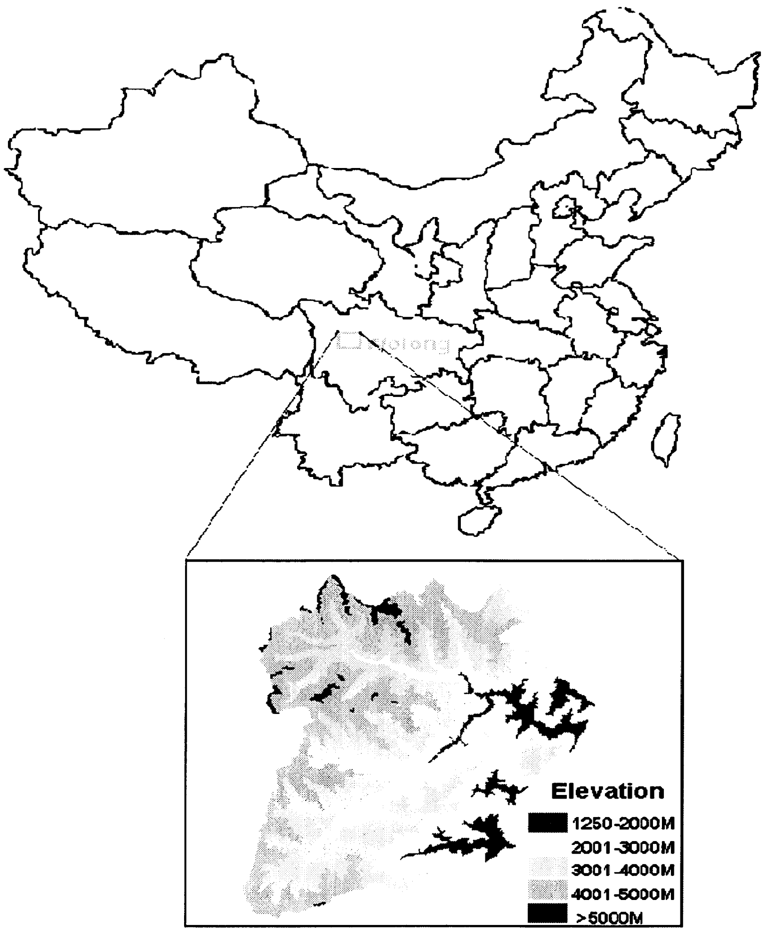

Fig. 1. The location and elevation of Wolong Nature Reserve in China.

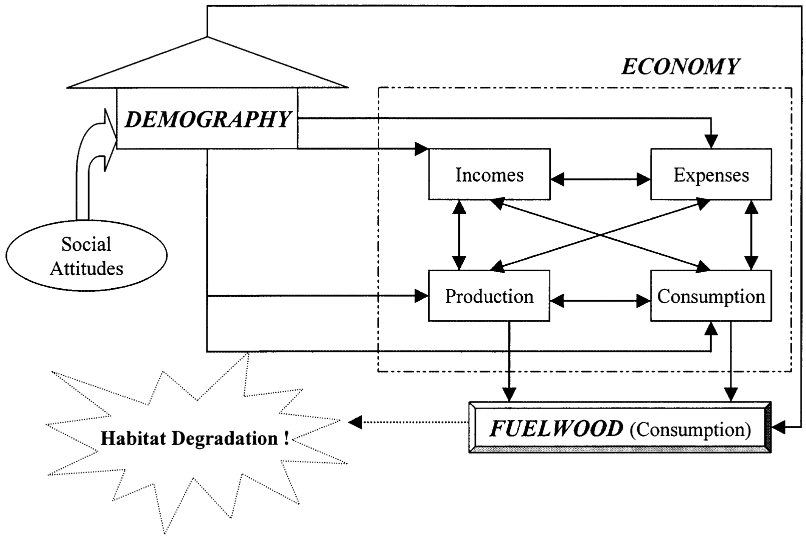

Fig. 2. The conceptual structure of PANDA_DEEM. The dashed arrow and star box are assumed impacts of fuelwood consumption on the giant panda habitat.

OMY consists of two main components. One is *Production_and_Consumption* of the simulated household, and the other is *Incomes_and_Expenses*. *DEMOGRAPHY* determines the extent of *Consumption* and provides the necessary labor for *Production*. Component *Incomes_and_Expenses* simulates all the income and expense items that could occur in a household with the above demographic, consumptive, and productive characteristics. *Incomes* is mostly determined by *DEMOGRAPHY*, e.g. availability of labor (people between 21 and 60 in the model) and educational level of labor (average schooling years of labor). *Incomes* is also associated with *ECONOMY* (*Production* specifically). *Expenses* is mainly determined by *DEMOGRAPHY*, such as number of people and age structure of the household. *Production* and *Consumption* can impact *Expenses*, e.g. growing crops needs chemical fertilizers; (3) submodel *FUELWOOD* is driven by the following factors: *DEMOGRAPHY*, *Production* (fuelwood used for cooking pig fodder), and *Consumption* (fuelwood used for heating in winter and for household food cooking).

The data for parameterizing PANDA_DEEM were obtained from the interviews with 50 households, conducted by the authors from June to August, 1998 in Wolong Nature Reserve. The 50 households were randomly selected in Wolong Township (one of the two townships in the Reserve), the region where most of the pandas inhabit. The questionnaire includes: (1) fuelwood use; (2) incomes and expenses; (3) production and consumption; and (4) demography. We also asked the interviewees about their attitudes towards some social issues, such as the number of children they prefer to have, the marriage age they prefer, and the schooling years they prefer for their children.

All the interview results were entered into a Microsoft Access database. The information from five of the households was unreliable because their estimates of fuelwood consumption were inconsistent with their consumption and production needs. Thus the associated data from these five households were excluded from use. From the remaining 45 households, we randomly selected 30 households for model development and the other 15 households for model validation.

2.3. Submodels

2.3.1. Submodel DEMOGRAPHY

This submodel is individual-based, simulating the life history of an individual as he/she goes from birth (or the starting point of the simulation if the individual is already in the household, or the year when the individual moves into the household), through each age group, to death (or the end point of the simulation if the individual is still alive, or the time when the individual moves out) in an annual time step. The age-group classification is based on the status of occupation which an individual at a certain age is most likely to take: (1) age 0–5 — infant to pre-school period; (2) age 6–12 — elementary school period; (3) age 13–15 — middle school period; (4) age 16–20 — high school or technical school period; (5) age 21–60 — adult period when people work as main labor force; and (6) age 61 and over — retirement period. The individual stays in that age group until the age exceeds the age group's upper threshold when the individual moves into next age group (Fig. 3).

