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Implementation of a Participatory Modeling Framework

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This paper presents the results of management-oriented research on energy, forest, and human health issues in a remote mountain area, the Sagarmatha National Park and Buffer Zone (SNPBZ), Nepal. The research was based on a broader, integrated participatory framework ultimately intended for use in adaptive management. The present study focused on the application of a participatory modeling framework to address problems related to energy demand and consumption, forest condition, and indoor air pollution, which were defined by the stakeholders as important issues to be addressed. The models were developed using a generalizing design that allows for user-friendly adaptation to other contexts (free download at http://hkkhpartnership.org). Moreover, we simulated management scenarios in collaboration with all modeling actors with the aim of building consensus on the understanding of the system as well as supporting decision-makers' capacity not only to respond to changes, but also to anticipate them. Importantly, the system dynamics assessment found that the SNPBZ forests are affected by an increasing demand for fuelwood (occurring due to tourism growth), as one of the main sources of energy. Selected forests show an average reduction of 38% in forest biomass from 1992 to 2008. This shows that the business-as-usual *scenario is unlikely to result in the preservation of the current forest status; in fact, such preservation would require 75% of fuelwood to be replaced with alternative energy sources. At the same time, a 75% reduction of fuelwood use (and an 80% reduction of dung use) would reduce indoor carbon monoxide (CO) concentrations to the standard limits for CO exposure set by the World Health Organization.*

Keywords: *Participatory modeling; system dynamics; energy management; forest management; indoor air pollution; Sagarmatha National Park and Buffer Zone; Nepal.*

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Introduction

Energy is a prerequisite for the survival, development, and economic welfare of human beings. Various energy sources have been explored by human society to fulfill energy needs. However, biomass, especially wood, still constitutes a primary energy source in rural areas of developing countries (Nepal 2008). For example, in the Himalayan Mountain region, fuelwood is one of the principal sources of energy for cooking, space heating, and water heating in rural households (Rijal 1999). Fuelwood harvesting has been identified as one of the most significant causes of forest decline in rural areas of developing countries (Bhatt and Sachan 2004). Many rural areas are also major tourism attractions. The rise in human population and the uncontrolled growth of tourism in rural and remote tourist destinations has created great pressure on forestlands, resulting in their degradation and heavy depletion of the resource (Nepal 2008). The situation is particularly serious in the fragile Himalayan ecosystem, which is facing large-scale forest decline (Prasad 2000; Prasad et al 2001; Stevens 2003; Nepal 2008). Heavy exploitation of fuelwood can also significantly affect both the environment, through emissions of greenhouse gases causing global warming (Omer 2008), and human health, through indoor combustion in poorly ventilated houses (Pandey and Basnet 1987; Hessen et al 2001). Therefore, it is necessary to develop and adopt renewable energy sources as an alternative to present energy sources to ensure the sustainable use of natural resources, which are vital both for social–ecological systems (SESs) and for the tourism industry in the Himalayan region.

Participatory modeling can provide a platform for integrating scientific knowledge with local knowledge; when executed well, it provides an objective, value-neutral place for a diverse group of stakeholders to contribute information regarding natural resource issues of interest (Cokerill et al 2006). While participatory modeling has been widely accepted and promoted, it has also been criticized by practitioners, natural resource managers, and development scientists. Much of the criticism revolves around the apparent lack of rigor, structure, and analytical framework provided by these approaches. The strength of these approaches lies in the highly transparent and open-ended exploration of the issues, problems, and objectives that characterize the complex environment typical of many resource management situations. It is imperative to have a general mechanism or comprehensive framework (Cooke and Kothari 2002).

Salerno et al (2010) address this problem by proposing a 5-module framework coupling hard and soft methodology for the development of participatory modeling that enables an overall modeling process; this framework has its roots in adaptive management, computer-supported collaborative work, and SES theory. The process begins with a participant-led *system bounding* (Module 1), including a historical profile, assessments of issues and drivers, and the development of a common understanding of the future. Module 2 (*qualitative modeling*) represents the conceptualization of the system, exploring the SES in an iterative way. *Management-oriented research* (Module 3) uses the outputs from Modules 1 and 2, defining data requirements to supplement mental models with quantitative relationships. Module 4 (*quantitative modeling*) makes it possible to properly anticipate system change employing mathematical models, theories, and hypotheses pertaining to natural phenomena. *Adaptive management* (Module 5) is a stakeholder evaluation of the process and outcomes in terms of policy and management implications. The present paper applies this methodology and framework to support the participatory modeling of energy management issues and the relevant impacts on forests and human health. The case study presented was conducted from 2006 to 2009 in the Sagarmatha National Park and Buffer Zone (SNPBZ), Nepal.

After identifying key actors, scenario planning (Daconto and Sherpa 2010) was used to identify the drivers and key issues of the SES, and simple qualitative models of past and future dynamics were created. In what follows, we describe the main features of our case study as well as the key management constraints identified through the first scenario planning session with concerned stakeholders (Module 1). We continue with a description of the methods used to collect the data—in the literature and in the field, according to a management-oriented research plan—that were identified as necessary to address the management issues selected by the stakeholders. This is followed by a presentation of the data themselves from a management-oriented perspective (Module 3). For each model developed, we briefly present its aims and qualitative design, combining Modules 2 and 4, while we focus more extensively on presenting management scenarios (Module 5). In closing, we elaborate our lessons learned, drawing conclusions for a broader application of the adopted participatory modeling framework.

Social-ecological system (SES) bounding

SNPBZ is situated in the northeastern part of Nepal, amidst the world's highest peaks. The park encompasses extremely rugged terrain, deeply incised valleys, and glaciers; the elevation ranges from 2300 m (Surke village in the BZ) to the summit of Mount Sagarmatha (Nepali name of Mount Everest) at 8848 m (Figure 1). It spreads over a total area of about 1400 km^2, including the upper catchment of the Dudh Kosi River basin. Byers (2005) and Salerno et al (2008) have described the climatic and physical–chemical features of SNPBZ, which are determined by the monsoon regime with most precipitation (70–80%) occurring between June and September. Although relatively small in size, SNPBZ has a broad range of bioclimatic conditions, with 4 bioclimatic zones: a forested lower zone; a zone of alpine scrub; the upper alpine zone, which includes the upper limit of vegetation growth, and the Arctic zone, where no plants can grow (United Nations Environment Programme [UNEP] and World Conservation Monitoring Centre [WCMC] 2008). Land cover classes for elevation ranges in SNPBZ are summarized in Table 1, which shows that almost one third of the territory is characterized by snow and glaciers, while less than 10% of the park area is forested.

