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The Global Warming Potential of Building Materials: An Application of Life Cycle Analysis in Nepal

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This paper analyzes the global-warming potential of materials used to construct the walls of 3 building types—traditional, semimodern, and modern—in Sagarmatha National Park and Buffer Zone in Nepal, using the life-cycle assessment approach. Traditional buildings use local materials, mainly wood and stone, while semimodern and modern buildings use different amounts of commercial materials, such as cement and glass wool. A comparison of the greenhouse gas emissions associated with the 3 building types, using as the functional unit 1 m^2 of wall, found that traditional buildings release about one-fourth of the greenhouse gas emissions released by semimodern buildings and less than one-fifth of the emissions of modern buildings. However, the use of thermal insulation in the modern building walls helps to reduce the energy consumption for space heating and consequently to reduce the global warming potential. In 25 years, the total global warming potential of a traditional building will be 20% higher than that of a modern building. If local materials, such as wood, are used in building construction, the emissions from production and transportation could be dramatically reduced.

Keywords: *Building material; global-warming potential; life-cycle assessment; climate change; Sagarmatha National Park; Nepal.*

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Introduction

The growing threat of climate change is raising concern about the control of greenhouse gas emissions in both developed and developing countries. Developing countries are particularly susceptible to climate change (Pouliotte et al 2009; Gentle and Maraseni 2012; Pandit 2013), because of their limited capacity to cope with the associated hazards (Olmos 2001; UNFCC 2007). Within developing countries, some communities may be more vulnerable than others. For example, the effects of climate change are usually more severe in rural areas, often characterized by limited livelihood options, poor access to services, and inequitable access to productive assets (Gentle and Maraseni 2012; Ortiz-Montemayor 2012; Shrestha et al 2012). Mountain areas are probably the most exposed to hazardous processes, including climate change, because of their higher ecological and economic complexity (Luthe et al 2012; Delay et al 2015). At the same time, because of the large presence of natural ecosystems and land-use types, mountain areas are essential providers of ecosystem services such as biodiversity, water, recreation, and carbon sequestration (Viviroli et al 2007; Grêt-Regamey et al 2008; European Environmental Agency 2010; Glass et al 2013). Any change in these fragile ecosystems must be carefully considered, as their value extends far beyond their physical boundaries.

Mountain areas have been central to the research agenda for sustainable development ever since Rio 1992 (Preston 1997; Gurung et al 2012; Messerli 2012). They are also interesting because their exposure to a variety of natural and economic hazards at different times and scales has allowed their communities to develop specific adaptation strategies often embedded in local traditional knowledge. Thus, they could be a good laboratory for the study of how the introduction of new technologies can impact local and global environmental sustainability and, in general, local livelihood patterns (Gansach and Meir 2004; Gardner and Dekens 2007; Gurung et al 2012; Barua et al 2014; Weyerhaeuser and Nowrojee 2014).

The Himalayan region is a paradigmatic example both of the value of mountain areas as global resources and of the many threats arising from global and local drivers (Gansach and Meir 2004; Ramakrishnan 2007). Although not the most important, human population growth accompanied by an expansion of settlement areas (Bhatta 2013) is a source of local change. Because of their greater ease of heating, reinforced concrete buildings are replacing traditional wood and stone masonry buildings in the region. This may create a heat-island effect and thus add to regional warming (Pandit 2013). The building sector has a considerable worldwide environmental impact (Scheuer et al 2003), with 20–30% of the global carbon footprint (McKinsey and Company 2009). At the global level, building construction consumes 24% of the raw materials extracted from the lithosphere (Zabalza Bribián et al 2011) and produces high levels of pollution as a result of the energy consumed during the extraction, processing, and transportation of materials (Morel et al 2001).

To assess how building choices can contribute to sustainable development in mountain areas, it is important to consider their entire life cycle and to evaluate the environmental impacts associated with the extraction, production, and transportation phases, identifying and quantifying the energy and materials used and the waste released to the environment (Sonnemann et al 2003; Pittet et al 2012). Interest in documenting the environmental impact of building materials and processes is increasing in developed countries, aiming to reduce their energy consumption (Cole 1999; Pittet et al 2012), but information in this field is still scanty. Due to the lower efficiency of most smaller manufacturing plants, materials produced in developing countries may generate larger environmental impacts per unit (Buchanan and Honey 1994; Fava 2006; Asif et al 2007; Pittet et al 2012). Furthermore, the extraction, manufacturing, and transportation processes may be less efficient, and this may alter their environmental impact (Cole 1999; Pearlmutter 2007; Huberman and Pearlmutter 2008; Pittet et al 2012). More research is needed to better understand the environmental performance of building materials in developing countries.