The model incorporates the following events, possibly taking place in a person's life, into the model: birth, death, emigration out of the household through marriage or going to college, and immigration into the household through marriage (the main legal way to move into the Reserve). As to the death process, the model creates a random number (between 0 and 1) for each individual each year and compares it with the mortality associated with the corresponding age group (Fig. 4). If the random number is smaller than the mortality of the group to which the individual belongs, then the individual dies; otherwise survives and moves into the next year. This process repeats every year until the individual dies, moves out of the household, or the simulation ends. The yearly mortality rates of different age groups of the whole Reserve (1994–1996) were used as equivalents to death probabilities for an individual over time: 0.745% for age 0–5 group; 0.090% for age 6–12 group; 0.131% for age 13–15 group; 0.196% for age 16–20 group; 0.291% for age 21–60 group; and 5.354% for age 61 + group (Wolong Nature Reserve, 1994–1996).

There are two major types of emigration: emigration through marriage and emigration through education. Emigration through marriage is based on the fact that girls generally tend to move out of the household and live with their husbands, and that boys set up new households after marriages. This event is set to occur at the age of 22, the average marriage age calculated from our field data. For simplicity, all the children except the youngest move out of the household when they

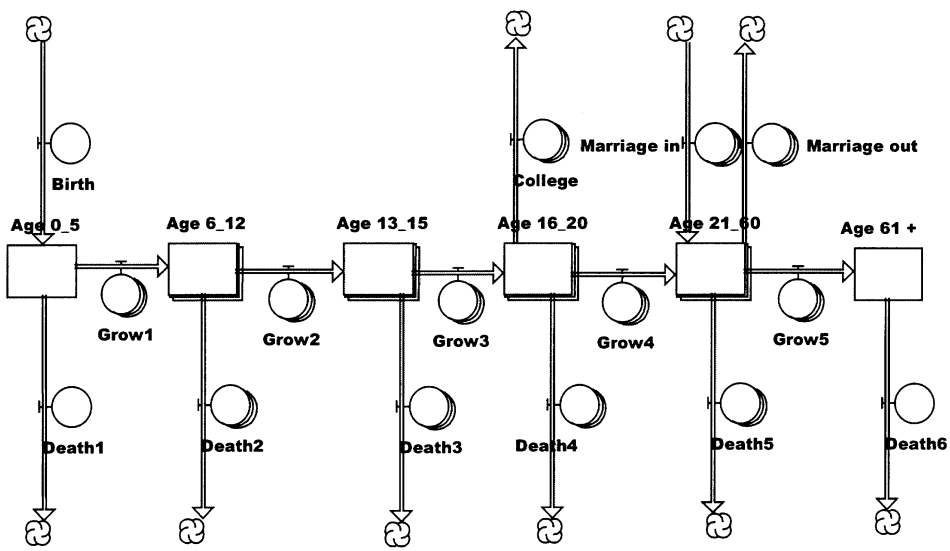

Fig. 3. Age groups and the associated events in the life span of an individual.

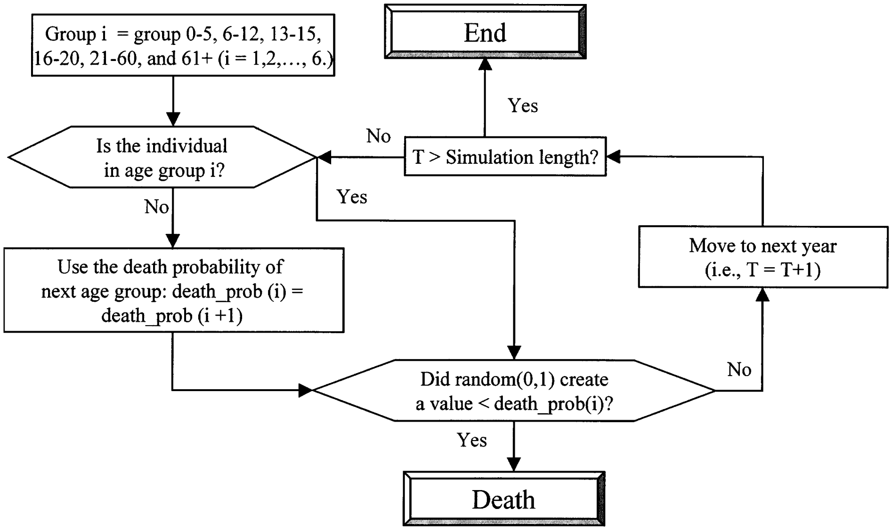

Fig. 4. Simulation of the death process.

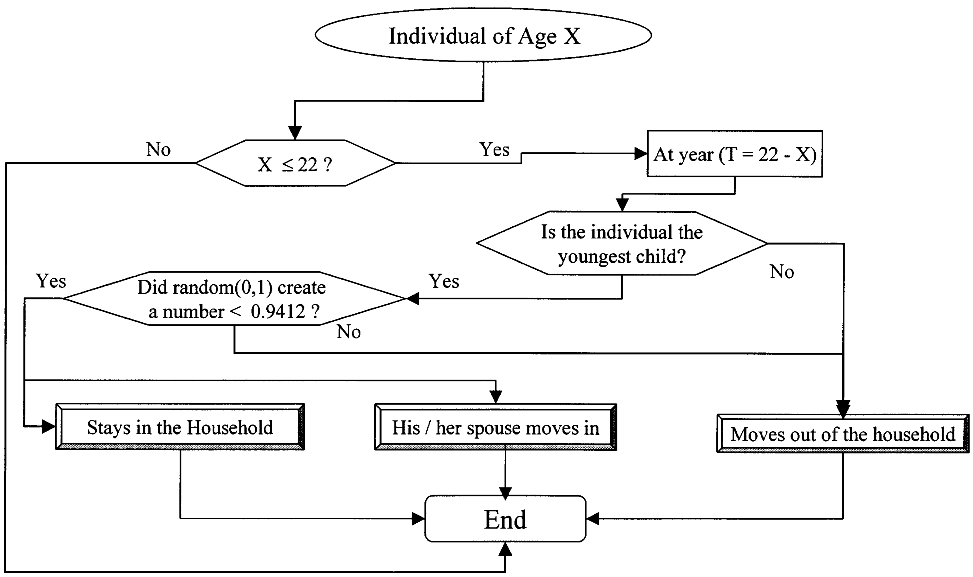

Fig. 5. Emigration and immigration through marriage.

reach 22 years old (Fig. 5). Emigration through education is based on the fact that if a young person could go to college or technical school he would find a job in a city instead of staying in the household as a farmer (Liu et al., 1999a,b). Our data show that 9.6% of the people in the age group 16–20 passed the national entrance examination and went to colleges or technical schools in 1996, thus the probability that an individual in this age group will go to college and move out is set at 0.096 (Fig. 6).

