Agent-based modeling in coupled human and natural systems (CHANS): Lessons from a comparative analysis

Supplemental Online Materials

1 Demographic submodels

1.1 Marriage

1.1.1 Marriage probability

Both ABMs first check if a person (male or female) has reached the *allowed minimum age of marriage* (22 years old for Wolong and 15 for Chitwan) and if the person is below the *allowed maximum age of marriage* (Chitwan only; both are empirically determined, Supplement-Table 1, italicized terms in the text are state variables; the same hereafter). If so, s/he is placed in a list of single people that qualify for marriage (qualify list hereafter). When a randomly generated number is less than an empirical probability (this probability is determined differently in each model; see below), this male or female will marry a female or male who is local (also in the qualify list) or comes from outside as an in-migrant (Supplement-Table 2). Otherwise, the person will stay as a single (or remain in the qualify list) till the same "test" next time step.

Supplement-Table 1: Person-level state variables in the Wolong and Chitwan ABMs. †In the Chitwan ABM agent relationships are tracked with direct references to the class instances that represent other agents, rather than with ID numbers. For example, a person agent maintains a reference to the household class instance it is a member of, allowing direct reference to attributes of its household.

	Wolong ABM		**Chitwan ABM**	
Variable	Present	Description	Present	Description
Person ID	Yes	Unique Identifier	Yes†	Unique Identifier
Father ID	Yes	Identifies father	Yes†	Identifies father
Mother ID	Yes	Identifies mother	Yes†	Identifies mother
Spouse ID	Yes	Unique Identifier	Yes†	Identifies spouse
ID of belonged HH*	Yes	Links to household agent	Yes†	Links to household agent
Age	Yes		Yes	Age of person in months.
Sex	Yes	Male or female.	Yes	Male or female.
Ethnicity	No	No data on how ethnicity affects resource use and other decisions	Yes	High caste Hindu, low caste Hindu, Terai Tibeto-Burmese, Hill Tibeto-Burmese, Newar
# of schooling years	Yes	Mostly range from 0 – 12; 15 or 16 and above possible.	Yes	Can range from 0-15 years, in monthly time steps.
Schooling status	No		Yes	Tracks whether an agent is currently in school, out of school, or not yet in school (too young to attend).
Final schooling level	No		Yes	The final level of schooling this person will achieve (provided they live to that age, and/or do not out-migrate prior to that

				age).
Spouse status	Yes	A flag for with spouse or not (including spouse dead). Spouse is tracked through an index.	No	Spouse is tracked through spouse ID.
Current # of children	Yes		Yes	Tracks number of children for initial agents in the model.
Child list	Yes	List of all children can be derived (not saved attribute)	Yes†	List of all children of this agent
Time of last birth	No	Derived through the age of the youngest one in child list	Yes	Tracked as a specific state variable in the Chitwan ABM.
Time of last outmigration	No	Permanent out-migration alone is considered. No need to track it	Yes	Tracked to allow
Allowed # of children	Yes	It reflects China's birth control policy (default at 2; other #s are for policy test)	No	No policy limit in Nepal.
Expected # of children	Yes	An integer from 0 - 5 set to the woman with probability from empirical data	Yes	Stores the maximum possible number of children a particular woman can have.
Not leave parental-home intention	Yes	A probability that an eligible adult does not leave parental home after marriage.	No	This variable is not person-specific in the Chitwan ABM.
Allowed min. age of marriage	Yes	A policy control parameter (default to 22 by law)	No	This variable is not person-specific in the Chitwan ABM. The same minimum age applies to all persons in the model.
Actual age/time of marriage	Yes	The time step the agent got married is tracked in the model for use in the first birth timing submodel.	Yes	The time step the agent got married is tracked in the model for use in the first birth timing submodel.
Max. age for childbearing	Yes	A single maximum age of childbearing applies to all agents (policy control; default to 50).	Yes	A single maximum age of childbearing applies to all agents in the model (default to 45).
Interval between marriage and first child	Yes	A parameter set to a woman (policy control); the realized interval >= this parameter	Yes	Calculated by the first birth timing submodel
Birth interval	Yes	A parameter set to a woman (policy control); the realized interval >= this parameter	Yes	The birth interval (time until the next child) is recalculated following every birth.
Target years of schooling (for young children & newborns)	Yes	Random integer between 0- 9 (for adults set at their current number of years)	Yes	Number between 0-15 (for adults set at their current number of years).
Mother's years of schooling	Yes	Years of schooling tracked for all agents	Yes	Years of schooling tracked for all agents
Mother ever worked for pay outside home	No	No data in Wolong	Yes	From empirical data from initial agents, follows probability distribution for others.
Number of children	No	Can be derived (not saved as an attribute)	Yes	From empirical data from initial agents, follows probability distribution for others.
Father's years of schooling	Yes	Years of schooling tracked for all agents	Yes	From empirical data, follows probability distribution for