This study was carried out in the Himalayan region of Nepal, which attracted about 100,000 tourists in 2013 (Nepal Tourism Statistics 2014). The government of Nepal is planning to implement a policy to attract more tourists. Although increased tourism is likely to bring new income opportunities for local communities, it will also contribute to a rapid growth in building construction, which could worsen the region's already severe pollution (Manfredi et al 2010; Salerno et al 2010), especially if the current preference for concrete over traditional wood and stone continues. In Himalayan regions, wood and other traditional building materials are found near people's homes, while other materials, such as glass wool, polystyrene foam, and alkyd resins, must be transported by road but also by air due to the difficult road connections.

In such situations, a life-cycle assessment (LCA) study, which looks at emissions during every stage of a process from extraction of raw materials to construction of the finished product (from cradle to gate), can support the choice of technology and materials that minimize the environmental impact of construction (Petersen and Solberg 2005; Gustavsson and Sarthe 2006; Zabalza Bribián et al 2011; Passer et al 2012). We conducted a comparative LCA, from cradle to gate, of the building materials used in 3 types of houses in the mountain region in Nepal to identify major emission sources and their potential contribution to the greenhouse gases as well as ways to reduce emissions and contribute to more sustainable development.

Study site

The study was conducted in Sagarmatha National Park and its buffer zone, in northeastern Solu-Khumbu District in Sagarmatha Zone in Nepal, at 27°30′19″–27°06′45″N latitude and 86°30′53″–86°99′08″E longitude (*Supplemental material*, Figure S1, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1). Elevation ranges from 2800 to 8848 m above mean sea level. The park lies within an area of 1148 km^2 of which 69% is park land, 28% is grazing land, and 3% is forested (Stevens 2003). It is divided into 2 village development committees (local administrative units), Namche and Khumjung; a third, Chaurikharka, forms a buffer zone to the south of the park. Its elevational zones range from forest to alpine scrub, an upper alpine zone that includes the upper limit of vegetation growth, and an above tree line zone where no plants can grow (Aryal et al 2010).

The primary economic activities in the park are tourism and agriculture. It is a popular tourist destination, containing the world's highest peaks, and can be reached only by airplane or on foot.