Immigration into a household is based on the fact that one child (usually the youngest son or the youngest daughter in case of no son in the household) stays with his/her parents, bringing his/her spouse into the household at the time of marriage (22 years old on average). The probability that the youngest children stay with their parents is 0.941. So his/her spouse immigrates into the household with the same probability of 0.941. The corresponding flows are shown in Fig. 5.

2.3.2. Submodel ECONOMY

This submodel consists of two components, *Production_and_Consumption*, and *Incomes_and_Expenses*. The type and magnitude of *Production_and_Consumption* are closely related to the typical life style of a rural household in Wolong. The amounts of corn, potato, rice, and pork are set to be state variables because they constitute the dominant food that local households rely on. Farmers grow potatoes and corn as their staple crops, exchanging most of the potatoes for rice, and using most of the corn to feed

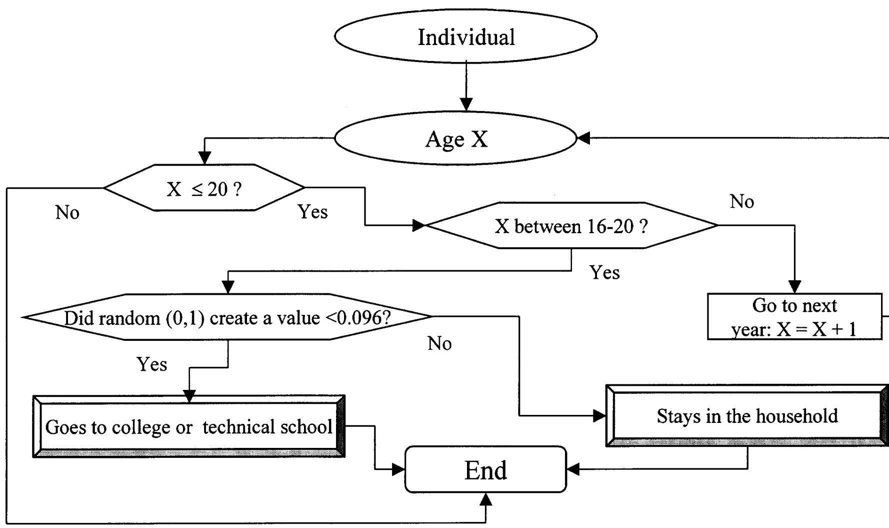

Fig. 6. Emigration through education.

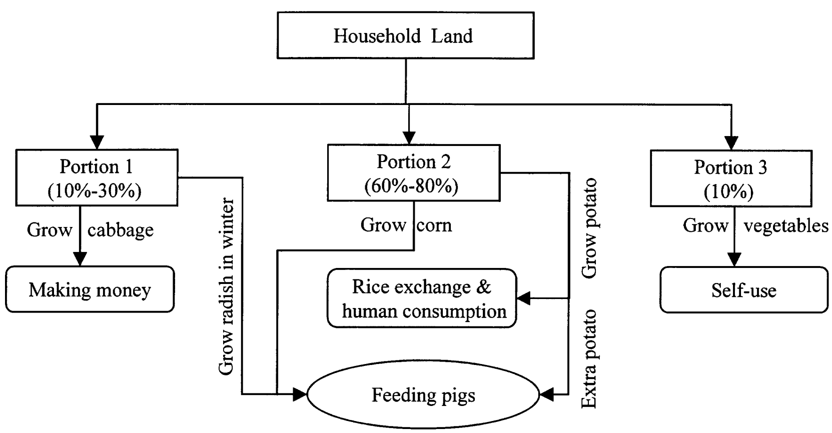

Fig. 7. Land-dependent life style of Wolong farmers. A large portion of their land (portion 1 and portion 2) is used to grow pig fodder.

pigs. A special type of radish is planted in winter as complementary fodder for pigs (Fig. 7). The pork (or bacon) thus produced was mainly for household use, but an increasing portion of it has been used for trade as the number of tourists, the main purchasers of local bacon, has increased over time. Self-consumed vegetables, including beans, celery, and radishes, are ignored in the model because they are of relatively small quantities. Furthermore these vegetables use a small portion of land (often intercropped with the staple crops or planted in winter, non-growing season of the staple crops). The only commercial vegetable, cabbage, is taken into account in the model because it is an important source of income.

The input to this *Production_and_Consumption* cycle includes land and labor. The amount of land is controlled by the government, whereas the availability of labor is associated with the present household demography, which in turn is determined by the government birth control policy and the farmers' birth attitudes. This *Production_and_Consumption* cycle impacts the amount of fuelwood use in two ways: (1) corn and radishes have to be cooked before being fed to the pigs; and (2) most of the food items (e.g. potatoes, vegetables, pork, and rice) have to be cooked for human consumption.

The following paragraphs discuss the important parameters for this submodel: (1) when corn is used to feed pigs, the input-output weight ratio is approximately 6:1, implying that the consumption of 6 units of corn by pigs can bring about 1 unit of pork. The input-output ratio for potato and pork is approximately 12:1; (2) the average productivity of radish is 30 000 kg/ha; the average area for planting (used as model input) radish is 0.146 ha; and the input–output ratio for potato and pork is 13:1; (3) the rate of exchanging potatoes for rice is 3.5, i.e. 3.5 units of potatoes are equivalent to 1 unit of rice in the market: (4) the regression between household size and household potato use quantity per year is:

$$\text{Household\_Potato\_Use} = 79.638 \times \text{Household\_Size} - 30.656 \quad (n = 28,\ R^2 = 0.476,\ P = 0.000048). \tag{1}$$

The total production of potato (or corn) is determined by its productivity, once the total area of land is fixed. Corn productivity and potato productivity were positively associated with per hectare expense. Because observed values of corn and potato productivity are never below 600 and 11 250 kg/ha, respectively, we used a maximal function to select a higher value between the calculated and the lower limit values:

$$\text{Corn\_productivity} = \text{Max}\,(1937.100 \times \text{LOGN}\,(\text{Per\_hectare\_expense}) - 11254.000,\ 600.000) \quad (n = 30,\ R^2 = 0.56,\ P < 0.0001). \tag{2}$$

$$\text{Potato\_ productivity} = \text{Max}\,(5662.900 \times \text{LOGN}\,(\text{Per\_hectare\_expense}) - 29342.000,\ 11250.000) \quad (n = 30,\ R^2 = 0.591,\ P < 0.0001). \tag{3}$$

However, if there is no labor (number of people between 21 and 60 is zero), we assume the productivity would be reduced by multiplying a Corn_labor_index of 0.8. In the Reserve, we did observe that the households without labor had a lower productivity even though they hired relatives and friends to help them with the farming work. This is also the case for potato productivity.