In 2008, the park included about 100 settlements with 6221 local residents, mostly of the Sherpa people, with over 1892 head of livestock. Although in many villages, traditional agriculture and animal husbandry are still the main sources of livelihood, more recently the local economy has become dependent upon tourism and tourism-related activities (climbing, portering, guiding, and lodge management), which represent increasingly important employment sources for local communities (Department of National Park and Wildlife Conservation [DNPWC] 2003). Exceptional natural beauty and diversity

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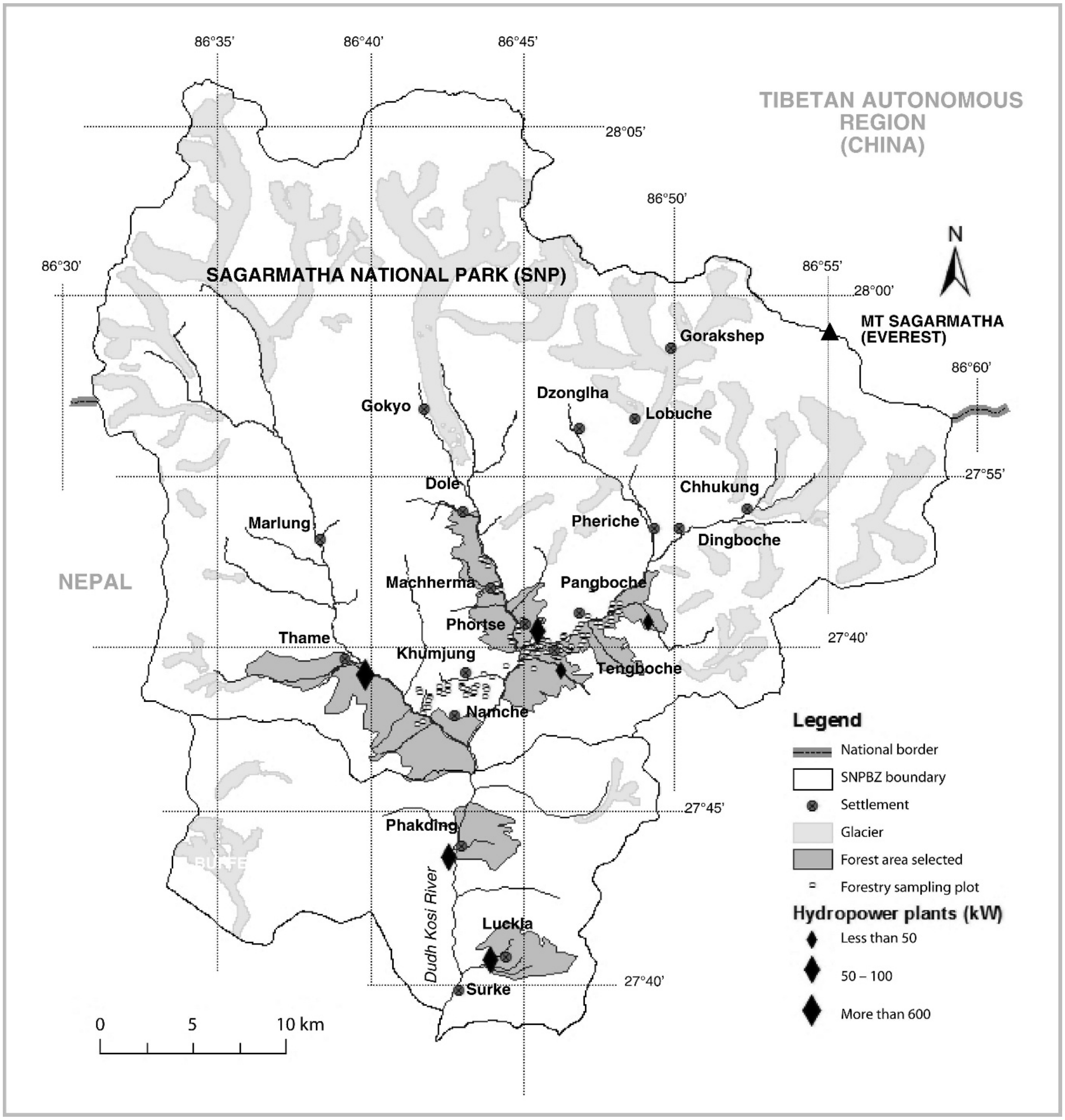
FIGURE 1 Map of SNPBZ (Nepal) with main settlements, forestry sampling plots, hydropower plants, and selected forest areas exploited by fuelwood collection. (Map by Gaetano Viviano)



in cultural and biological endowment dominated by Mount Everest make SNPBZ a prime destination for nature- and adventure-loving tourists. The growth of mountaineering and trekking tourism since the 1970s has had a major influence on the SES, often with a positive economic impact, providing tourism-related employment opportunities, but also causing landscape and cultural changes (Daconto and Sherpa 2010; DNPWC 2003). The number of international visitors reached 28,800 people in 2008 (Caroli 2008). The high influx of tourism puts

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TABLE 1 Land cover classification by elevation zones in SNPZB. (Source: Bajracharya et al 2010)

Land cover (ASTER 2006)	Area per elevation zone (10^4 m^2)				Total area (10^4 m^2)	%
Class name	2000–3000	3000–4000	4000–5000	>5000		
Forest	2716	6677	386	0	9779	7.0
Shrub	353	3990	12,248	96	16,687	11.8
Grass	34	685	5800	1696	8215	5.8
Bare soil	210	567	19,714	41,094	61,585	43.7
Built-up area (including cultivated area)	308	375	259	0	942	0.7
Glacial lakes	0	0	429	393	822	0.6
Snow and glaciers	0	0	4600	38,189	42,789	30.4
Total					**140,819**	**100.0**

additional pressure on precious local resources, such as fuelwood, which remains the predominant source of energy for the majority of people in the park for cooking, boiling, and heating (DNPWC 2003) because it is relatively accessible and affordable, especially at lower altitudes. Overexploitation of forest resources is omnipresent in the region currently, but fuelwood is not produced adequately to meet the increasing demand for energy caused by a booming tourist industry and growing local population (UNEP and WCMC 2008). The limited supply of reliable and efficient energy has compelled a majority of the population to burn fuelwood, resulting in deforestation as well as indoor and ambient air pollution and health hazards (Pandey and Basnet 1987; Nepal 2008).

