APPENDIX 1: METHODS AND SUPPORTING INFORMATION

We developed the agent-based model (ABM) using the RepastJ 3.1 libraries (http://repast.sourceforge.net). Agent-based modeling (ABM) is an approach to representing the properties, behaviors, decision-making strategies, and actions of interacting components in a dynamic system that is composed of actors and their environment. ABMs can be run to evaluate the aggregate system-level implications of individual behaviors, and the diversity and interactions thereof. Because ABMs derive system-level outcomes from component interactions, the approach can represent and model non-linear dynamics, positive and negative feedbacks, heterogeneity, learning and evolutionary decision-making strategies (i.e. adaptation), and a range of other analytically intractable processes (Holland 1995). Furthermore, the ABM approach can be used as a framework to integrate various sources of data, theories, and conceptual models (Janssen and Ostrom 2006, Robinson et al. 2007). Others have successfully used ABM in a similar the context to evaluate the effects of institutional configurations and heterogeneous actor characteristics on collective outcomes in commons dilemmas (Deadman et al. 2000). This supporting text describes our ABM in detail.

Household agent utility

In our model, household utility is a function of the household's desire for three goods -- consumption, leisure, and adherence to institutional rules which lead to a resource extraction level for the household. The extraction level chosen by the household is the level of the household's resource use. During each time step, a household agent randomly selects 10 different levels of resource extraction and chooses the extraction level, x, that maximizes the following utility function:

$$U(x) = C(x)^{\alpha_C} * L(x)^{\alpha_L} * A(x)^{\alpha_A} \quad \text{(S1)}$$

where U(x) is the utility for the household at a given extraction level, C(x) is the utility derived from consumption, L(x) is the utility derived from leisure, A(x) is the utility derived by adhering to institutional pressures, and αC, αL , αA , are the weights that represent preferences for consumption, leisure, and institutional adherence, respectively. The three preference weights sum to one and ensure trade-offs among consumption, leisure, and adhering to institutional pressures.

For the experiments described in this paper, the ten candidate levels of extraction are selected from a normal distribution centered on the households previous level of extraction with a variance of 0.02, resampling as needed to have all ten candidate samples in [0,1], the normalized range of extraction levels. For an initial burn-in period, we set the extraction level to a number drawn from a uniform distribution over [0.00, 1.00]. We also ran experiments in which the standard deviation was 0.01 and 0.05, and in which the candidate levels of extraction were chosen from a uniform distribution over [0,1]; the model results were qualitatively similar to those reported in this paper for all those conditions.

C(x) – Consumption

The consumption component of a household's utility is a function of subsistence cooking requirements in m^3 (s), fuelwood extraction (x), and the rate at which marginal utility decreases once subsistence has been met (f in [2]).

$$C(x) = s + f \cdot (x - s), x \geq s; x , x < s \quad \text{(S2)}$$

where f is 0.2, and the subsistence cooking requirements (s) for each household is calculated as a function of household size and per capita energy requirements:

$$s = (h_s \cdot w) / (e \cdot d) \quad \text{(S3)}$$

where h_s is the size of household (i.e. number of occupants), w is the per capita energy requirement for cooking per month (240 MJ), e is the energy content of wood (16 MJ, World Bank 2004), and d is the average density of oak and pine (600 $kg \cdot m^{-3}$). Using the average household size of 4.75 individuals, the per capita monthly subsistence requirement is 0.25 m^3 of fuelwood. We selected subsistence requirements based on the existing literature about average household size in hilly environments in the Indian Himalaya. Because variations in subsistence requirements have a relatively predictable effect on harvesting goals, we focused our experiments on changes in institutional and network structure parameters for essentially similar levels of subsistence needs. The utility derived by consumption for different preference weights applied to the consumption component are shown in Figure 5.

(Figure 5 here)

L(x) – Leisure

Markets for firewood are largely non-existent in the locations studied. The primary expense incurred by household agents' firewood extraction is time - invariably, the cost of time in "leisure" (i.e., all non-fuelwood gathering activities) forsaken to extract forest resources. The leisure component is calculated based on the gathering time required for firewood collection and the amount of labor available for firewood collection. The function takes the following form:

$$L(x) = 1 - T / h_l , \quad T \leq h_l \qquad (S4)$$

where T is the time spent gathering firewood per month (as calculated in the section titled firewood collection, below) and h_l is the total household labor endowment. We set h_l at 5 hrs per day as a representative value of the total number of firewood collection labor hours provided by the female household head and young children. A maximal value of 1 for L(x) represents all household time spent in leisure; L(x) declines as shown in Figure 6 below, demonstrating the reduction in utility obtained by the leisure component (Equation S4) of Equation [1] for different levels of household fuelwood extraction when forest resources and preference for leisure ($\alpha L = 0.33$) are fixed.