Rice is the staple food in Wolong, but not grown there. In order to obtain enough rice, local residents usually use potatoes to exchange for rice from the outside market. If the rice from the exchange is not enough to meet the household demand (household size* per capita need, 148.5 kg per person — an average of the selected 30 households in 1997), we assume that extra money will be spent to purchase the rice needed.

Pork is the basic meat in Wolong. Our interview showed that almost every household had enough pork to eat, so the total quantity of pork demand of each household was equal to household size times per capita need. However, pork is not purchased from the market in the case of shortage because local residents can reduce pork consumption by increasing the consumption of other food, e.g. rice, potatoes, and sometimes meat of wild pigs obtained from poaching. The pork is sold if extra

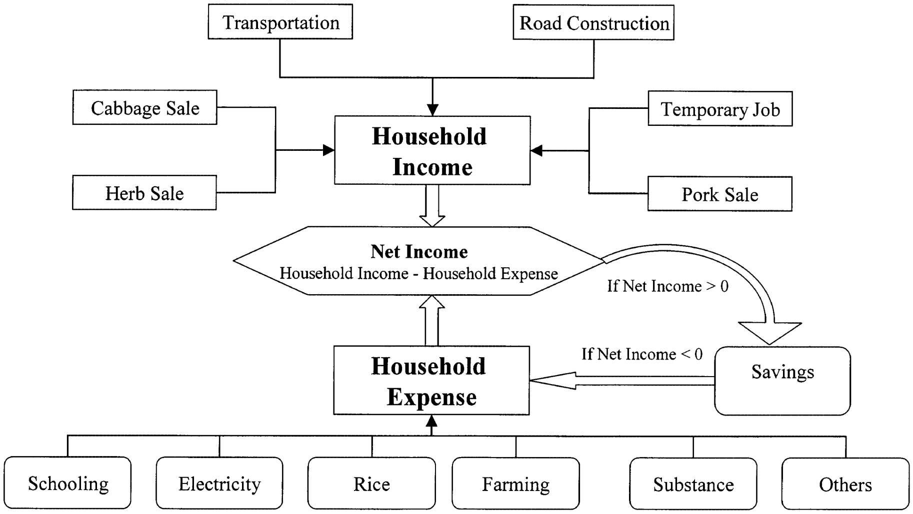

Fig. 8. Household potential incomes and expenses. See Section 2.3.2 for variable definitions.

quantity exists. The market price for pork was 12 Yuan/kg in 1997 and 1998 (1 US$ = 8.3 Yuan).

Another very important component in the sub-model *ECONOMY* is *Incomes_and_Expenses*. The difference between the incomes and expenses, i.e. yearly net income, is set to be a state variable because it represents the economic status of the household, and determines (at least affects) household expense decisions. The potential income sources for a typical household include cabbage sale, herb sale, pork sale, construction of roads, local transportation, and temporary jobs. The potential expenses include children's schooling, purchase of electricity, purchase of rice, farming facilities, and subsidiary substance ('Substance' in Fig. 8) that refers to alcohol, cigarettes, salt, soybean sauce, and so on (Fig. 8).

All the incomes or expenses in the future should have been converted to present values by using a discount rate if we were interested in the accumulated incomes or expenses. However, the amount of fuelwood consumption at a given time, which is our focus in this model, is the function of various demographic, income, and expense factors at that time. As long as the function (the relationship between the annual amount of fuelwood consumption and those demographic, income and expense factors) does not change over time, there is no need to discount the future money and calculate its present value. Furthermore, for short-term simulations presented in this paper, no significant differences exist between using and not using a typical discount rate (5%).

Transportation includes the shipping of local agricultural/forest products to the outside and industrial/consumptive goods to the reserve. Transportation can provide the highest income (13 250 Yuan on average) if a household is able to do it, but few households can afford it because of the high expense to purchase vehicles. This income requires three pre-requisite conditions: at least 3 years of education (the smallest number of schooling years for those households owning trucks observed in the survey), at least 20 000 Yuan of accumulated savings (half of the price for a small truck — we assume this is necessary for buying a truck based on our interviews with farmers), and enough labor (the number of people between 21 and 60 is greater than or equal to 1).

Income from temporary jobs refers to the income from such jobs as building hydropower stations, building houses for other residents, and working in local restaurants. It depends on the availability of the labor and the average schooling years of the labor. If the household head is illiterate (all the households with income from temporary jobs have schooling years larger than 0), or the number of people between 21 and 60 (defined as labor in this model) is zero, the household is not able to obtain this type of income. Otherwise the household gets an average annual income of 1421.79 Yuan.

Road construction requires physical power and results in a relatively low income of 750 Yuan per year (25 Yuan per day, 30 days per year on average). Thus we assume no income arises from road construction for a household that has no labor or gets transportation income. Otherwise if the random variable creates a value less than 0.350 (35% of the local farmers obtained road construction income in 1997), the household can earn an average of 750 Yuan.

Like road construction, herb collection requires physical power and the associated income is relatively low. Thus if the household receives income from transportation or no labor exists, herb income is set at zero. In addition, because no households with nine or more schooling years collect herbs, we set this variable to zero if the educational level is equal to or greater than 9 years. Otherwise if the random variable creates a value less than 0.47 (14 out of 30 households have herb income), the herb income is set to be the function of the educational level (in terms of schooling years of the labor in the household):

$$\text{Herb\_income} = -123.100 \times \text{Education-level} + 1093.000 \quad (n = 14,\ R^2 = 0.528,\ P < 0.0001). \tag{4}$$

Cabbage sale is one of the main income sources in Wolong Nature Reserve. Approximately 96% of the farmers plant cabbage. We found cabbage income (Yuan) has a significant positive relationship with the cabbage land area (ha):

$$\text{Cabbage\_income} = 20515.000 \times \text{Cabbage-land} - 161.380 \quad (n = 25,\ R^2 = 0.609,\ P = 0.0000042). \tag{5}$$

Local residents tend to satisfy their demands for pork/bacon first and sell the extra in the form of bacon. The conversion rate from pork to bacon is approximately 0.6–0.7, because pork loses weight due to water loss when it is processed by smoke. Consequently, bacon has a higher price than pork. The total amount of income, whether from pork sale or bacon sale, is almost the same. So bacon income is only set to be a function of the amount of pork available. Specifically, bacon income occurs only if the household has extra pork, which is the difference between the quantity of pork available in a given year and the quantity needed by the household. The quantity of pork available in a given year depends on the amount of corn, radish and potatoes used to feed pigs; the quantity needed by the household is the product of household size times the per capita yearly consumption.

Household expenses include children's schooling costs, electricity costs, purchase of rice, farming facilities, and subsidiary substance. In order to obtain the annual average expenses that a household has to spend for students in elementary school, middle school, and high school, we did a pre-interview of ten households. The associated results were 335 Yuan/year per student, 1842 Yuan/year per student, and 5175 Yuan/year per student for elementary school, middle school, and high school expenses, respectively (the corresponding results based on those 30 households that were later used for model verification were 355 Yuan/year per student, 1750 Yuan/year per student, and 3940 Yuan/year per person).