Management-oriented research

Energy demand and consumption

Data on household energy demand and consumption and resource availability were collected in 2 field visits conducted in Autumn 2007 and Spring 2008 in 35 selected settlements along major trekking routes in SNPBZ; these constitute around half of all the park's settlements. The households were categorized as *residential* (houses for private accommodation), *commercial* (eg lodges and shops), and *institutional* (eg schools, hospitals, local offices, and monasteries). Based on the architecture and construction materials used, the households were further differentiated into *traditional*, *semimodern*, and *modern*. Proportions of sampled houses were selected based on the total number of available different types of households. A random structure sampling method (Sutherland 1996) to cover all of these household types was applied, resulting in coverage of about 20% of all households in SNPBZ. A questionnaire survey was applied to 170 selected households altogether to gather information on aspects of energy use in the park. The identification of sources, types, and patterns of energy consumption (including types of energy-consuming equipment used for household purposes, the amount of energy used in different household activities, and the total wattage of electricity used per day); the measurement of building dimensions; and the identification of insulation materials was conducted during the household survey. Demographic information was also collected from each interviewee by a unified standard questionnaire. Spot measurements of global solar irradiation, wind velocity, and the feasibility of hydropower were also collected. Data on energy generated by existing alternative energy sources (photovoltaic [PV] panels, solar thermal [ST] panels, and wind power) and their characteristics were also collected (Salerno et al 2009).

Forest condition and fuelwood consumption

A forest inventory was carried out to collect information on the floristic composition of the forest as well as on more quantitative aspects (eg structural parameters) of the tree species (Kunwar and Sharma 2004). In this paper, we present the data that were found necessary to implement the qualitative model of forest management issues described further on. In order to simplify this model, we used forest biomass as an indicator of forest health (Sharma et al 2008), without considering other aspects, such as those connected with biodiversity.

Data for biomass computation: Three forest surveys were conducted during spring (May–June 2007 and 2008) and autumn (September–October 2008) in the park. Forest parameters were collected in 105 temporary square plots (20m × 20m), in locations chosen by a stratified random sampling method (Sutherland 1996; Figure 1). In every plot, an inventory was made of the different species and

FIGURE 2 Woman carrying wood in SNPBZ, Nepal. (Photo by Sudeep Thakuri)

individual plants, and tree height (H), diameter at breast height (Dbh), coverage, and seedling and sampling density were measured. These data were quantitatively analyzed for abundance, density, and frequency (Salerno et al 2009). For all forest plots, the diameter frequency distribution was calculated, and the average basal area (BA) of each tree species in the plot was computed using Dbh. We used the allometric relationships available from earlier studies in Nepal (Sharma and Pukkala 1990) to estimate the stem biomass (SB). After calculating the stem volume (BA × H), this was multiplied by the species-specific wood density to get the SB for each plot (Sharma et al 2008). However, due to the nonavailability of other required species-specific parameters for all tree species in the plots, the SB computation was possible only for the dominant species (ie *Abies spectabilis*). The reference condition for SB for the kinds of forest in the plots was assessed using the SB table prepared by Yoda (1968).

Survey on fuelwood extraction: Fuelwood extraction in SNPBZ was quantified through social survey techniques (Gillham 2008), such as focus group discussions with a representative sample of 4–5 people living in each visited settlement (18 in total); questionnaires; and interviews with local key informants, including park managers, guides, porters, and members of forest user groups (Figure 2).

Spatial distribution of biomass: On the basis of information collected on fuelwood extraction and locations in which people from each settlement collect wood in SNPBZ, the forest areas most subject to human pressure (in terms of the extraction of fuelwood) were individuated (Figure 1). To estimate the total SB for each forest area and its variation over time mainly due to fuelwood extraction, remote sensing imagery was used and appropriately calibrated with data from field surveys (Lu 2006; Monserud et al 2006). In particular, we used the Advanced Land Observing Satellite–Advanced Visible and Near Infrared Radiometer–type 2 (ALOS–AVNIR–2) satellite images of October 2008. To compare radiometric data with field measurements, a regression analysis was applied linking spectral values to calculated SB at corresponding locations. The spectral values were expressed as a normalized difference vegetation index (NDVI) extracted by processing data from these satellite images. The NDVI was calibrated with SB data from more than 50 sampled plots. Landsat thematic mapper (TM) imagery of November 1992 was also used to make a historical comparison in order to estimate the changes in forest biomass over 16 years (Labrecque et al 2006; Tan et al 2007).

Indoor air pollution

Data on indoor air quality (IAQ) and inhabitants' respiratory health status were collected in November–December 2008 in 35 households in the village of Thame and surroundings, where 105 individuals over 14 years of age (70 from Thame and 35 from neighboring villages) were sampled. Thame was chosen as a reference village for investigating indoor air pollution issues because it is characterized by a heavy reliance on biomass fuels and a lack of chimneys in most households. The village is situated along one of the main trekking routes, located at 3800 m and with around 330 inhabitants; both of these features represent an average condition within SNPBZ. Moreover, Thame is a rural village where outdoor air pollution is very scarce due to its remoteness from traffic pollution or industry.

As described above for the survey on energy, the households were classified according to different types of buildings. Questionnaires were developed to collect information including: the type of house and kitchen details (eg the type of openings and stoves and the number of chimneys); information about energy consumption (eg the types and quantities of fuels used and the purpose of their use); and individuals' clinical history, smoke habits, and the presence of respiratory symptoms. The indoor carbon monoxide (CO) density as an indicator of IAQ in the kitchen during cooking time was measured, and the average concentration for 8 hours was calculated (Goldstein 2008). Other data collected included kitchen ventilation efficiency; the amount of fuelwood and dung used for cooking and space heating, disaggregated by building type; and the amount of CO emission per fuel type during biomass fuel combustion. Data collected from *residential–traditional* and *commercial–modern* buildings were found to be the most significant and representative and were therefore used to calibrate the model. A spirometry test was also performed on all

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people according to the American Thoracic Society/ European Respiratory Society guidelines (Miller et al 2005) to assess their lung function and measure pulmonary parameters. Other health status data (ie blood pressure, pulse, oxygen in the blood, height, and weight) were also taken (Salerno et al 2009).

Management-oriented research results

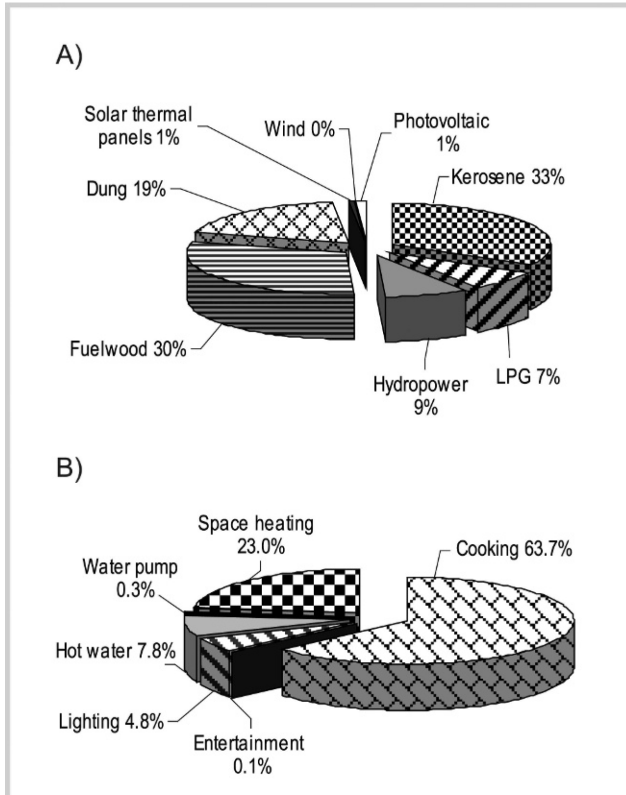
The following major findings of field research activities conducted in SNPBZ on energy demand and consumption, forest condition, and indoor air pollution (Salerno et al 2009) were used for implementing and calibrating the relevant system dynamics models.