				others.
Father ever worked for pay outside home	No	No data in Wolong	Yes	From empirical data from initial agents, follows probability distribution for others.
Male-Marry-Out Rate	Yes	Yearly probability that a male migrates out through marriage	No	Migration through marriage is handled implicitly – see "In-migration" in Section 3.7.1.
Female-Marry-Out Rate	Yes	Yearly probability that a female migrates out through marriage	No	Migration through marriage is handled implicitly – see "In-migration" in Section 3.7.1.
Female-Bring-Male-In Rate	Yes	Yearly probability that a female marries a male in-migrant	No	Migration through marriage is handled implicitly – see "In-migration" in Section 3.7.1.
Male-Bring-Female-In Rate	Yes	Yearly probability that a male marries a female in-migrant	No	Migration through marriage is handled implicitly – see "In-migration" in Section 3.7.1.

In Wolong these probabilities are empirically derived based on age and sex. Building on the literature in Chitwan (Yabiku 2006a, 2006b), the empirical probability is set as an endogenous variable that hinges on a number of person-level and community-level state variables. Also, the Chitwan ABM disallows marriage between ethnic groups, following our empirical analysis of the household registry data. Another difference in the Chitwan ABM is that all qualified agents marry, either with local qualified people or in-migrants, to simplify the marriage process.

Supplement-Table 2: Person-level actions in the Wolong and Chitwan ABMs.

	Wolong ABM		**Chitwan ABM**	
Action	Present	Description	Present	Description
Bear a child	Yes	See submodels	Yes	See submodels
Grow	Yes	Add one year to age	Yes	Add one month to age
Marry	Yes	See submodels	Yes	See submodels
Establish a new household	Yes	See submodels	Yes	See submodels
Out-migrate	Yes	See submodels	Yes	See submodels
In-migrate	Yes	See submodels	Yes	See submodels
Die	Yes	If random # < age group mortality, die	Yes	See submodels
Divorce	No	Traditionally very rare	Yes	See submodels

1.1.2 Spouse choice

In the Wolong model, if the bride or bridegroom comes from outside of Wolong as an in-migrant, the model sets the in-migrant's age randomly from 5 years younger to 5 years older than his/her spouse. If both the bride and the groom are from Wolong, they are randomly "matched" for marriage, provided that their age difference is not more than 5 years, and that they are not brother and sister. The maximum 5-year age difference between spouses comes from our field observation and best estimates (we do not have accurate data).

The Chitwan ABM takes account of the age difference between spouses in a slightly different manner. Couples are formed in the Chitwan ABM by stepping through the qualified agent list, and assigning a probability of marriage to each potential spouse (who must be of the same ethnicity) based on the age difference between spouses. Our empirical analysis suggests women tend to be younger than their husbands in Chitwan. Probabilities of marriage are assigned to potential spouses based on the empirically observed spouse age difference histogram. Couples are formed by drawing a random number, and assigning a spouse considering the age difference-dependent probability of marrying each potential spouse.

Below we provide the pseudo code for a generalized marriage submodel that is distilled from the two ABMs. In this example, the code loops through all person agents at a given time step (not shown below). For a certain person agent, the code first checks if that person can marry by calling the *Qualified-for-marriage* function; if qualified, the person agent may then get married in the *Marry* function (the terms in parentheses of the pseudo code are input data needed to implement the function). If a qualified person agent does not get married, s/he will remain in a list of single person agents, go through the other processes in the model (submodels below), and be considered for marriage again in the next time step. In the *Marry* function, the female-marry-probabilities can be calculated from a function such as a regression model with agent attributes and local environment as independent variables or from an empirically-derived histogram. Note that function names are in italicized font, brackets are used to begin and end a function, and semicolons are for the end of a statement for an action. Due to space limitations, we do not show the pseudo code for the rest of the submodels. For the pseudo code and more details see the website at http://complexity.sdsu.edu/CHANS-ABMs/pseudo-code.