(Figure 6 here)

A(x) – Adherence to organizational rules versus network norms

The last factor in the household agent's utility function, A(x), represents the utility derived by adhering to institutional rules. A(x) is a weighted function of two factors that represent the relative importance the agent places on adhering to institutional rules or network norms:

$$A(x) = r \cdot R(x) + (1 - r) \cdot N(x), \quad 0 <= r <= 1 \qquad (S5)$$

The weighting factor r, which can vary across households, determines the degree to which a particular household places more importance on adhering to institutional rules (higher r) or on network norms (lower r). R(x) is zero if the level of extraction, x, is greater than the amount, x_s, prescribed by the formal institution (designed to maintain a sustainable forest); R(x) increases to the extent the household's extraction level x is less than the amount prescribed for that household:

$$R(x) = 0, \quad x >= x_s \qquad ; 1 - (x - x_s), \quad x < x_s \qquad \text{(S6)}$$

where x_s is the extraction level prescribed by the formal institution. N(x) increases to the extent the household's extraction level x matches the level of extraction suggested by community norms:

$$N(x) = 1 - |x - x^*| \qquad \text{(S7)}$$

where x* is the average extraction level of the household's neighbors during the previous time step.

Firewood collection

Firewood and community forests are perceived as a free common pool resource for use by local households. Therefore, markets for firewood are non-existent in the study region and instead the cost of firewood is a function of collection or gathering time, which is typical for firewood and minor forest products in rural areas in India (Heltberg et al. 2000). However, as households extract firewood resources they degrade the forest from the edge inward and are forced to spend more effort and time in subsequent firewood collections (Kumar and Hotchkiss 1988; Baland et al. 2004). We use a simplified approach to model time spent collecting firewood and assume that when firewood is abundant, a minimum of 2 hrs is required to make a single firewood gathering trip. However, gathering time increases exponentially as the resource is depleted (Equation S8 and Fig. 7). The rate of increase in gathering time is a function of the initial and remaining size of the forest, proportion of the forest in branches, the population of the village, and average biomass per square meter, which we simplify as follows:

$$t = 2 + (F_i / F_r) \quad \text{(S8)}$$

where F_i is the initial forest amount (≈76,000 m^3) and F_r is the forest remaining.

(Figure 7 here)

The average head-load carried by an adult individual in a single trip approximates 30 kg (Bembridge and Tarlton 1990, Irfanullah 2002, Adhikari et al. 2004). Since households must make several trips to satisfy their subsistence cooking requirements, we calculate the overall time allocated to firewood collection per month using the following equation:

$$T = \min (x \cdot c_{max} \cdot d/p \cdot t , h_l) \quad \text{(S9)}$$

where T is the gathering time per month, x is the extraction level of the household, c_{max} is the maximum consumption level of the household (which is 3·s in equation S3), p is the average head load per trip, d is the average density of oak and pine (600 $kg \cdot m^{-3}$), t is the gathering time for a single trip (a function of forest remaining, from Equation S8 and shown in Fig. 7), and h_l is the total available labor for firewood collection or leisure (and other activities) to each household.

Resource growth

We take a simplified approach to model forest resources and growth. The resource represents a closed canopy maturing mixed pine and oak forest. The forest grows on average at a rate of

2.7% per year (0.14 kg · m^{-2}· yr^{-1}, Birdsey 1992). We introduce some variability around the mean (0.01% per month) to incorporate stochastic climatic events that may alter the growth rate (Figure 8). The villagers in our study area primarily use forest fodder and lop branches for fuelwood. However, observations of above-ground biomass and carbon allocated to individual tree components (e.g. stem, bark, branches, and foliage) vary widely. Jenkins et al. (2003) compare their research to literature, which collectively demonstrates a range of 7-30% for softwood species and 15-95% for hardwood species. We simplified these results and divided the above ground biomass and carbon values in half to obtain the amount found in branches, which is the biomass of use to villagers for fuelwood.