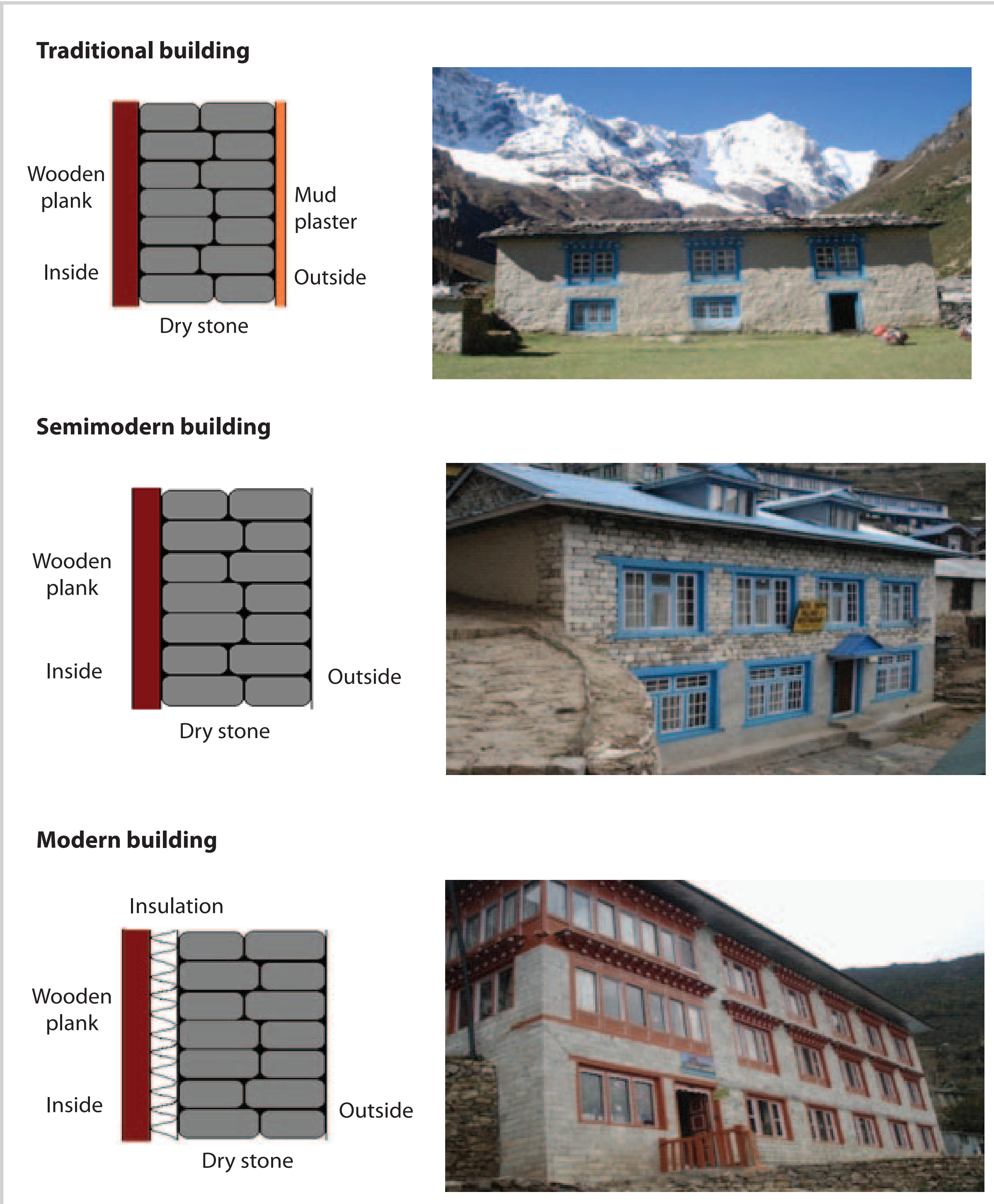
Materials and methods

Building types and materials

This study focused on the walls of 3 types of buildings: traditional, semimodern, and modern (Figure 1). Traditional buildings, known as Sherpa houses, are built mainly of wood, stone, and mud. Semimodern buildings incorporate some modern aspects, including limited insulation material (polystyrene) and cement. Modern buildings, built mainly for tourism, also use imported construction materials such as cement and glass wool (*Supplemental material,* Figure S2, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1). (While the walls of the 3 building types are made of different materials, the roofs are all made of the same material, primarily corrugated galvanized iron, and thus were not included in the analysis.)

Wood is used mainly for internal support structure and stone or soil for the envelope. Different installation techniques are used, such as compressed clay, sun-baked

FIGURE 1 Wall cross section and exterior appearance of different building types: traditional; semimodern; modern. (Photos and design by Silu Bhochhibhoya; sources: semimodern, Bhochhibhoya and Cavalli 2017; modern, Bhochhibhoya et al 2016)



mud bricks (Sestini 1998), and 0.7–0.8 m thick dry stone masonry.

Pine (*Pinus wallichiana*) and fir (*Abies spectabilis*) are the most common woods used in construction (Stevens 2003). Park regulations allow the use of 30 m^3 of wood in construction of one new building, for which royalties must be paid to the park. Additional wood is brought from Jiri, a hilly region 51 km aerial distance from the park, mostly

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by helicopter. This study assumed that, in the walls of semimodern and modern buildings, 50% of the wooden planks came from Jiri and 50% from the park, while in traditional buildings, 100% came from the park.

Another building material, white mud, locally known as *kamero*, is abundant in the park and has been extensively used as a binding and insulation material since the 20th century, in the form of a 0.05 m plaster over stone walls. Research has been carried out on ways to incorporate it in modern building technologies (Morel et al 2001).

Another locally available material used in all building types is dry stone, usually obtained from cropland or riverbed and shaped manually using a chisel and saw.

Some commercial materials have been gradually adopted in the park, including glass wool and polystyrene for insulation, used in modern and semimodern buildings, respectively, and cement for binding. Glass wool and polystyrene are imported from China and India, while cement and other construction materials are transported from areas near Kathmandu.