1.2 Divorce

At the time of our modeling, divorce in Wolong was very rare, and was therefore excluded from the Wolong ABM. In Chitwan, divorce, though still rare, is becoming more common. A preliminary model of divorce is included in the Chitwan ABM to allow modeling the impact of divorce on the landscape, population structure, and household size in Chitwan (Yu and Liu 2007). In the Chitwan ABM we allow divorce by setting a fixed monthly probability of divorce that the modeler can vary. Future work will take into account person-level, household-level and community-level covariates and model the monthly probability of divorce for each married agent using logistic regression. If a random number is less than the divorce probability for a marriage, the two spouses will divorce. The woman either will return to her parent's household, or, if her parent's household no longer exists, she will establish a new household in a randomly selected neighborhood according to the household establishment submodel. The man will remain in the original household, together with child agents, if any.

1.3 Fertility

1.3.1 Birth

The Wolong and Chitwan ABMs allow childbearing only to married couples, given that at both sites we observe nearly zero childbearing outside of marriage. At any given time step, the ABMs first examine the number of children ever born already accumulated for each married woman. If this is the first birth after marriage, the Wolong model ensures that enough time has passed since marriage for a birth to occur (Supplement-Table 1). The Chitwan models handles the first birth after marriage separately – see below.

If a woman has already had her first child, but has fewer children than her *desired number of children,* and if enough time has passed since the birth of her youngest child (the birth interval), then, in the Chitwan ABM, she bears a child, while in the Wolong ABM she bears a child with probability of 0.35 (if less than 30 years) or 0.35/age difference$^{0.4}$ (if older than 30 years; probability function is derived from a combination of calibration, heuristics, and field observation). In both the Wolong and Chitwan ABMs, the birth interval for each woman's next child is calculated after each new birth, based on the empirically observed birth interval distribution. Because of the stochastic nature of this process, a woman may not reach her *desired number of children*, as she may die or reach her *maximum age for childbearing* first.

1.3.2 First birth timing

First birth timing (which we define as the time interval between marriage and the first live birth) is an important demographic variable, as delayed childbearing can affect other life decisions as well as aggregate population features. In Chitwan, prior work has established that first-birth timing is affected by socioeconomic and environmental covariates (Ghimire and Hoelter 2007; Ghimire and Axinn 2010). We model first birth timing in Chitwan using the results of a discrete time event-history analysis (drawn from the findings of Ghimire and Hoelter 2007). Using this regression model, we calculate the probability of first birth to each eligible woman (married women who have had no children) at the beginning of each time step. A first-birth occurs if a random number that is drawn is less than this probability. The Wolong ABM sets the default first-birth timing at 2 years (empirically observed), and allows it to be a parameter for policy control that ranges from 1 to any number of interest.

1.4 Household dynamics

1.4.1 Household establishment

In both the Wolong and Chitwan ABMs, new households (for their characteristics see Supplement-Table 3) are established at the time of marriage and perform a set of actions (Supplement-Table 4). New households in Wolong are randomly located at a pixel that is not greater than 37 degrees in slope, 2,620 m in elevation, and that is within a user specified distance from the parental house (default at 800 m). Males, at a given probability (*not leave parental-home intention* parameter, Supplement-Table 1, determined by socioeconomic and demographic factors, An et al. 2003, 2005), will not form a new household but will continue living with his parents at the time of marriage if the male is the youngest (or only) male child. For a female who marries a male, she will form a new household with her husband after marriage unless: 1) she is the only child, or 2) she has only sisters and she is the youngest one.

In the Chitwan ABM, new households are also established at time of marriage. Given the generally flat landscape in Chitwan, elevation is not considered in determining new household locations. New households are created at marriage with a probability equal to the *household fission rate*, which is set based on empirical data (Section 3.5). If a random number is less than the fission rate, a new household is created at marriage. For details on vegetation change due to household establishment, see the submodel in Section 4 of this supplement.

Supplement-Table 3: Household-level state variables in the Wolong and Chitwan ABMs.

Variable	Wolong ABM		Chitwan ABM	
	Present	Description	Present	Description
HH* ID	Yes	Unique HH Identifier	Yes	Unique HH Identifier
X & Y **c**oordinates	Yes	Several HHs can be in the same pixel (the same X & Y)	No	Tracked at community level.
Elevation (m)	No	Can be derived through locating the pixel of the HH.	Yes	Elevation in meters from an SRTM digital elevation model.
Electricity price	Yes	1996 price (based on data of 1999; varies by village)	No	Not modeled in Chitwan ABM.
Hypothetical electricity price	Yes	A parameter set by user (for policy test)	No	Not modeled in Chitwan ABM.
Outage level	Yes	Read from input data. 0, 1, and 2 for low, mid, and high	No	Not modeled in Chitwan ABM.
Hypothetical outage level	Yes	A parameter set by user (for policy test)	No	Not modeled in Chitwan ABM.
Voltage level	Yes	Read from input data. 0, 1, and 2 for low, mid, and high	No	Not modeled in Chitwan ABM.
Hypothetical voltage levels	Yes	A parameter set by user (for policy test)	No	Not modeled in Chitwan ABM.
Own household plot	No	No data	Yes	From empirical data from initial agents, follows probability distribution for others.
Own land	No	No data	Yes	From empirical data from initial agents, follows probability distribution for others.
Rent out land	No	No data	Yes	From empirical data from initial agents, follows probability distribution for others.
Use any non-wood fuel	No	No data	Yes	From empirical data from initial agents, follows probability distribution for others.
Time of last migration	No	No data	Yes	From empirical data from initial agents, follows probability distribution for others.