Energy demand and consumption

Fuelwood from forests remains one of the major energy sources in SNPBZ, constituting 30% of all energy use; kerosene is the most common energy source (33%), and dung (19%) and liquefied petroleum gas (LPG; 7.5%) are used less often (Figure 3A). Energy in SNPBZ is mainly used for activities such as cooking, boiling water, space heating, and lighting. Because of the scarcity of wood, and considering the rise in tourist flows, today people are increasingly using commercial fuels, especially kerosene, which is mainly used in commercial buildings like tourist lodges and hotels for space heating and cooking. Although kerosene combustion produces greenhouse gas emissions, thus contributing to environmental degradation, it does not create indoor air pollution.

Figure 3B shows that most energy is consumed for cooking (64%). The field survey indicated that fuelwood and electricity are the major energy sources for this purpose, followed by kerosene and LPG. Fuelwood, dung, and electricity are the major energy sources for heating, which constitutes 23% of energy use in the area. LPG, ST, and electric geyser are mainly used for heating water. We found that renewable energy sources, such as solar, wind, and hydropower, are abundantly available in the region, but energy produced from these sources is still rather scarce (overall little more than 10%). In particular, the park already hosts hydropower stations (HPSs) with a capacity ranging from 15 kW to 630 kW plus other pico-HPSs, providing approximately 7260 kWh day^{-1} to the entire park (ie 9% of the total energy supplied). PV energy is used widely for lighting in the park, especially in areas without access to hydropower and other sources of electricity. Considering that the average global radiation measured was about 206 W m^{-2} in 6 hours per day of total sunshine hours, the total energy production by all PV panels found in the park was less than 18 kWh day^{-1} (1% of the total energy supplied). ST panels used to heat water, primarily for bathing purposes, were found mainly below Pheriche, but were less common at higher altitudes since the low temperatures in winter may cause frost, which can destroy the commonly used collectors and

FIGURE 3 (A) Major energy sources in SNPBZ; (B) energy use for different household activities in SNPBZ.



conduits. The energy produced by existing ST panels was found to be little more than 1% of the total energy supplied, around 24 kWh day^{-1}. Very small-scale (capacity between 0.1 and 0.5 kW) wind power systems are in operation over Pheriche, while isolated large-scale ones have not been built so far, mainly due to thin air density, higher costs of installation at these altitudes, and negative visual impact on the landscape for the tourism industry. Energy generation from wind power thus remains negligible in the park so far (Figure 3A).

Forest conditions and fuelwood consumption

Altogether, 17 species of trees representing 11 genera and 8 families were recorded. The dominant species in plots were mainly *A. spectabilis* and *Betula utilis*, followed by *Rhododendron campylocarpum*. The maximum Dbh found was 116 cm (*A. spectabilis*). The SNPBZ forests are characterized by an average stem BA of 27.2 m^2 ha^{-1} and 1.052 stems ha^{-1}. Among the species, *A. spectabilis* had the highest BA with a value of 43.7% relative BA. SB obtained for *A. spectabilis* ranged from around 150 to 0.1 t ha^{-1}, with an average value of 37 t ha^{-1}. Table 2 indicates the 13 forested areas in SNPBZ (Figure 1) most subject to exploitation due to fuelwood collection, showing the

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TABLE 2 Main forest areas in SNPBZ where local people collect fuelwood, with an indication of respective forest size, monthly growth rate, and change in biomass (%) from 1992 to 2008. The forest biomass variation is indicated by − when a decrease was observed and by + when an increase was observed.

Forest name	Area (km^2)	Fuelwood extraction (t $year^{-1}$)	Forest growth rate (10^{-3} kg $month^{-1}$)	Biomass variation from 1992 to 2008 (%)
Luckla	9.3	47.5	0.21	−22
Phakding	8.3	34.7	8.71	+22
Namche	2.6	5.5	2.24	−18
Below Kongde–Sotarmo	12.4	26.6	1.06	−53
Dole	5.6	0.9	0.89	−61
Phortse	4.0	7.3	0.45	−40
Tengboche	2.1	1.4	0.89	−40
Tengboche North	0.8	1.5	5.71	+12
Opposite Tengboche	6.7	20.6	0.12	−29
Kele	6.1	0.7	0.89	−67
Omaka	10.0	22.5	0.45	−60
Pare	19.2	2.3	0.89	−59
Debuche	1.4	2.8	1.68	−56
Mean				**−38**
Minimum				**−67**
Maximum				**−22**
Standard deviation				**+28**

amount of fuelwood extraction; this was quantified by social survey techniques and ranged between 0.7 t $year^{-1}$ in Kele forest and 47.5 t $year^{-1}$ in Luckla forest. The table also reports the monthly forest growth rates calculated for each forest area, which vary between 0.12×10^{-3} and 8.71×10^{-3} kg $month^{-1}$.

An example of the estimation of changes in forest biomass over time in the selected forest areas is shown in Figure 4: the comparison between 2 satellite images of Luckla forest in November 1992 (Landsat TM) and October 2008 (ALOS–AVNIR–2) shows a decrease of 22.3% in forest biomass, assuming a linear trend, observed over 16 years. Regarding the whole SNPBZ—the 13 forested areas considered in the model—an average reduction of 38% in forest biomass over the same period (2.4% on a yearly basis) was found, but with a high standard deviation (28%) that highlights a different degree of exploitation of the SNPBZ forests. As shown in Table 2, Kele forest showed the highest decrease in biomass (−67%). By contrast, biomass increase was observed only for the forests of Phakding (+22%) and Tengboche North (+12%).

Indoor air pollution

The kitchens of most private houses in SNPBZ are equipped mainly with open fireplaces for cooking (and heating in winter), known as *traditional cooking stoves* (TCS) fueled by wood. Due to the lack of a chimney or other fume outlet, these facilities emit fumes directly into the kitchen area (Figure 5). By contrast, modern buildings, especially tourist lodges, commonly have *improved cooking stoves* (ICS) with a pipe or chimney.