Life-cycle assessment of building materials

LCA can provide quantitative and comparative values for the environmental impacts of various building materials and technologies (Singh et al 2011; Zabalza Bribián et al 2011; Takano et al 2015). The system boundary defines the unit processes to be included in the system (ISO 14040 2006). In this study, a cradle to gate approach was used, from the acquisition of raw materials to product manufacturing, transportation, and assembly (Consoli et al 1993; ISO 14040 2006; ISO 14044 2006). LCA was used to quantify the emissions, energy use, and material consumption of a building system in the construction phase of the life cycle. The building wall manufacturing includes the different processes for acquiring, transporting, and processing materials. *Supplemental material*, Figure S2 (http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1) provides a flowchart of the processes used for the 3 housing types under study. For traditional buildings, this includes mud, wooden planks (supplied from within the park), and stone. For semimodern buildings, it includes these materials as well as cement and polystyrene; for modern buildings, it includes all of these plus glass wool. For semimodern and modern buildings, half of wooden planks are transported by helicopter.

The postconstruction phase was not considered due to the limited information on disposal and waste products. The life expectancy of buildings in the study area is difficult to predict, because their age varies significantly. The functional unit considered for all building types was 1 m^2 of wall (Cole 1999).

Since LCA is a data-intensive method, the preparation of the data is a fundamental step (Takano et al 2015). Both primary and secondary data were used in the model. The quantities of material and the energy necessary to build 1 m^2 of wall were ascertained for 91 buildings in 9 park settlements. The data were collected through interviews with park residents and with retailers of building materials in Kathmandu. The questionnaire was prepared according to LCA standards (ISO 14044 2006) and covered materials used in construction, material sources and quantities, transportation distance and means, and energy used for processing and transportation.

For each building type, the data collected in the interviews were averaged and used to build an LCA model (*Supplemental material*, Table S1, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1). For emission factors, Nepal-specific data are not available, so secondary data from Ecoinvent v3.1 (Frischknecht et al 2005), an European database internationally recognized as a complete database to perform LCA, were used and adjusted for conditions in Nepal. The Ecoinvent database provides well-documented and comprehensive process data for thousands of products in many areas such as energy supply, materials, and waste. The energy and materials used to produce equipment, tools, and infrastructure were not considered in the analysis.

To perform the LCA, generate the emissions factors, and analyze the relative contributions of different processes to the emissions, we used GaBi 6.0, a software package developed by PE International to analyze the environmental impact of products and services over their whole life cycle. Global-warming potential (GWP), generally regarded as a major indicator in LCA studies (Knauf 2015), was chosen as the unit of measure for the comparison, expressed in terms of carbon dioxide equivalents (CO_{2eq}). Also called the "greenhouse effect," GWP produces an increase of temperature in the lower atmosphere that can lead to climate and environmental changes. No matter where the contributing greenhouse gases originate, they contribute to the same global phenomenon, and GWP, as an environmental impact category, is therefore considered to be global. The time frame for the assessment was 100 years, as recommended by the 1997 Kyoto Protocol and the Intergovernmental Panel on Climate Change (IPCC 2013). The relative contribution of each process to global warming was calculated using the CML 2001 method, which is incorporated in GaBi and was developed by the Institute of Environmental Sciences of Leiden University in the Netherlands. CML 2001 was used because of its broad international acceptance and common application in the building sector (Ortiz et al 2009; Filimonau et al 2011).

Results and discussion

The study findings on GWP, measured in g CO_{2eq} per 1 m^2 of wall, are summarized in Table 1 by building type and specific emission type, and in Figure 2 by building type and material. *Supplemental material,* Table S2 (http://dx.doi.