* HH represents household. The same convention is followed hereafter.

1.4.2 Household removal

In both ABMs, an existing household will be abandoned when its size becomes zero, for any reasons such as death, divorce, or out-migration (the Chitwan ABM will not remove an empty household if an out-migrant will later be returning to that household – see the "out-migration length" submodel). The location that contains the abandoned household will be labeled as without household and the model will allow vegetation to grow (Wolong ABM) or to return to agriculture (Chitwan ABM).

Supplement-Table 4: Household-level actions in the Wolong and Chitwan ABMs.

	Wolong ABM		**Chitwan ABM**	
Action	Present	Description	Present	Description
Collect fuelwood	Yes	At the chosen plot, cut trees at the amount of demand	No	Not modeled in Chitwan ABM.
Seek fuelwood plot	Yes	Seek a plot with minimized energy use among nearby forest plots	No	Not modeled in Chitwan ABM.
Calculate fuelwood demand	Yes	Consists of fuelwood for cooking fodder, for human food, and for heating house	Yes	Calculates fuelwood usage based on regression results.
Convert farmland to residence (build a house)	Yes	Equivalent to building a new house	Yes	Build a new household on agricultural land.
Out-migrate	No		Yes	Entire household out-migrates from Chitwan.

1.5 In-migration

In Wolong, any person whose age is above the allowed *minimum age of marriage* (default to 22, Supplement-Table 1) can bring in an in-migrant through marriage. At any time step, if a randomly generated number is smaller than the empirical yearly in-migration rate for males (or females), the male (or female) brings in a female (or male) into the reserve through marriage. In-migration through marriage is possible in the Chitwan ABM as in Wolong, though the probability of marrying an in-migrant is not set directly, but is instead dependent on the marriage market in Chitwan – if insufficient spouses exist for all person agents that are qualified to marry in a given time step, qualified individuals will marry in-migrants. We allow an entire household to in-migrate with probability specified by a fixed empirically derived parameter (similar to household out-migration as described above).

1.6 Out-migration

1.6.1 Decision to out-migrate

The Wolong ABM considers migration primarily in combination with marriage because the *hukou* (residence permit) system in China only allows a very limited number of situations in which a permanent out- or in-migration could happen, and marriage is the major venue for migration. Any person whose age is above the allowed *minimum age of marriage* (default to 22; Supplement-Table 1) and less than 30 years old (assumed maximum age for out-migration based on field observation) could be subject to out-migration through marriage. Another major type of out-migration is realized through education: young people (16-20 years old) may go to college or technical school and settle down in cities. In the Chitwan ABM, we model individual-level and household-level out-migration. At the individual level, a logistic regression model is used to calculate the probability of out-migration for any individual above the *minimum individual out-migration age*. The regression model (based on Massey, Axinn, and Ghimire 2010) takes into account a series of individual-level, household-level, and community-level (Supplement-Table 5) covariates to model the probability of an individual out-migration from the Chitwan Valley (long-distance migration in the terms of Massey, Axinn, and Ghimire 2010). If a random number is less than the calculated probability for an individual (the same for Wolong), that individual out-migrates starting in that time step. Household-level out-migration is also modeled in Chitwan, whereby we allow an entire household to out-migrate with probability specified by a fixed empirically derived parameter.

Supplement-Table 5: Community-level state variables in the Wolong and Chitwan ABMs.