(Figure 8 here)

LITERATURE CITED

Adhikari, B., S. D. Falco, and J. C. Lovett. 2004. Household characteristics and forest dependency: Evidence from community-based forest management in Nepal. *Ecological Economics* **48**: 245-257.

Baland, J. M., P. Bardhan, S. Das, D. Mookherjee, and R. Sarkar. 2004. The Environmental Impact of Poverty: Evidence from Firewood Collection in Rural Nepal. The Tenth Conference of the International Association for the Study of Common Property, August: 9-13.

Bembridge, T. J. and J. E. Tarlton. 1990. Woodfuel in Ciskei: A headload study. *South African Forestry Journal* **154**: 88-93.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems, Program manager, Global Change Research, Northeastern Forest Experiment Station, Radnor, PA.

Deadman, P. J., Schlager, E. and R. Gimblett. 2000. Simulating common pool resource management experiments with adaptive agents employing alternate communication routines. *Journal Artificial Soc and Social Simulation* **3**(2). [online] URL: http://www.soc.surrey.ac.uk/JASSS/3/2/2.html.

Heltberg, R., T. C. Arndt, and N. U. Sekhar. 2000. Fuelwood consumption and forest degradation: Household model for domestic energy substitution in rural India. *Land Economics* **76**: 213-232.

Holland, J. H. 1995. *Hidden Order: How Adaptation Builds Complexity*. Addison-Wesley, Reading, MA, USA.

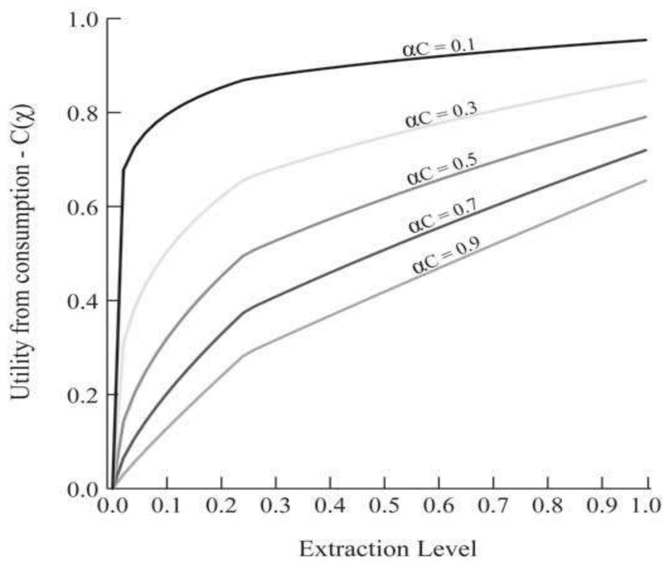
Irfanullah, S. 2002. Gujars in the Pakistani Hindu Kush-Himalayas: Conflicts and dilemmas about lifestyles and forest use. *Nomadic Peoples* **6**: 99-110.

Janssen, M. A. and E. Ostrom. 2006. Empirically based, agent-based models. *Ecology and Society* **11**(2):37. 37. [online] URL: http://www.ecologyandsociety.org/vol11/iss2/art37/.

Kumar, S. K., and D. Hotchkiss. 1988. Consequences of Deforestation for Women's Time Allocation, Agricultural Production, and Nutrition in Hill Areas of Nepal. International Food Policy Research Institute, Washington DC, USA.

Robinson, D.T., D. G. Brown, D. C. Parker, P. Schreinemachers, M. Janssen, M. Huigen, H. Wittmer, N. Gotts, P. Promburom, E. Irwin, T. Berger, F. Gatzweiler, C. Bernaud. 2007. Comparison of empirical methods for building agent-based models of land and resource use. *Journal of Land Use Science* **2**(1):31-55.