Elementary schooling expense occurs when there are children between 6 and 12 years old in the household. The Chinese government requires all children go to elementary school, so the probability that a household sends their children to elementary school (R_1) was set at 1. One child in elementary school needs an average of 355 Yuan per year for enrollment and textbooks. The total expense for elementary school S_1 is as follows:

$$S_1 = 355 \times \text{Number\_of\_children\_aged\_6\_to-12}. \tag{6}$$

The data from the pre-interview showed that the average expenses for a middle school student and a high school student were 1842 and 5175 Yuan, respectively, and that not all parents were able to, or wanted to, send their children to middle or high school, as they spent their limited income first on basic needs such as food, electricity, and farming facilities. Thus we used yearly net income as a criterion to determine whether a household will send children to middle school and high school. Because the yearly expense for middle school was 1842 Yuan, we set three levels of net income, 1842, 921, and 500 Yuan, to test what farmers would do if their net income was enough to pay the total (1842 Yuan), a half (921 Yuan), or only a small portion of the schooling expense (500). We then surveyed their willingness to send their children to middle school and high school at different levels of net income. If household net income per year was between 500 and 921, between 921 and 1842, or greater than 1842, 29.1, 51.0, or 68.2% of the respondents, respectively, said they would send their children to middle school. In the case that the household yearly net income was below 500 Yuan, we assumed the probability was zero. One point that should be made is that since the income levels of 921 and 1842 were based on results of the pre-interview of the ten households rather than the results of the 30 households used for model verification, the probabilities thus obtained should not exactly represent the probabilities for those 30 households. We will show later in the Section 3.2 that the model outcome is not sensitive to the income and expense items such as middle school and high school expenses. Therefore, we still used the income levels from the pre-interview and the associated probabilities in the model.

Similarly, when household net income was between 1000 and 2588, between 2588 and 5175, or greater than 5175, 15.4, 29.3, or 56.0% of the respondents, respectively, said they would send their children to high school.

If the number of people between 13 and 15 years old was equal to or greater than 1 and the random variable creates a number less than R_2 ($R_2 =$ 0.291, 0.510, or 0.682, the probability that the household would send their children to middle school), the yearly expenses for middle school were S_2:

$$S_2 = \text{Number\_of\_people\_between\_13\_and\_15} \times 1842, \tag{7}$$

The assignment of values to R_2 depends on the corresponding net income in the previous year. If a household had a very low net income (less than 500) but still wanted to send their children to school, a binary variable ('MidSchl Intention' in the model, 0 for no and 1 for yes) would be used. We set the default value of this variable to be 0 because a household generally does not send their children to school if they have very low net income — their subsistence needs (e.g. food and clothes) should be met first. However, when we want to test what would occur for a low-income household that wants to send their children to middle school, we set it to be 1. In this case as well as other cases, where yearly net income is lower than the average expense for middle school (1842), debt will occur (net income is negative).

Similarly, the yearly expenses for high school (S_3) are calculated by using Eq. (8) if the random variable creates a value smaller than R_3 ($R_3 =$ 0.154, 0.293, or 0.560, the probability that the household would send their children to high school):

$$S_3 = \text{Number\_of\_people\_between\_16\_and\_20} \times 5175, \tag{8}$$

The assignment of values to R_3 depends on the corresponding net income.

Every household uses electricity for lighting and for appliances such as TV, but the extents to which farmers use electricity differ with per capita income. In light of the fact that no household spent more than 720 Yuan for electricity in 1997, we used a minimal function to restrict the electricity costs:

$$\text{Yearly\_electricity\_expense} = \text{Min}\,(0.109 \times \text{Per\_capita\_income} + 37.870, 720.000) \quad (n = 30, R^2 = 0.605, P < 0.0001). \tag{9}$$

Rice expense occurs if the amount of rice exchanged from potatoes is smaller than the amount needed, which is expressed as follows:

$$\text{Rice\_expense} = (\text{Rice\_needed} - \text{Rice\_obtained}) \times \text{Rice\_price}, \tag{10}$$

$$\text{Rice\_needed} = \text{Household\_size} \times \text{Per\_capita\_rice\_need}, \tag{11}$$

$$\text{Rice\_obtained} = \text{Potato\_for\_rice/Market\_exchange\_rate}, \quad (12)$$

where Per_capita_rice_need and Market_exchange_rate are set at 150 kg per person and 3.5, respectively.

Farming expense, including expenditure on seedlings, chemical fertilizers, land films (used to keep corn seedlings from freezing damage), and tools, is equal to per hectare expense (Yuan/ha) times land area (ha). Average expense per hectare was 2026.8 Yuan.

Expenses for subsidiary substance ('Substance' in Fig. 8), including alcohol/beer, cigarettes, salt, and soybean sauce, are a positive function of household size:

$$\text{Substance\_expense} = 83.029 \times \text{Household\_size} - 55.673 \quad (n = 30,\ R^2 = 0.466,\ P < 0.0001). \quad (13)$$

Expenses for others refer to money used for clothes, religious activities, medical services, and some other social activities (e.g. sending gifts to a household with a newborn baby, giving money for a relative's wedding). It is a function of yearly income:

$$\text{Other\_expense} = 630.270 \times \text{LOGN (Yearly\_income)} - 3651.400 \quad (n = 30,\ R^2 = 0.562,\ P < 0.0001). \quad (14)$$

For those households with trucks, we assumed that they got loans from friends, credit unions, or banks and would pay back later. If the purchasing expense is X yuan and the household decides to return Y Yuan each year, then this loan return has to last for X/Y years. Here X and Y were set to be 40 000 (the price of a new small truck, Jian Yang, 1999, personal communication) and 5000 Yuan, respectively.

Yearly net income is connected to another state variable called 'Accumulated_Savings'. Yearly net income goes into Accumulated_Savings at the end of each year if it is positive. If it is negative, the money in Accumulated_Savings is used to offset the deficit (Fig. 8). If yearly net income keeps negative over time, there is a great possibility that some local residents resort to illegal activities such as clandestine logging and poaching (Jian Yang, 1999, personal communication). Thus the dynamics of yearly net income deserves extensive attention in terms of wildlife conservation.