	Wolong ABM		**Chitwan ABM**	
Variable	Present	Description	Present	Description
Neighborhood ID	No	Not applicable.	Yes	Unique community identifier
X & Y coordinates	No	Tracked by household agents.	Yes	Location in UTM45N coordinates
Electricity available	No	Tracked by household agents.	Yes	Is electricity available in the neighborhood (yes or no)
Land area: agriculture (m^2)	No	Not applicable.	Yes	Land use is tracked at the community level.
Land area: non-agriculture (m^2)	No	Not applicable.	Yes	Land use is tracked at the community level.
Land area: private buildings (m^2)	No	Not applicable.	Yes	Land use is tracked at the community level.
Land area: public buildings (m^2)	No	Not applicable.	Yes	Land use is tracked at the community level.
Land area: other (m^2)	No	Not applicable.	Yes	Land use is tracked at the community level.
Distance to urban center	No	Not applicable.	Yes	Distance from community center to Narayanghat (in km).
Distance to nearest market	No	Not applicable.	Yes	Distance from community center to closest market (in minutes on foot).

Distance to nearest employer	No	Not applicable.	Yes	Distance from community center to closest employer (in minutes on foot).
Distance to nearest bus	No	Not applicable.	Yes	Distance from community center to closest bus stop (in minutes on foot).
Distance to nearest health center	No	Not applicable.	Yes	Distance from community center to closest health center (in minutes on foot).
Distance to nearest school	No	Not applicable.	Yes	Distance from community center to closest school (in minutes on foot).
Closest neighborhoods	No	Not applicable.	Yes	A list of all the other communities in the model, sorted from nearest to farthest.

1.6.2 Out-migration length

The Wolong ABM does not consider non-permanent out-migration primarily due to legal restrictions on migration such as the *hukou* system. In Chitwan, once an individual becomes a migrant (as determined in the "decision to out-migrate" submodel), an out-migration length is calculated. First, if a random number drawn is less than the *permanent out-migration probability*, then that agent will be removed from the model, and the household will be tagged as having a permanent out-migrant member. We calculate this probability based on monthly household registry data from Chitwan, defining a "permanent" out-migrant to be a migrant who has left from Chitwan without returning for greater than 48 months. If the person does not become a permanent out-migrant, a second random number is drawn, and is used to compute an out-migration length from an empirically observed distribution. The agent will be added to a special group of person agents that, while not present in Chitwan, are still part of the model (their age increments every time step and they are still subject to the mortality submodel). If the agent survives until a number of time steps equal to their out-migration length has passed, the person then returns to his or her original household. Each household tracks a list of temporary out-migrants who are not currently present in the household, but who will be returning after an amount of time equal to their out-migration duration has passed.

1.7 Mortality

Every person is subject to a stepwise (yearly in Wolong and monthly in Chitwan) survival check: if a randomly generated number between 0-1 is less than the corresponding stepwise mortality rate for the age (age/sex in Chitwan) group the person belongs to, s/he dies and is removed from the model; otherwise s/he survives and is subject to all other related processes as described above.

2 Socioeconomic submodels

2.1 Potential fuelwood demand

There are two components to the fuelwood usage models in both of the ABMs: potential fuelwood demand, and tendency to use either electricity (in Wolong) or fuelwood (in Chitwan). Fuelwood demand in Wolong and in Chitwan is termed as "potential demand" as there is a substitute for fuelwood: electricity, or (primarily in Chitwan) liquefied petroleum gas (LPG). The potential demand for fuelwood in Wolong consists of three components: 1) fuelwood for cooking pig fodder, 2) fuelwood for cooking human meals, and 3) fuelwood for heating the house in winter. The demand for cooking pig fodder is set to be a linear function of cropland area because local farmers use cropland to grow corn or potatoes as pig fodder. The demand for cooking human meals is modeled, in a simplified form, as a linear function of household size. The demand for heating is set at two constants, for households with or without a senior person (60+ years old; An et al. 2001).

Households in Chitwan tend to make some use of fuelwood even if they possess an alternative stove (LPG, electric, etc.) in addition to their wood stove, as fuelwood is cheaper to use, and some households report preferring fuelwood stoves compared to other types of cook stoves. Potential fuelwood demand in Chitwan is calculated monthly, on a per-household basis, as a linear function of household size, ethnicity, and stove type (Zvoleff and An in review). Given the warmer climate in Chitwan compared to Wolong, relatively few households in Chitwan use fuelwood for heating.

2.2 Tendency to use electricity or fuelwood

In Wolong, we model likelihood of switching to electricity by taking into account concerns over electricity price, voltage stability, and outage frequency, as well as other socioeconomic or policy factors. With data soliciting local people's willingness to make this switch under a set of hypothetical conditions related to electricity price, voltage stability, and outage frequency, this probability is modeled in a logistic regression as a function of changes in electricity condition, age, schooling years, gender, household income, level of perceived transportation distance between fuelwood collection sites and major roads (comparing to a threshold distance, the perceived distance is then assigned to be low, moderate, or high), and township that the household under consideration belongs to (An et al. 2002). In Chitwan, we use a similar strategy, but instead model probability of fuelwood usage (rather than electricity usage) based on a series of household- and community-level state variables (e.g., household size and gender composition, whether a neighborhood has electricity, and distance to the main urban area).