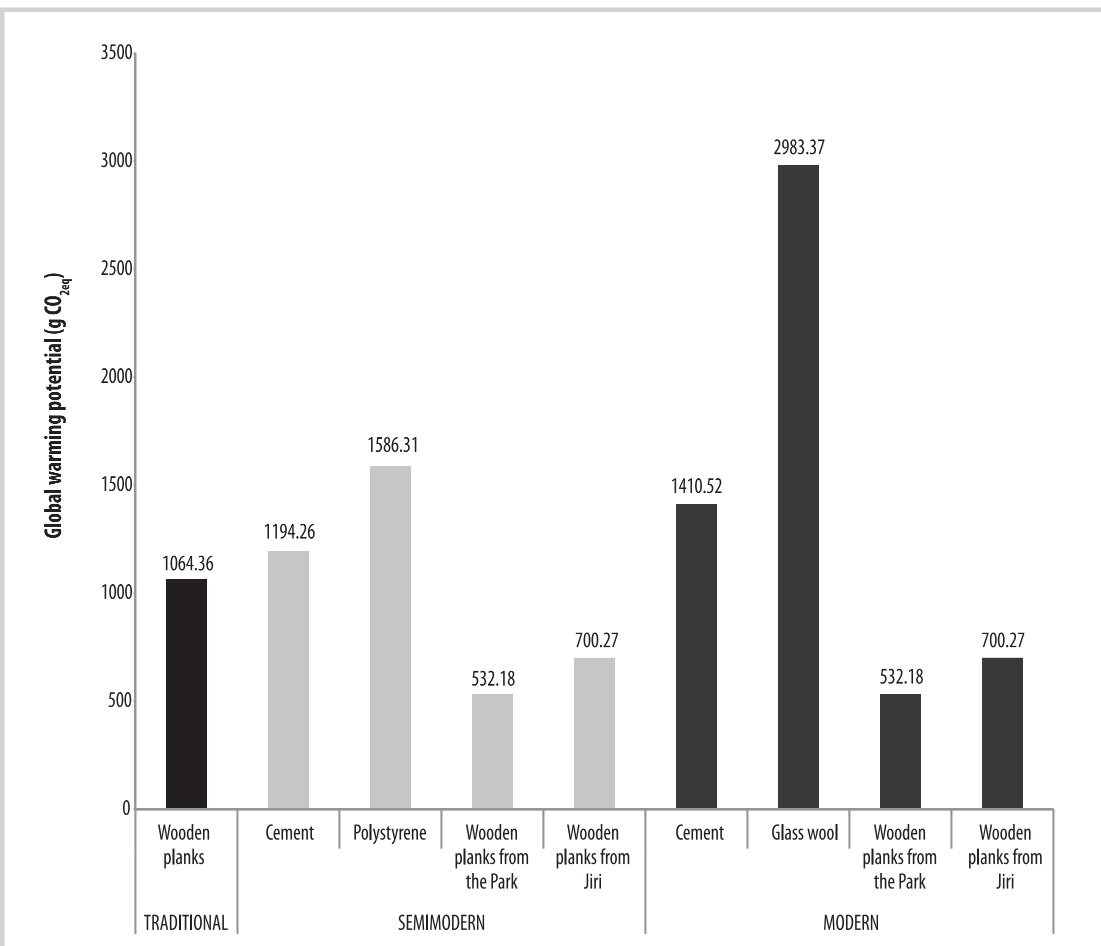
TABLE 1 Greenhouse gas emissions for the 3 building types.

	Emissions (g CO_{2eq})		
	Traditional	Semimodern	Modern
Inorganic	***989.48***	***3601.26***	***5335.33***
Carbon dioxide (abiotic)	833.10	3375.30	4999.52
Carbon dioxide (biotic)	5.95	65.21	153.87
Nitrous oxide	146.59	156.12	173.41
Sulfur hexafluoride	3.83	4.62	8.54
Organic	***74.89***	***411.76***	***291.01***
Nonmethane	0.77	4.13	9.53
Methane (abiotic)	73.85	406.41	277.85
Methane (biotic)	0.27	1.23	3.63
Total	**1064.37**	**4013.02**	**5626.34**

org/10.1659/MRDJOURNAL-D-15-00043.S1) breaks this information down in greater detail.

Walls in traditional buildings produce the lowest emissions, almost equally distributed between the alkyd paint used on the wood surface and the chainsaw used to cut planks from the trees felled by hand in the park. Mud and dry stone contribute less or not at all to CO_{2eq} emissions, because they are manually processed and transported. The GWP of walls in modern buildings is 5 times that of walls in traditional buildings. These buildings use commercial materials that are produced in China (glass wool) or in another part of Nepal (cement) and have to be transported to the park. Glass wool insulation panel manufacturing and transport produce more than 50% of emissions, while cement production and transport produce a little less than half that amount. About half the wooden planks used in modern buildings come from Jiri, 51 km outside the park, and must be transported by helicopter and lorry (*Supplemental material*, Table S1, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-

FIGURE 2 Global-warming potential of different building materials.



http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00043.1

00043.S1). The total contribution of wood used in modern buildings to global warming is slightly higher than that of wood used in traditional buildings (Figure 2).

The GWP of walls in semimodern buildings is lower than that of walls in modern buildings but still almost 4 times that of walls in traditional buildings. Their largest contributor to emissions is polystyrene, manufactured in India, which is used as insulation. Semimodern buildings use less cement than modern buildings (*Supplemental material*, Table S1, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1); cement is the third contributor to the GWP of modern buildings, closely following wooden planks (Figure 2).