2.3.3. Submodel FUELWOOD

Household fuelwood consumption, a factor directly affecting panda habitat, is driven by demands from heating, cooking, and pig fodder cooking. Fuelwood consumption quantity for heating in a household without a senior person (61 years old or above) was set at a constant (7.23 m^3 per year, an average of fuelwood consumed for heating for the households without senior people) because there was no statistically significant relationship between the quantity of fuelwood for heating and household size. Whether or not there is a senior person in the house, does however, affect the amount of fuelwood used for heating. A household with a senior person starts heating from early October to mid-April, lasting approximately 190 days; while that without a senior person does this from late October to early April, lasting approximately 160 days. Assuming the quantity of fuelwood use per day is a constant, a household with a senior person should consume 19% ((190–160)/160) more fuelwood than one without a senior person, i.e. $7.23 \times (1 + 19\%) = 8.60\ m^3$ per year.

The annual amount of fuelwood used for cooking is a function of the household size:

$$\text{Fuelwood\_for\_cooking} = 0.467 \times \text{Household\_size} + 0.703 \quad (n = 30,\ R^2 = 0.533,\ P = 0.0000046). \quad (15)$$

Fuelwood for pig fodder cooking depends on how much pork is converted from potatoes, corn and radishes. We calculated the average ratio between fuelwood for cooking pig fodder and pork produced as 0.0106 (SE = 0.0038) m^3/kg, indicating that 1 kg of pork produced consumes 0.0106 m^3 of fuelwood.

2.4. Model programming

PANDA_DEEM was programmed using STELLA 5.0 (High Performance Systems, Inc., 1997). A friendly graphic interface was developed to facilitate the communication between the user and the model.

The initial values of the state variables described in Section 2.3 were set at the average values of the associated variables. One exception is that the initial net income was set at 0 because we wanted to exclude the historical effects of net income.

2.5. Model testing and simulation

Model testing aims at justifying the reliability of the model and providing confidence for model application. Four approaches (model verification, model validation, sensitivity analysis, and uncertainty analysis) were used to achieve this goal. As mentioned in Section 2.3, we already obtained the equations and the parameter values for submodels *FUELWOOD* and *ECONOMY*. Submodel *DEMOGRAPHY* needs household size and ages of all the household members as model inputs. For simplicity, a concept of 'typical household' is used for model testing and simulation. A typical household is defined as a household with five people (three generations), one grandparent, two parents, and two children. The reason why we set household size to be five, and chose two children and one senior person, was based on the following observations: the average household size of the 30 households was 5.2 people, and 40%, 33%, and 3% of these 30 households had two, three and one children/child, respectively. Thus we chose two children, two parents, and one grandparent for this typical household.

We ran the model for different replicates and then calculated the average of fuelwood consumption amounts. These tests indicated that 50 runs could produce a relatively stable outcome. Because we were most interested in structural interactions between different variables in the submodels, we decided to use a short time length to run the model so that the basic structure of household demography did not change. A number of runs showed 4–6 years could keep the age structure of the typical household unchanged but still allow for some stochastic processes (e.g. whether a child of 9 years old at the beginning of simulation could go to middle school or not by the end of simulation) to function. We used 5 years as the time length. The model can be easily extended to do long-term (10 years or longer) simulations.

2.5.1. Model verification

We first used the data from the 30 households for model development to verify the model results. This approach can be divided into the following steps: (1) set the values of the demographic and socioeconomic variables to be exactly the same as those in the corresponding household; (2) run the model 50 times (replicates); (3) calculate the average of each run over time (5 years); (4) calculate the average of all the above 50 replicates and the associated standard error with respect to the observed value; (5) repeat steps 1–4 for all the 30 households; (6) use paired t-tests to test for the difference between the simulation results and the observed fuelwood consumption quantities for all these 30 households.

2.5.2. Model validation

The independent data from the 15 households that had not been employed for model development were used to validate the model. We followed the same procedure used for model verification in Section 2.5.1.

2.5.3. Sensitivity analysis

The purpose of conducting a sensitivity analysis is to evaluate how the amount of fuelwood consumption responds to relatively small changes in different components of the model. This process could help us to identify the most sensitive components. Also, it serves as an alternative approach to model testing because unusual responses of the model caused by a small change in one component may indicate some potential errors in model structure or model parameterization. To measure the sensitivity, we employed the following sensitivity index (Jørgensen, 1986):

$$S_x = (\mathrm{d}X/X)/(\mathrm{d}P/P), \tag{16}$$

Table 1
Sensitivity indices of socioeconomic parameters[a]

Parameters	Initial value	Sensitivity index
Elementary school expenses (Yuan per year)	335	−0.050
Middle school expenses (Yuan per year)	1842	−0.060
High school expenses (Yuan per year)	5175	−0.009
Truck costs (Yuan)	40 000	−0.012
Rice price (Yuan/kg)	2.6	−0.050
Transportation income (Yuan per year)	13 250	0.002
Road Income (Yuan per year)	750	0.003
Temporary job income (Yuan per year)	1421.79	0.011
Radish land (ha)	0.146	0.144
Potato/corn land (ha)	0.27	0.227

[a] At the beginning of a simulation, a household had five people (9, 12, 34, 35, and 78 years old).

where X is the value of dependent variable of interest and P is the parameter value under normal conditions; dX is the change in the dependent variable caused by dP, the change in parameter value. A larger S_x indicates a higher sensitivity of the dependent variable (here fuelwood consumption) to the change in a specific component.

We conducted sensitivity analysis of fuelwood consumption in response to changes in socioeconomic factors. We gave each of the values of the selected socioeconomic components (e.g. potato/corn land, and transportation income, see Table 1) a 10% increase and examined the model responses (Table 1). We ran the model 50 times and calculated the average amount of fuelwood consumption under each of these conditions. Then we calculated the S_x values based on Eq. (16).

2.5.4. Uncertainty analysis

Another alternative for model testing is uncertainty analysis, which is defined as a way 'to identify how model results vary with large variances in parameters' (Liu and Ashton, 1998). When a parameter has too much uncertainty (or a wide range of values), uncertainty analysis can be employed to examine how a model responds to the changes in the associated parameter. We first examined how the annual amount of household consumption responds to changes in household size (from 2 to 10), assuming one senior person exists in all the cases. Then we did the same thing except that no senior exists in all the cases.

We also examined how annual amounts of household consumption respond to the interactions between household size and area of corn/potato land (the most sensitive economic component based on our sensitivity analysis). We chose four household sizes (2, 5, 7, 9 people, with one senior person each) and six levels of corn/potato area: 0.033 (ha, smallest area observed), 0.135, 0.270 (the average area from the 30 households), 0.405, 0.540, and 0.675 ha. For each of these 24 combinations (four household sizes × six levels of land area), we ran the model 50 times

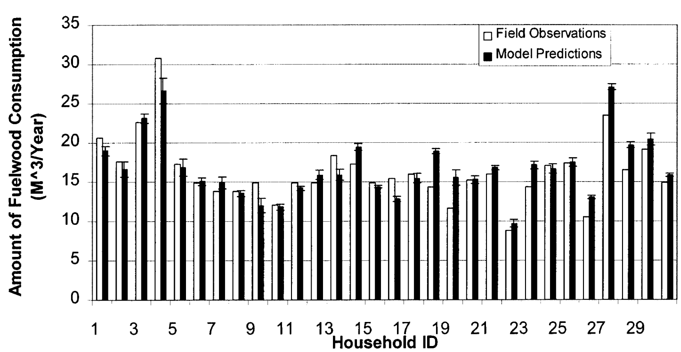

Fig. 9. Model verification — comparison between model predictions and field observations for fuelwood consumption of the 30 households in 1997. The field data associated with these 30 households were used for model construction.