In both models, the total fuelwood consumption is modeled as the potential fuelwood demand multiplied by one minus the tendency to use electricity (in Wolong) or as the tendency to use fuelwood multiplied by the potential fuelwood demand (Chitwan).

3 Biophysical submodels

The Wolong ABM represents vegetation in four classes based on a remote sensing classification (Linderman et al. 2004): deciduous forest, conifer forest, mixed forest, and non-forest. When the model begins, the Wolong ABM assigns volume and age to pixels of each vegetation type following a uniform distribution, drawing on data regarding the range of volume and of age for each vegetation type (Yang and Li 1992). Then for the following time steps (Supplement Table 6), pixels of each vegetation type grow at an average rate associated with the corresponding type and age group until either the volume or age cap is reached (Yang and Li 1992).

Fuelwood collection, if happening at a certain pixel, interrupts the above "natural" growth. The corresponding pixel will follow the above growth pattern until collection happens. This collection may terminate if a minimum volume is reached (then the household(s) switches to a nearby pixel) or the corresponding household(s) stop collecting fuelwood (e.g., the household is dissolved; see Section "Household fission").

According to our 2009 surveys, current fuelwood collection activities in Chitwan take place in community areas, in community forests of the buffer zone, and in the border areas of the Chitwan

National Park. Very few households, however, report collecting live wood (only 14% of households report collecting half or more of their fuelwood as live wood). The vast majority of wood collected is deadwood. The Chitwan ABM does not model fuelwood collection impacts on forest volume, as the field data in Chitwan suggest wood collection is unlikely to have a strong direct impact on forest cover. In Chitwan, the impact of wood collection is confined mainly to the supply of woody detritus on the forest floor.

Supplement-Table 6: Scales in the Wolong and Chitwan ABMs.

Variable	**Wolong ABM** Description	**Chitwan ABM** Description
Temporal scale:		
Temporal resolution	One time step is equal to one year	One time step is equal to one month
Model timescale	The Wolong ABM runs for a user-specified timescale, starting in 1996	The Chitwan ABM runs for a user-specified timescale, starting in 1996
Spatial scale:		
Spatial resolution	90 m and 360 m pixels	Land is tracked for each neighborhood entity at the square meter level. Digital elevation model is 90 m resolution.
Total spatial extent	Lattices of 602x696 (90 m) or 151x175 (360 m), around 54 km x 63 km	Grid of 319x189 (90 m), around 29 km by 17 km

4 Human-environment interaction submodels

In Wolong the major human-environment interaction occurs through fuelwood collection. The Wolong ABM assumes that each household is aware of all the forest pixels within a certain buffer (3,600 m) of their household. With total fuelwood consumption calculated above (Section 3), the household seeks a site to collect fuelwood. Following He et al. (2009), households collect fuelwood within a short- (<1,080 m), mid- (1,080-2,160 m), or long- (over 2,160 m) distance category from the household at three empirical probabilities of 48.1%, 27.3%, and 24.6%, respectively.

To choose a site from the pixels within the chosen distance-category, the Wolong ABM endows the fuelwood collector with artificial intelligence to calculate the least-cost distance between his/her household and all forest pixels within the chosen distance category. Within a user specified area of geographical and environmental awareness (centered around his/her current location along the path), the collector moves in an energy-saving path that 1) does not return to his or her previous location, 2) minimizes deviation from the straight line between his or her household and the pixel in consideration, 3) favors pixels with lower elevation than his or her current pixel, or the pixel with the smallest elevation increase. When a path between a candidate forest pixel and his/her household is determined, the total length is calculated with an adjustment applied based on the slope between adjacent pixels along the route. The final fuelwood collection site is the one with the least cost path. The household compares the length of the least cost path with a distance bound (default to 800 m) to decide whether the household has a high-, mid-, or low-level perceived distance to collect fuelwood. The perceived level of distance is used to calculate the probability to switch from fuelwood to electricity (Section 2).

Land use and land cover change is the primary landscape change modeled in Chitwan, with land use change within the populated area of Chitwan occurring primarily due to new building construction. When a new household is constructed in Chitwan, the land area it occupies is determined from a probability distribution of household land areas taken from the CVFS mapping data. To simulate land use conversion, an amount of land equal in area to the area of the new household is deducted from either the agricultural land use category (preferentially) or the non-agricultural vegetation land use category (if insufficient agricultural land exists) and is added to the private buildings category of the appropriate neighborhood. The household is preferentially built in the husband's parent's neighborhood (if enough land is available) or in the closest neighborhood to the husband's parent's household that does have available land.