Figure 5



1.0
0.8
0.6
0.4
0.2
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Utility from consumption - C(χ)
Extraction Level
αC = 0.1
αC = 0.3
αC = 0.5
αC = 0.7
αC = 0.9

Figure 6

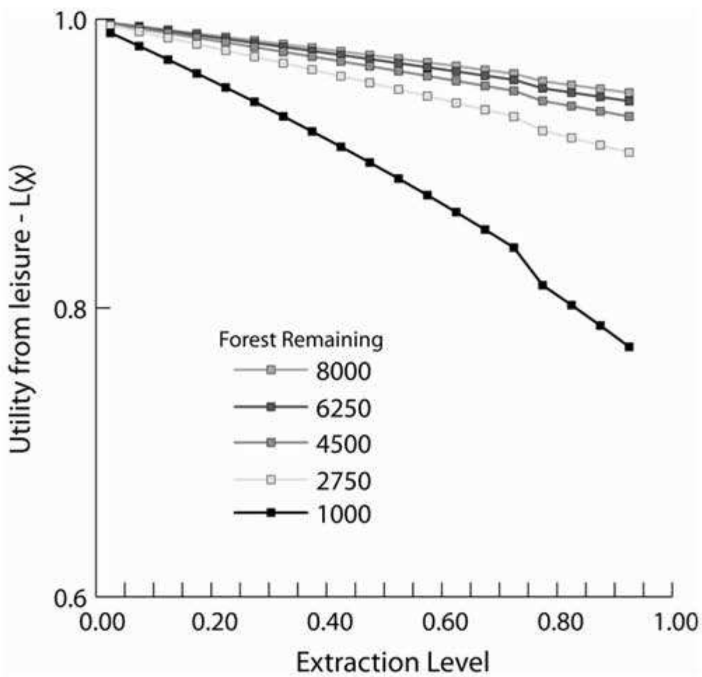


Figure 7

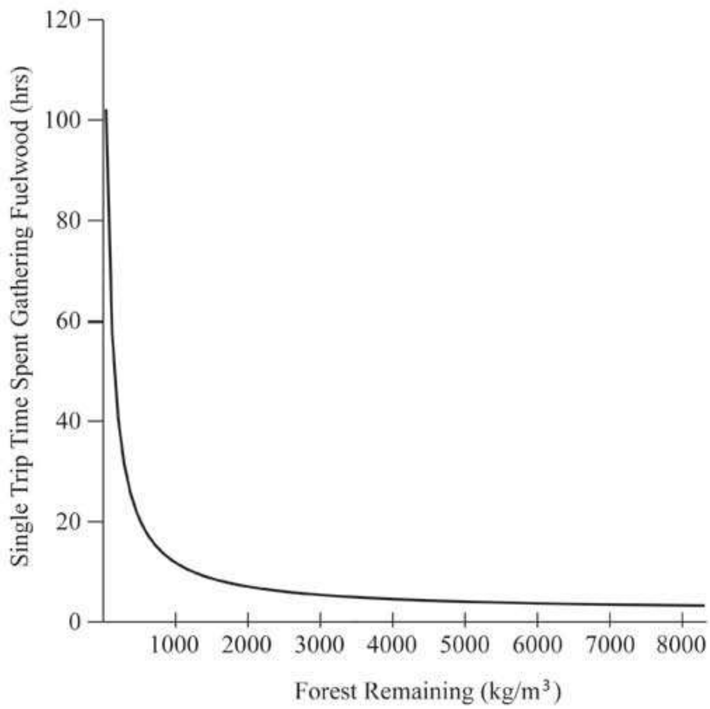
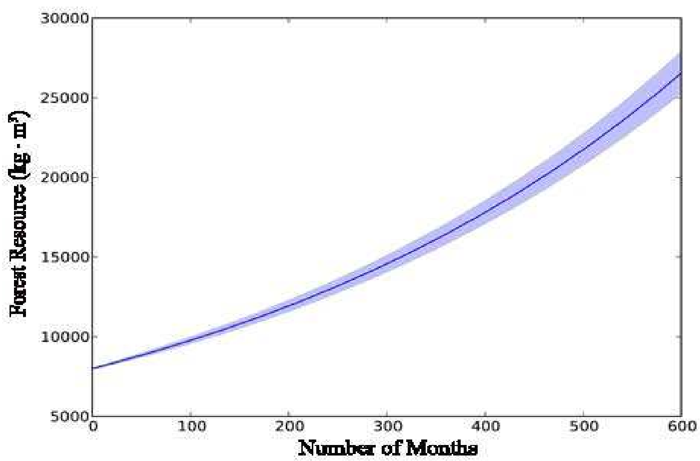

120
100
80
60
40
20
0
Single Trip Time Spent Gathering Fuelwood (hrs)
1000
2000
3000
4000
5000
6000
7000
8000
Forest Remaining (kg/m³)

Figure 8



30000
25000
20000
15000
10000
5000
0
100
200
300
400
500
600
Forest Resource (kg · m³)
Number of Months