In our investigation, the measured efficiency of ventilation systems was only 20% in residential–traditional buildings but 65% in commercial–modern ones, as shown in Table 3. The table also reports the daily amount (kg day^{-1}) of fuelwood and dung used as energy sources per building type, and the measured average indoor CO concentration. The average indoor CO concentration for 8 hours varied between 0.006 and 0.034 g m^{-3} in houses with ICS, depending on the stove type. The average maximum concentration was found to be 0.093 g m^{-3} with 0.030 g m^{-3} in cooking hours and 0.012 g m^{-3} in general (average for 8 hours). The highest concentration of about 0.230 g m^{-3} was observed during

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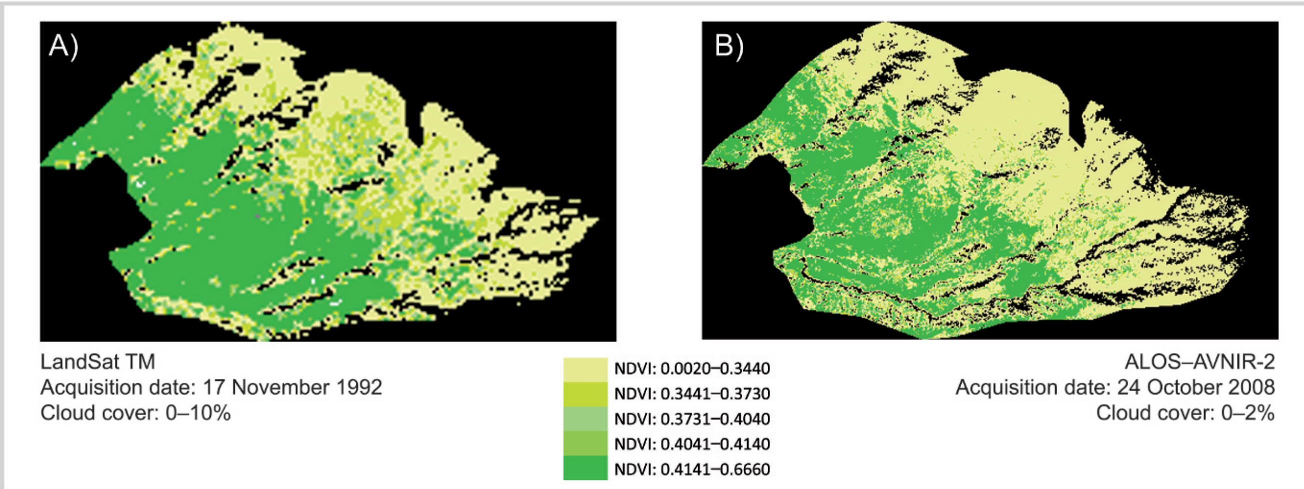
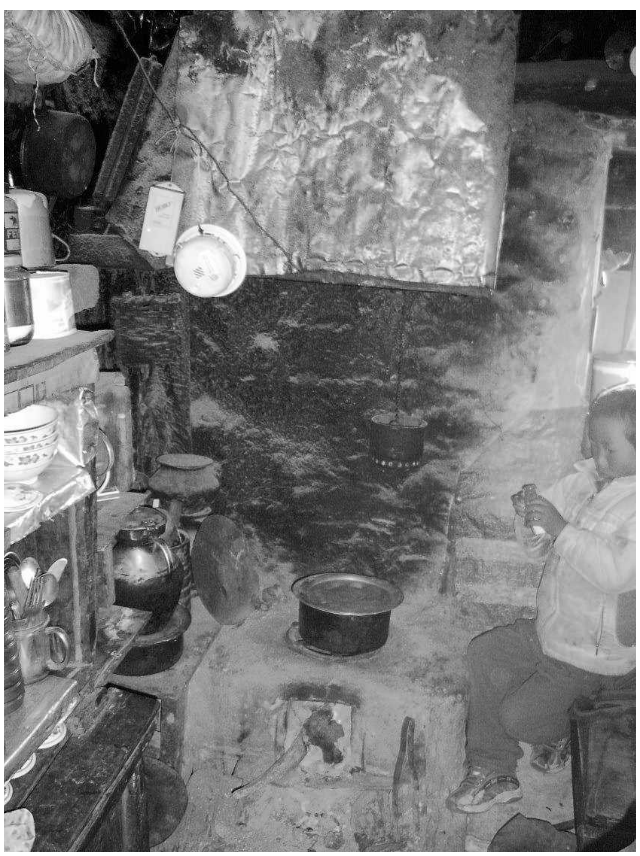
FIGURE 4 Satellite imagery showing forest biomass in Luckla Forest in 1992 (A) and 2008 (B).



cooking time (about 2 hours average) in houses using TCS, whereas the minimum concentration was recorded while no cooking was being done as well as when the electric heater was used for cooking. The average 8-hour time-weighted concentration agrees well with other similar studies in rural Nepal (about 0.003–0.021 g m^{-3} for ICS and 0.010–0.045 g m^{-3} for TCS; Environment and Public Health Organization 2008). The measured CO emission from the combustion of 1 kg of fuelwood and dung was 3.48 and 4.97 g kg^{-1}, respectively.

FIGURE 5 A traditional metal stove without a chimney in a residential house in Thame. (Photo by Atindra Sapkota)



Exposure to high concentrations of CO due to biomass combustion (ie fuelwood and dung) is the major cause of chronic obstructive pulmonary disease (COPD; Mannino and Buist 2007). The spirometry test indicated that the majority of the population sampled (82%) had no respiratory obstruction; however 13% had mild and 5% moderate obstruction (Pellegrino et al 2005). Due to the lack of a reversibility test, we could not discriminate between asthma and COPD. Notably, out of the 18% of the population with pulmonary obstruction, 71% were women (fewer than one third were males). The percentage of females with probability of COPD was higher than expected in the general population (4–10%; http://www.goldcopd.com). These results imply that the female population runs a higher risk of being affected by respiratory diseases, particularly COPD, because they spend more time in the kitchen and are thus more affected by IAQ. Similar studies in other parts of the developing world have also shown that women and children suffer most from IAQ (Balakrishnan et al 2004).