5 CHANS characteristic features

5.1 Observation and emergence

To enable analysis of model output, including the possibility of emergent outcomes, the Wolong and Chitwan ABMs collect the following data at any specified time step: 1) population size, composition by age and sex, and basic flows (in- and out-migration), 2) the number and spatial location of households,

3) the gender, age, ethnicity (Chitwan only), marriage, fertility, and household membership state variables for each person agent, and 3) events (births, deaths, etc.) for later analysis and for verification and validation (An et al. 2005; Zvoleff and An in review). The Wolong ABM further tracks the amount and spatial distribution of panda habitat in response to changes in demographic, economic, and psychosocial factors. It also models how changes in the environment may feedback into local people's perceptions and decisions about fuelwood consumption. The Chitwan model tracks more detailed demographic information than does the Wolong ABM (first birth times, marriage times, migration histories), but has a less detailed representation of land use which is tracked at the community level.

Both models also have features that are determined by model structure, and do not allow for emergence. For example, modeling mortality is necessary for us to build realistic models including human agents, but mortality is not a key variable of interest in either the Chitwan or Wolong model. For this reason, mortality in both models is set to be a function of only age (Wolong) or age and sex (Chitwan) of each individual. Given this simple relationship, the crude death rate in each model is not a variable of interest, and could be predicted based on total population size and age and gender structure.

5.2 Reciprocal effects and feedback loops

The Wolong ABM allows feedback through the realized household fuelwood demand, which has a negative relationship with distance between the corresponding household and the nearest fuelwood collection site (An et al. 2005). This means that intense use of fuelwood, thus distancing nearest forest providing such fuelwood, would feedback into a decreased fuelwood demand.

Feedbacks are represented in the Chitwan ABM between land use and several of the demographic submodels. Following empirical results, women in neighborhoods that are predominantly agricultural are more likely to get married early, and to have their first birth soon after marriage (Yabiku 2006a, 2006b; Ghimire and Hoelter 2007; Ghimire and Axinn 2010; Zvoleff and An in review). Land use, in turn, is influenced by the behaviors of individuals in the model. If individuals marry early, then new households will be established faster as they are established probabilistically at marriage. If new households are established faster, then conversion of land out of agriculture will occur faster, as new households are established on agricultural land. This process can act as a negative feedback loop, as conversion of land out of agriculture will lead to women delaying marriage timing and the initiation of childbearing after marriage.

5.3 Nonlinearity and thresholds

Nonlinearities in Wolong are prevalent, including nonlinear relationships set in the model as parameters or decision rules, such as those in the fuelwood demand model (Section 3.7; online supplement). An exemplar emergent nonlinearity may be the one between the threshold used to calculate perceived distance for collecting fuelwood and the simulated habitat area in 20 years: The habitat area declines nearly linearly when this threshold value is less than around 5,000 m, after which the habitat stops declining and even slightly increases (An et al. 2005). There are many other nonlinear emerging relationships (e.g., population size vs. age at first marriage) documented in An and Liu (2010).

There are also nonlinear relationships in outcomes from the Chitwan model. For example, our field results indicate household size is the most important predictor of per-person fuelwood consumption in Chitwan. However, the likelihood of switching from firewood to an alternative fuel source for cooking increases as household size decreases, in part due to the decline in available labor for fuelwood collection. In our observed data we see trends toward decreasing household size (from a mean of approximately five persons per household in 1998 to 4.45 in 2006). This complex relationship between fuelwood demand, usage probability, and household size is seen in the Chitwan model outcomes, where variations in the migration and household fission models can cause fuelwood usage to vary in unexpected ways.

5.4 Surprises

Surprises in the Wolong ABM are also abundant in our simulation outcomes. For instance, when the age of marriage changes from 22 to 38 years old, the number of households within the reserve nearly remains unchanged for about 16 years, and then starts increasing (An and Liu 2010). This “16 year dormancy” is a surprising outcome at first glance. In another instance, as described in Section *Nonlinearity and thresholds*, the amount of habitat declines nearly linearly when the threshold (used to calculate perceived fuelwood collection distance) is less than around 5,000 m, after which the habitat stops declining and even slightly increases. In Chitwan, there are surprising dynamics in several instances. One example is the impact of changes in desired family size. If the probability distribution for the desired number of children is shifted to the left (meaning families choose to have fewer children) population growth slows as expected. If it is shifted to the right population growth increases. However, fuelwood harvesting volume changes relatively slowly even with a more rapid increase in population.