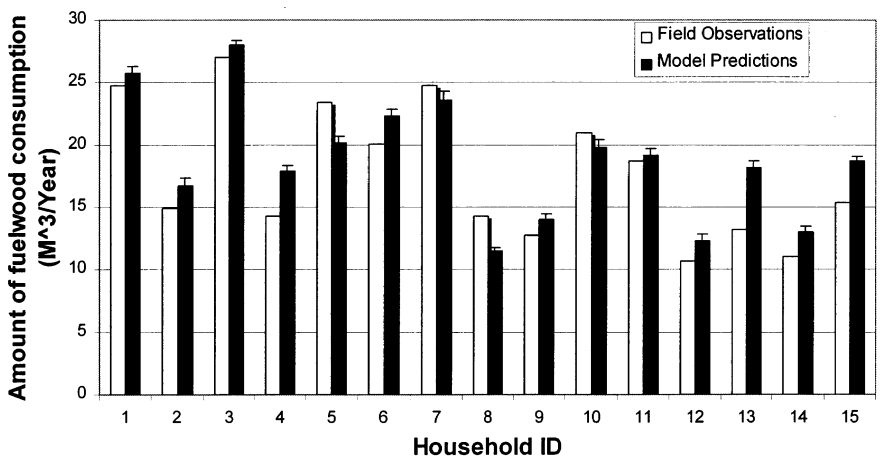

Fig. 10. Model validation — comparison between model predictions and field observations for fuelwood consumption of the 15 households in 1997. The field data associated with these 15 households were not used for model construction.

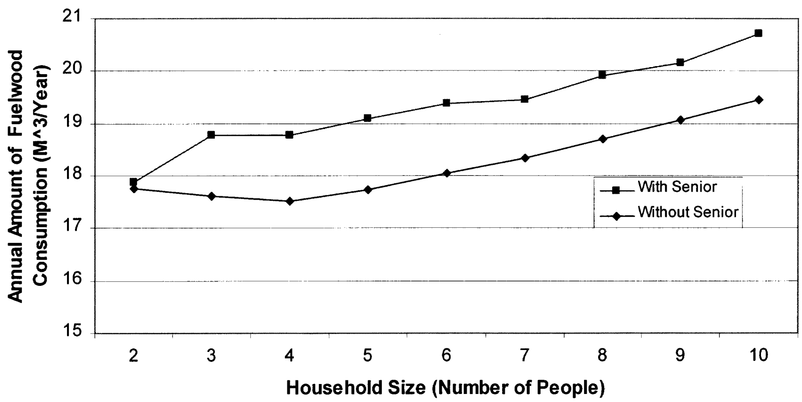

Fig. 11. The relation between amount of fuelwood consumption and household size. Household age structure has impact on fuelwood consumption.

and calculated the amounts of annual fuelwood consumption.

3. Results

3.1. Verification and validation results

The model outcomes agreed well with the observations (Figs. 9 and 10). The paired t-tests show that the model results matched well with the 30 observations ($P = 0.233$, $T = -1.220$) in model verification. The model outputs also agreed well with the 15 independent observations ($P = 0.1453$ $T = -1.550$) in model validation.

3.2. Sensitivity analysis results

Amount of fuelwood consumption was not very sensitive to economic components except for two items, i.e. radish land and potato/corn land (Table 1). A negative relationship existed between amount of fuelwood consumption and expense-related items, suggesting that more expenses in a household would lead to less fuelwood consumption if other conditions were kept unchanged. Furthermore, there was a positive relationship between amount of fuelwood consumption and income-related items, suggesting higher incomes would lead to more fuelwood consumption.

3.3. Uncertainty analysis results

A household with a senior person consume more fuelwood than one of the same size without a senior person and this trend was not obvious when the household size was two (Fig. 11). The annual amount of fuelwood consumption for households with seniors increase with the household size; whereas the annual amount of fuelwood consumption for households without seniors show a slight decline first as the household size increase from two to four, and then increase from four to ten (Fig. 11).

Amount of fuelwood consumption increase with the area of corn/potato land at each of the household sizes (Fig. 12). As corn/potato land increase, the differences among different household sizes became smaller and smaller. In the household with two people: as land area increase, the amount of fuelwood consumption increase at a faster speed in the region around 0.1 ha. It became higher than the amounts of fuelwood consumed by a household of five people from approximately 0.2 ha, and reached the same amount of fuelwood consumed by a household of seven people when the land area came to approximately 0.65 ha.

4. Conclusions and discussions

The age structure plays an important role in determining the household fuelwood use (Fig. 11) regardless of other factors (e.g. household income) that have the potential to offset this influence. This can be explained from three perspectives: (1) households with aged people start heating earlier and end heating later each year (Section 2.3.3), and thus need more fuelwood; (2) a household without a senior person, for instance, may have one more person of labor than that with a senior, and thus may result in more income. In Section 3.2, we mentioned the positive relationship between amount of fuelwood consumption and income level. In this sense, a household with a senior person should use less fuelwood due to lower income; (3) the ultimate amount of fuelwood consumption depends on which factor (age structure and more income) dominates under different conditions. Fig. 11 shows that age structure plays a dominant role in determining amount of fuelwood consumption for households of three people or more. However, economic components may offset the differences of fuelwood consumption caused by age structure under some conditions. For instance, a two-person household without a senior could have one more person of labor, thus could earn more income. As discussed before, this may slightly in-

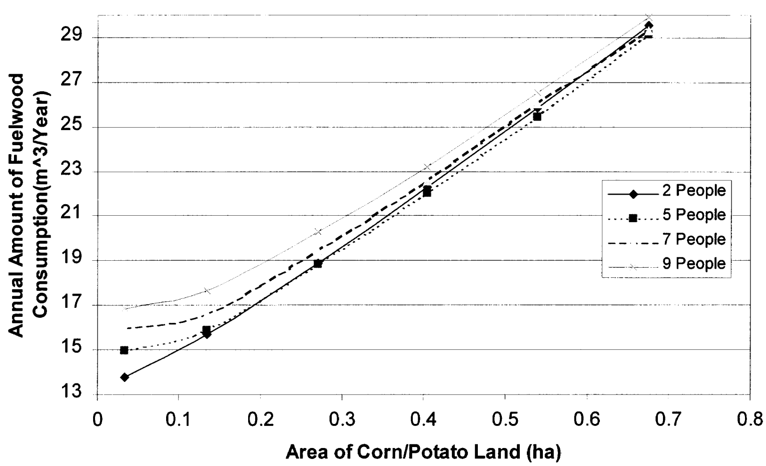

Fig. 12. The relationship between annual amount of fuelwood consumption and area of corn/potato land.

crease the amount of fuelwood consumption, thus decreasing the difference of amount of fuelwood consumption between a household with a senior and that without a senior.