Designing the models

Figure 6 shows the qualitative models developed during the participatory modeling process conducted in SNPBZ with the aim of facing the issues related to energy management, forest sustainability, and human health problems due to indoor air pollution. These qualitative models were then translated into quantitative system dynamics models to develop possible management

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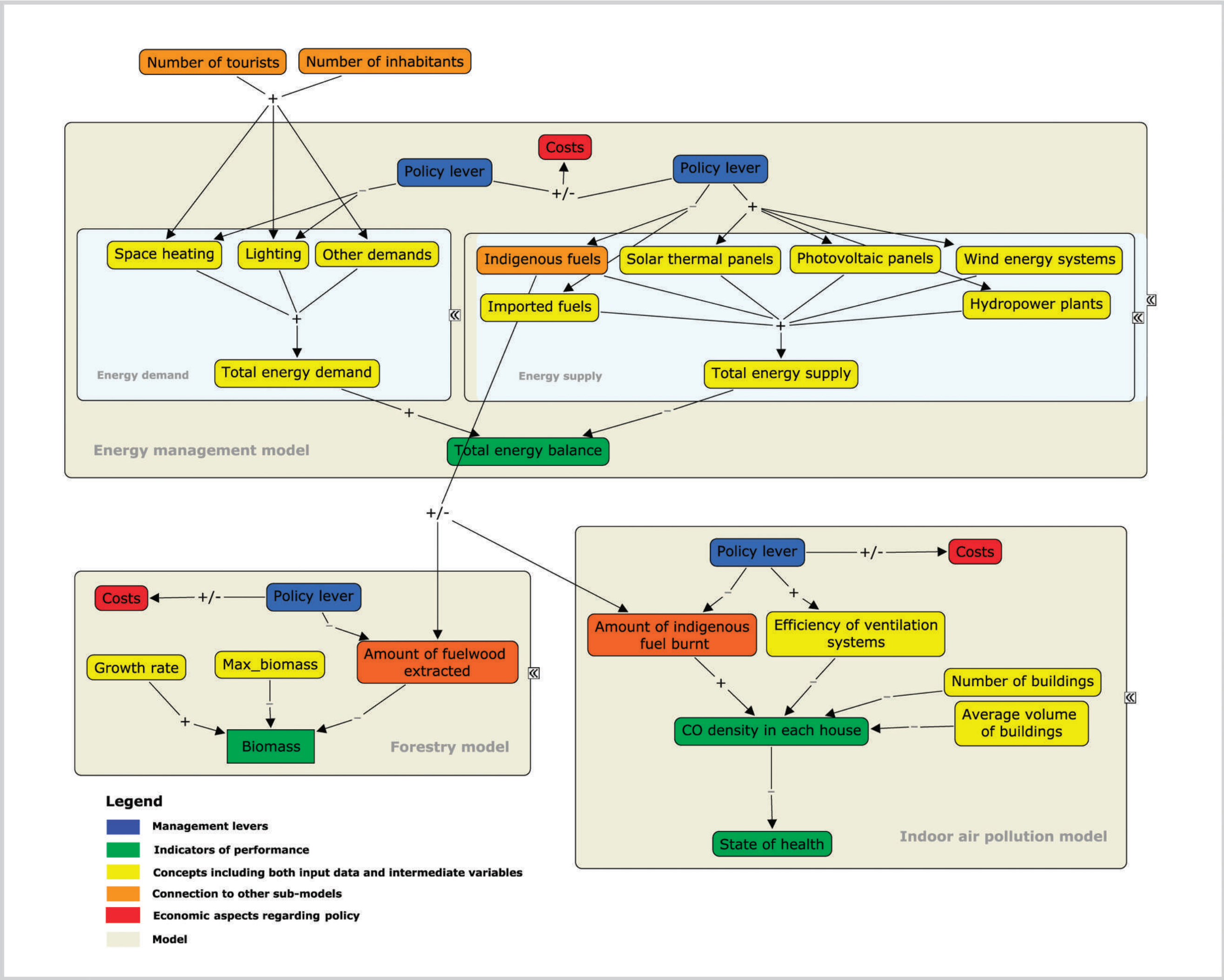
TABLE 3 Data on ventilation efficiency, average indoor CO concentration, and amount of fuelwood and dung used as energy sources. All of these data were disaggregated per building type, considering particularly residential–traditional and commercial–modern buildings.

Variables	Type of building		Unit
	Residential–traditional	*Commercial–modern*	
Efficiency of ventilation system	20	65	%
Average indoor CO concentration	0.105	0.053	g m^{-3} per household
Dung used	3.9	0.8	kg d^{-1} per household
Fuelwood used	66.0	13.7	kg d^{-1} per household

FIGURE 6 Qualitative models of SNPBZ for the management of energy, forest, and indoor air pollution. Colors represent modeling meanings; link arrows are labeled. The symbols +, −, and ± are used as linking phrases to indicate causal relationships between the connected concepts, describing either positive or negative (inverse) relationships or relationships that can be either positive or negative depending on conditions.



scenarios. Approaches, design, and tools used within the participatory modeling process are described in detail in Salerno et al (2010).

Energy management model

The energy management model describes the demand and supply components for each selected settlement in order to assess the *total energy balance* and the related *costs*. The *total energy demand* is the sum of energy used for different purposes, including space heating, lighting, and other activities generalized in the model and indicated under *other demands*. Particularly, the energy demand for *space heating* is related to many factors, such as building type, base surface of buildings, volume of the heated room, insulation, and characteristics of walls and windows. Such features allow for the calculation of parameters such as heat required and thermal dispersion (Spakovszky 2006). Moreover, the total energy required (energy demand) is proportional to the number of inhabitants and tourists present in each settlement, which are model input variables coming from the tourism and population dynamic models developed in a separate study (International Centre for Integrated Mountain Development 2009). The *total energy supply* is related to different energy sources, such as *imported fuels* (ie kerosene and LPG); *indigenous fuels* (ie fuelwood and dung); and nonconventional available energy sources, including *photovoltaic panels*, *solar thermal panels*, *wind energy systems*, and *hydropower plants*.

All of these energy sources may be influenced by different management policies and relevant economic implications. *Imported fuels* are derived from the amount of fuel used and the energy produced for the combustion of a kg of each fuel type. *Indigenous fuel*—in particular the amount of fuelwood used—is influenced by the current number of fuelwood extraction permits as well as by the *amount of fuelwood extracted* from the forestry model. At the same time, in the model, the amount of dung used as fuel comes from the water pollution model described in Manfredi et al (2010). Regarding the alternative energy sources, the energy produced by both *photovoltaic panels* and *solar thermal panels* depends on the panels' surface and on the energy produced per m^2. The energy produced by *wind energy* (aeolic) *systems* is correlated with the number of wind energy systems (WSs), system power, the efficiency of the electric distribution network, and the hours of activity of the aeolic system. The *total energy supply* is also correlated with the hydropower energy available in each settlement, which depends on the energy produced by all of the *hydropower plants* in the park area, the percentage of use of hydropower energy of each settlement, and the efficiency of the electric distribution network.