We further evaluate potential reasons for these surprising outcomes. On the one hand, some surprises may come from the way(s) the modeler sets the agents, corresponding parameters or rules, which represents an advantage (artifact to some extent) of the agent-based modeling approach. The surprises regarding the “16 year dormancy” (Wolong) and “fuelwood’s tardiness to population increase” (Chitwan) belongs to this class. As we take an in-depth look into the mechanism governing household dynamics, we find that household establishment usually follows marriage, and births happen after marriage. This means a 16-year delay in marriage (from 22 to 38) would thus delay the related births for about 16 years. The consequence of the 16-year birth delay on household dynamics will only surface out when these birth-delayed children come to the point of marriage and establishing their corresponding households. On further reflection, this relationship makes sense - the efficiency of fuelwood consumption increases with household size. Therefore, adding more people to an already large household has little relative effect on total consumption (as per-person resource usage efficiency is relatively high for large households)..

On the other hand, some surprises may come from the unique characteristics of humans (e.g., agents and their attributes), the environment (e.g., forest type, initial volume, growth rate, topography), and the way humans and the environment interact (e.g., through fuelwood collection). The above 5,000+

m habitat unresponsiveness (within 5000 m, the bigger the perceived fuelwood collection distance, the lower the habitat; An et al. 2005) belongs to this class. Many reasons may account for this unresponsiveness, e.g., when this perceived distance goes beyond a big distance level (here 5,000 m, equivalent to more easiness to collect fuelwood), then local households may lose motives to switch using fuelwood (thus cutting trees and destroying habitat) to electricity (An et al. 2002). Or it could arise from the fact that collection of the same amount of fuelwood, if scattered on a large landscape with heterogeneity in forest type, volume, and growth rate, does not substantially degrade habitat or cause habitat loss. This type of surprises, termed "strong surprises", may provide more useful insights about the corresponding CHANS, but should be trusted or put into policy only after careful model verification and validation: Surprises may come from bugs in code or mistakes in parameters and/or rules.

5.5 Legacy effects and time lags

Time lags are common in CHANS, which are observed in both the Wolong and Chitwan models. The Wolong ABM, for instance, demonstrates that population size, the number of households, and panda habitat area respond to changes in family planning related factors (e.g., age at first marriage, time interval between marriage and the first birth, the maximum age for childbearing) with increasing time lags (An and Liu 2010). Changes in demographic behaviors can often have lagged effects. For example, changes in fertility preferences can take several decades to show strong influence on land use, as it takes 18-20 years for children to reach the age at which they form their own household units and begin to bear children.

5.6 Resilience

Resilience refers to the ability of CHANS to absorb shocks and to maintain multiple stable states and function after a disturbance (Folke et al. 2002). One example of resilience in Wolong is that when fertility increases, e.g., from 2 to 3, the panda habitat would respond very little even in 40 years. This "lack of response" probably has contribution from areas "with fast-growing tree species" (Liu et al.

2007). Such areas will remain as panda habitat as long as the increased fuelwood collection, owing to fertility-induced population growth, does not exceed forest growth rate. In Chitwan land use change is similarly resilient to moderate changes in fertility or migration rates that affect the population balance. The primary determining factor behind land use change is new household establishment. This process is largely a legacy effect of past demographics – due to past high fertility rates, there was a large youth bulge in Chitwan in 1996. As this population ages and begins to establish new households, the effect is land transition out of agriculture. While large sudden shocks (substantial in-/out-migration following a crisis for example) could affect land use change temporarily, it does not affect this general dynamic.

5.7 Heterogeneity

Heterogeneity exists in nearly all the state variables associated with the person, household, and community (Chitwan only) agents in both ABMs. Different places in Wolong, with spatial heterogeneity in topography and forest volume/growth rate (Sections 3.2.2 and 3.7, respectively), would have varying degree of tolerance for fuelwood collection. Therefore socioeconomically and demographically similar households or communities, even with having similar fuelwood demand, may exert varying impact on nearby panda habitat dynamics. In the Chitwan model, one example of spatial heterogeneity is due to ethnic variation in marriage rates, fertility preferences, and resource usage, which influence the spatial patterns of land use and population change we observe. For example, upper-caste Hindus and Newars, who predominate in the urban center of Chitwan, tend to delay marriage and wait longer after marriage to initiate childbearing. This spatial heterogeneity influences the spatial patterns of population and landscape change in the outcomes of the model.

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