The high sensitivity values for corn/potato land and radish land may result from the land-dependent life style (Fig. 7). Due to the natural economy in the Reserve, farmers do not have enough opportunities to earn money from industrial and commercial activities. The most feasible way is to raise as many pigs as possible. By doing this, farmers can not only meet their own needs for meat consumption, but also can make money through selling their bacon to tourists and local restaurants. However, keeping more pigs requires more fodder to feed them and more fuelwood to cook the fodder. As mentioned above, local farmers' income sources are very limited, so they have to rely on their land instead of purchasing from market. Here the land-dependent life style results in the route of 'more land — more fodder production — more pigs — more fuelwood for cooking fodder'.

The relatively obtuse responses from income- or expense-related components, consistent with this land-dependent life style, are explainable in terms of local farmers' subsistence demand. Farmers mostly depend on their land for subsistence, but they still have to trade for the necessary goods such as chemical fertilizers and land films. So the impacts from economic status (incomes and expenses), though small, still exist. The positive relation between fuelwood consumption and the income-related items can be explained in two aspects: (1) higher income can increase their crop productivity by allowing the purchase of more chemical fertilizers, thus resulting in more fodder to feed pigs. In turn, more fuelwood is needed to cook the fodder; (2) though higher income increases the ability to use electricity, most of the residents do not tend to do so if some cheaper or free substitutes (here fuelwood) are easily accessible and their income is not high enough to replace fuelwood with the electricity. In fact, our survey in summer 1999 showed that 78.18% of the 220 interviewees thought that the high price of electricity, with respect to their low income, was one of the barriers to switching from fuelwood to electricity for cooking and heating. Similarly, we can explain the negative relationship between fuelwood consumption and expense-related items because more expenses are equivalent to less income when other conditions stay unchanged.

It may be unusual that the amount of fuelwood consumption falls slightly when the household size is small (from two to four, Fig. 11). This phenomenon can also be explained in terms of the land-dependent life style. When a relatively large area of cropland is fixed (0.27 ha for corn/potato and 0.146 ha for radish), a household of small size (e.g. two to four people) has a greater ability to grow more pig fodder because land for growing human food is much less than that for a household of large size. As a result, the fewer people, the more fuelwood for cooking pig fodder. But when the household size reaches a certain threshold (here four people), this trend will diminish because the additional people need more food, thus the land for growing pig fodder decreases drastically. As a result, household size plays a more important role in determining amount of fuelwood consumption, and amount of fuelwood consumption displays a positive relationship with household size.

The results of the uncertainty analysis (Fig. 12) are also consistent with the above-mentioned land-dependent life style. When land area is small, people have no way to grow a large amount of fodder to feed pigs, thus the portion of fuelwood for cooking pig fodder is small, and the household size plays a dominant role in determining annual amount of fuelwood consumption. This is the reason why large differences are shown for households with small areas of corn/potato land. As the land area increases, amount of fuelwood consumption for cooking pig fodder takes a dominant role in determining total amount of fuelwood consumption, thus reducing the difference caused by household size. However, it is rare to see a small household (e.g. two people) with a large amount of cropland (e.g. 0.6 ha) and a large household (e.g. nine people) with a very small amount of cropland (e.g. 0.1 ha). Our field data show that there is a positive relationship between the amount of cropland and the household size (Fig. 13). This implies that a large household usually has more cropland and consumes more fuelwood than a small one does. In Fig. 12, the upper right region may

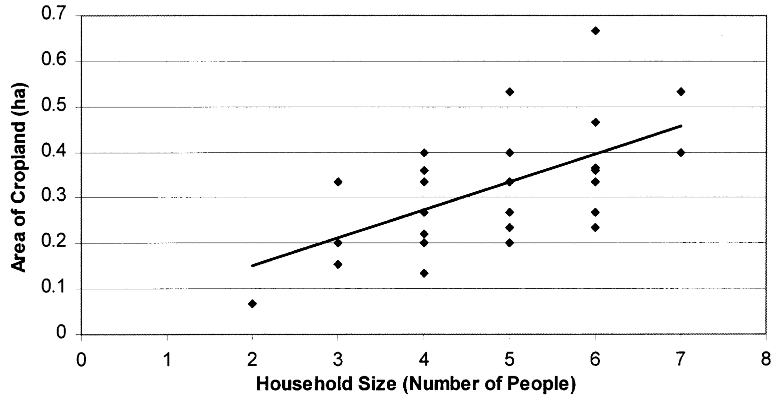

Fig. 13. The relationship between cropland area and household size ($n = 30$, $R^2 = 0.343$, $P = 0.00068$).

represent fuelwood consumption by large households, whereas the lower left region may reflect fuelwood consumption by small households.

The significance of this model rests on the following aspects: (1) as a household-based model, its submodel *DEMOGRAPHY* follows the life span of each individual in the household, thus can simulate the household population dynamics; (2) this model contains stochastic components in addition to those deterministic components, thus is able to simulate some random events at a given time, such as going to college; (3) the model provides a useful tool for analyzing interrelationships among various variables in the model, mostly based on field observations. Furthermore, it can be used to study the dynamics of fuelwood consumption over time; (4) this model can provide insights into how subsistence demands and social attitudes interact with each other and then impose additive impacts on panda habitat degradation, which is important to enable local administrators to make scientifically sound and economically reasonable decisions; (5) this model provides a good foundation for evaluating the impacts of fuelwood consumption by all households across the entire Reserve.

Acknowledgements

We thank Jian Yang, Yinchun Tan, and Han Xiao for their assistance in data acquirement and model parameterization. We are also grateful to Vicky Markham Dompka, Daniel Rutledge, and George Schaller for their useful comments on earlier drafts of this paper. We owe thanks to Jialong Xie who provided assistance in programming the model and analyzing the data. We are also indebted to the financial support from the National Science Foundation (NSF), National Institute of Health (NIH), American Association for the Advancement of Sciences, the John D. and Catherine T. MacArthur Foundation, Michigan State University, the Natural Science Foundation of China, Ministry of Science and Technology of China (G2000046807), China Bridges International and the Chinese Academy of Sciences.

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