Indoor air pollution model

The indoor air pollution model was developed with the aim of: (1) evaluating the CO concentration in the houses as an index for IAQ and (2) estimating the state of the local population's health in the study area. The model can calculate the CO density in each house by considering the *amount of indigenous fuel burnt*, which is linked with the energy management model through the *indigenous fuels* concept (for the SNPBZ case study, the amount of firewood and dung) used in each selected settlement, which is also influenced by the respective number of tourists and inhabitants (Figure 6). Considering the amount of CO emitted by the combustion of 1 kg of indigenous fuels together with the *number of buildings* and the *average volume of buildings* in each settlement, the total *amount of CO produced* in each house is obtained. Through such variables, the model can calculate the CO density in each house that will be reduced considering the efficiency of ventilation systems per building type. Based on World Health Organization (WHO) standards for COPD risk related to CO exposure (0.01 g m^{-3} $hour^{-1}$), the model enables an estimation of the *state of health* of the residents.

Forestry model

The development of the forestry model (Figure 6) was conceived to address the problem of forest thinning, which represents a key management issue in SNPBZ (Stevens 2003). Increased tourist flows are contributing to a rising demand for energy sources, such as fuelwood, consumed in the lodging and food businesses. The model aims to assess forest biomass as a performance indicator of forest condition. Following Muetzelfeldt and Taylor (2001) and Mazzoleni et al (2003), vegetation biomass is modeled as a simple logistic equation, considering on one hand both the *growth rate* of the forest and its reachable maximum biomass (*max__biomass*), and on the other hand human pressure on forests due to the extraction of fuelwood (*amount of fuelwood extracted*), the main indigenous energy source. The model equation is

$$\frac{dB_i}{dt} = g_i \times B_i \times \left(1 - \frac{B_i}{M_i}\right) - E_i \text{ with } i = 1,\ldots,13,$$

where B_i (kg m^{-2}) is the *biomass* in the *i*-th forest area (for SNPBZ, we identified 13 main forest areas where local people collect fuelwood); t ($month^{-1}$) is time; g_i ($month^{-1}$) is the *growth rate* estimated considering the satellite imagery of each forest area in 2 different periods, as previously described; M_i is the maximum biomass (*max__biomass*) of *i*-th forest area estimated; and E_i is the *amount of fuelwood extracted* (kg m^{-2} $month^{-1}$; Figure 6). By acting on the management levers that make it possible to change extraction rules, and consequently the amount of fuelwood extracted, it is possible to observe different sustainable and nonsustainable forest scenarios.

Adaptive management

The above 3 models were useful in developing and analyzing different scenarios simulating the effects of

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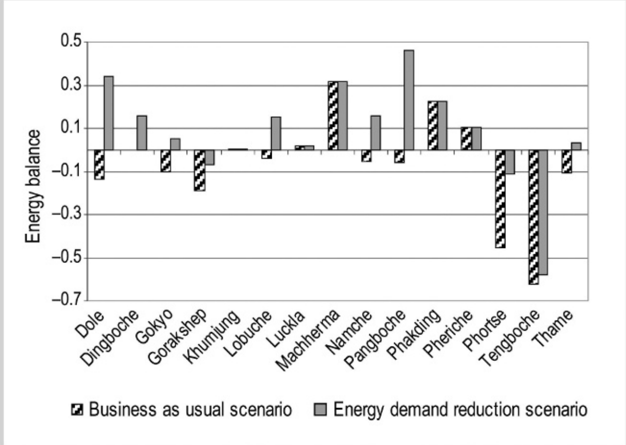
specific management options (or policy levers) applied in each model and on which the model user may act directly. The initial scenarios obtainable by running the models without implementing any policy lever depicted the same results obtained from the data acquired during the relevant management-oriented research. This phase made it possible to calibrate the models, or rather to define the parameters, using field data. The basic scenario, reflecting the current situation in which no specific policy lever is implemented, is defined here as *business as usual*. In what follows, we present the most significant scenarios we developed and discussed with local stakeholders.

Reduction of the energy deficit

An evaluation of the business-as-usual scenario showed that the yearly energy deficit at the park level (all energy sources considered) is around 7% of the demand (~4000 kWh), while the really critical situation is evident at the settlement level, with the majority of settlements in energy deficit condition (even over 50%) compared to the energy demand (Figure 7). Future scenarios aiming for a reduction of this energy deficit can contemplate the implementation of management policies to contribute either to saving energy (ie reducing the demand) or increasing energy supply (ie using alternative sources of energy). Exploring the first possibility, we simulated a scenario combining 2 policy levers: the introduction of energy-saving lamps and the improvement of insulation. With such a scenario, the total energy demand at the park level would be reduced by 14%, thus canceling the overall deficit. Of 15 settlements, 9 would show an energy surplus (in particular, Dole, Machherma, and Pangboche), while for only a few of them (particularly Tengboche and Phortse), the application of these combined policies would not be sufficient for zeroing the deficit. The estimated cost to realize these scenarios, considering all selected settlements, is US$ 85,000, with an energy consumption cost of US$ 3800 day^{-1}.

The second option explores the possibility of improving the energy supply. In this regard, we explored only the possible adoption of sustainable management policies promoting alternative energy sources. Findings from the management-oriented research showed that feasible options for this purpose in SNPBZ represented mainly HPSs and ST panels, while PV panels do not seem to be cost-effective, and WSs have a high visual impact. The second scenario thus projected covering the current SNPBZ deficit (4000 kWh day^{-1}) by proposing to build 1 or several new HPSs. With the model, we found that the new HPSs to be installed should have a total capacity of 700 kW for resetting the whole deficit for each settlement. The estimated cost to realize new HPSs has a magnitude of around US$ 2 million, plus extra costs for building or renovating the hydroelectric grid. Moreover, total costs for energy consumption (including distribution costs, operating costs, etc) would be around US$ 4500 day^{-1}. A

FIGURE 7 Business-as-usual scenario and energy demand reduction scenario for the selected settlements in SNPBZ.



variant in such a scenario consists of introducing STs to supply the energy demand for heating water. Using the model, we estimated that the total area needed for new STs was 270 m^2, and the corresponding costs amounted to US$ 100,000, plus possible costs for shipping and installation. The remaining energy deficit could be covered by installing 1 or more new HPSs with a total capacity reduced now to 500 kW, implying manufacturing and maintenance costs of US$ 1.5 million, plus extra costs for the hydroelectric grid. In this case, the energy consumption would be around US$ 4300 day^{-1}.

Reduction of forest impacts through alternative energy sources

As described above, the SNPBZ forests are affected by the increasing demand for fuelwood as a main source of energy. Figure 8 presents the business-as-usual scenario for the 13 selected forested areas illustrated in Figure 1. Analyzing variations in forest biomass from 1992 to 2008 as a parameter to estimate their health status, we see that current conditions in these areas can be considered unsustainable. The biomass reduction in most of the forest areas has generated fragmentation, thickness of the forest, and loss of habitat. Only 2 forest areas show a countertrend of increased biomass: Tengboche North and Phakding. For the former, this increase could have occurred because it is an area of sacred forests, while the improved conditions of the latter could be a result of fuelwood extraction that is moderate for the size of the forest (Table 2). The main scenario developed to preserve forest conditions has the final goal of maintaining the current biomass level in all forests. In this regard, we projected establishing restrictions on current extraction practices through the introduction of new extraction rules. (Under current rules, the park and/or Forest User Committee allow the collection of fuelwood by 2 persons

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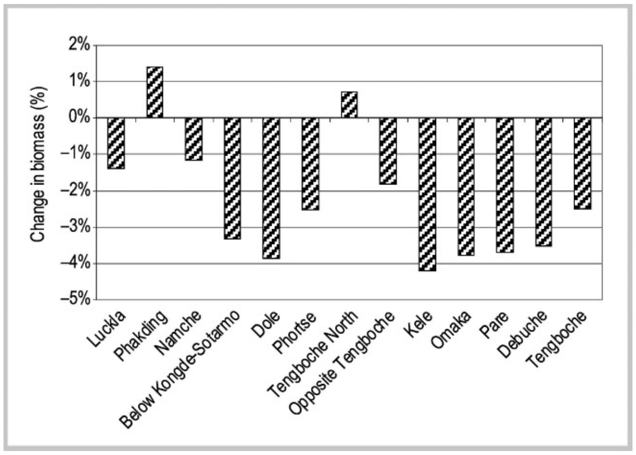
FIGURE 8 Business-as-usual scenario: mean annual biomass variation from 1992 to 2008 for the 13 selected forests in SNPBZ.



per household twice a year for 15 days each, designating the forest areas [except for Phakding]. According to this regulation, around 2 *baris* [2 × ~50 kg] of fuelwood can be collected per household per day during these periods.) Using the model, we calculated that the maximum allowable level of fuelwood extraction that would guarantee the current biomass level is 28% of the current practice. This result shows that the business-as-usual scenario is very unlikely to preserve the current forest status: in fact, 75% of the fuelwood currently used should be replaced with alternative energy sources. At the same time, a reduction of fuelwood use would lead to reduced indoor CO concentrations due to combustion. In this scenario, we considered reducing energy demand by improving the insulation of buildings (estimated cost around US$ 50,000), increasing the alternative energy supply by introducing STs to heat water (estimated cost around US$ 100,000, plus possible extra costs for shipping and installation), and installing additional HPSs (estimated cost around US$ 4 million for 1400 kW total capacity).

Indoor air pollution

In SNPBZ, many houses are equipped with open fireplaces for cooking with an unsuitable ventilation system, conditions that cause indoor air pollution, as specified above. Our scenarios were developed with the aim of reducing human diseases related to exposure and high CO density. The first scenario concerns the introduction of new chimneys in residential buildings in which the efficiency of the ventilation system is very low (20%). As shown in Table 4, this management option allows a CO density reduction of more than 50% for the residential–traditional buildings (from 0.15 to 0.06 g m^{-3} hour^{-1}). Nevertheless, the WHO exposure standard limit (0.01 g m^{-3} hour^{-1}) is much lower.

Considering the benefits achieved in the previous scenario, we looked for a combination of management policies in order to reach an indoor CO concentration not exceeding the WHO exposure standard limit (*current CO/WHO's CO limit* equal to 1). In implementing the

TABLE 4 Three scenarios from the indoor air pollution model considering residential–traditional and commercial–traditional buildings.

	Business-as-usual scenario		*Improved cooking stoves* scenario		*Improved cooking stoves* and *reduction of traditional fuel* scenario	
	Residential–traditional	Commercial–modern	Residential–traditional	Commercial–modern	Residential–traditional	Commercial–modern
Dung consumption (kg day^{-1})	3.9	66.0	3.9	66.0	0.8	13.2
Fuelwood consumption (kg day^{-1})	0.8	13.7	0.8	13.7	0.2	3.4
Chimney ventilation efficiency (%)	20	65	65	65	65	65
Indoor CO density (g m^{-3} hour^{-1})	0.15	0.08	0.06	0.08	0.01	0.01
Actual CO/ WHO CO limit (adimensional)	**15**	**8**	**6**	**8**	**1**	**1**

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model, we found the following levels of reduction of traditional fuels: 75% for fuelwood consumption (the threshold that guarantees forest preservation) and 80% for dung. The estimated cost for this policy entails around US$ 500 for the installation of a chimney and US$ 200 for new cooking devices using alternative energy sources (US$ 300,000 for all selected settlements), as well as additional costs for acquiring the alternative energy sources according to the previous scenarios.

Conclusions

This paper has shown how a methodology and framework developed with the participation of a broad range of stakeholders (Salerno et al 2010) was applied and the findings obtained. The application of the 5-module framework to explore energy and related health problems in SNBPZ has shown that fuelwood and kerosene are the main sources of energy for cooking and for heating space and water. Considering the rapid increase in tourism in recent years, pressure on forestlands has intensified, resulting in forest thinning, degradation, and ultimately the depletion of resources. The use of fuelwood also affects local people's health due to CO emissions in traditional houses, where proper ventilation systems are usually absent. Furthermore, the energy balance in many settlements in the park suffers from a considerable deficit due to remoteness and massive tourist flows. In this context, research efforts focused on collecting data to address these management issues. An interactive modeling process allowed for the simulation of dynamics and relationships among tourism and immigration flows, energy demand and consumption, forests conditions, and indoor air pollution. We concluded the process with an adaptive management phase providing management scenarios. The business-as-usual scenario showed that we are unlikely to preserve the current forest status (in light of the reduction in forest biomass of, on average, 38% from 1992 to 2008). In fact, 75% of the fuelwood currently used should be replaced with alternative energy sources to preserve the current status of the forest; at the same time, a 75% reduction in fuelwood use (and an 80% reduction in dung use) would lead to reduced indoor CO concentrations that no longer exceed the WHO standard limits for CO exposure.

The development and application of participatory modeling in the Sagarmatha area has contributed to furthering knowledge and awareness of important conservation and health issues in SNPBZ as well as to the exploration of environmental policies to resolve them, in collaboration with local stakeholders. We hope that this example of our experience in SNPBZ—as well as the models presented (downloadable free of charge at http://hkkhpartnership.org), which were developed with the participation of local stakeholders and technicians using a generalizing design that allows for user-friendly adaptation to other contexts—will be of use to stakeholders and decision-makers who need to deal with similar issues in other remote mountain areas in developing countries.

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