These results are consistent with other studies on this topic. Wood has a lower GWP than other construction materials—such as concrete, bricks, and steel—because its CO_2 emissions are almost completely offset by the CO_2 absorption of trees (Buchanan and Levine 1999; Zabalza Bribián et al 2011). Wood's already low impact could be further reduced by 48% by avoiding the use of the alkyd resin and further limiting the importation of wooden planks from Jiri.

Pittet et al (2012) compared wall-building technologies and concluded that, in order to substantially reduce energy consumption and the related CO_2 emissions, technologies using earth (adobe and cob), wattle and daub, and stone, with limited use of cement or lime mortar and plaster, should be encouraged. A study of the environmental sustainability of different building materials in Sri Lanka (Emmanuel 2004) found that wattle and daub (created from local materials) was the most environmentally sustainable, compared to other wall materials such as brick, cement, *cabook* (laterite), and rubble. A study by Asif et al (2007) found that concrete and mortar were responsible for 99% of the total CO_2 emissions of home construction, mainly generated during production. Hence, local building materials are better for the environment than equivalent commercial materials, also because they do not require long-distance transportation (Morel et al 2001).

The construction of walls in semimodern and modern buildings, on the other hand, using commercial materials such as glass wool, polystyrene, and cement, results in considerably higher CO_{2eq} emissions, mainly during production and transportation. Insulation materials with a high level of industrial processing are the largest contributors to GWP. Zabalza Bribián et al (2011) showed that insulation materials of natural origin, such as cellulose fiber and sheep's wool, produced 75% and 98% less CO_{2eq} emissions, respectively, than commercial insulation such as polystyrene. Insulation made of kenaf (*Hibiscus cannabinus*) fiber has a significantly lower environmental impact than synthetic insulation (Ardente et al 2008). Using natural and locally available materials could reduce emissions by at least half.

Transportation of commercial building materials contributes significantly to CO_{2eq} emissions. Materials such as glass wool and polystyrene are transported from China and India to the capital city, Kathmandu, by lorry, from where they are transported to the park by air. Other commercial building materials such as cement and wooden planks are also transported to the park by air.

To propose strategies for the reduction of GWP, it is useful to understand which process contributes the most to the emissions related to each material and what chemicals are involved. As reported in Table 1, the most common chemical emission during construction of all building types is CO_2, followed by nitrous oxide in traditional buildings and methane in semimodern and modern buildings. While fossil-fuel CO_2 emissions are 6 times higher in modern buildings than in traditional buildings, the amount of nitrous oxide is only 20% higher. Semimodern buildings showed the highest methane emissions, due to the insulation material manufacturing process.

Details about the emissions generated by the different manufacturing and transportation processes for each material are reported in *Supplemental material*, Table S2 (http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1). The percentage of CO_2 in the total CO_{2eq} emissions was 80% for wooden planks and polystyrene, 97% for cement, and 93% for glass wool. CO_2 made up 97% of the emissions from the transportation of wooden planks from Jiri.

Except for cement, for which transportation has a higher impact, production generally produces the highest emissions. This is particularly true in the production of insulation materials—polystyrene, used in semimodern buildings, and glass wool, used in modern buildings—which generated almost 3 and 5 times more emissions, respectively, than the production of wooden planks. In the case of polystyrene, three-quarters of the greenhouse gases emitted are CO_2, and the rest is mainly methane. Glass wool transportation also emitted more than polystyrene transportation, because glass wool is needed in larger amounts (*Supplemental material*, Table S1, http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00043.S1).

As a result, construction of walls in modern buildings has a higher environmental impact than that of semimodern and traditional buildings. However, modern buildings, with their heavy insulation, are more thermally efficient—requiring 13 W m^{-3} to heat a room, compared to 16.6 W m^{-3} for traditional buildings and 17.44 W m^{-3} for semimodern buildings. Based on these heating requirements, the yearly energy consumption and CO_{2eq} have been estimated for a typical house and added to the CO_2 previously calculated for the wall materials. Assuming the house is heated with a 6 kW wood heater that uses mixed logs, after only 5 years the total emissions per unit of volume (including wall materials and heating) of the traditional building would equal those of the modern building. With a life span of 25, 50, 75, or 100 years, the total GWP of a traditional building would be 20%, 24%, 25%, or 26% higher, respectively, than that of a modern building.

Emissions of CO_2, the main gas emitted during the life cycle of the considered materials, could be offset by more use of wood combined with sustainable forest management. Wood contains stored carbon that is released to the atmosphere only when the wood is burned or consumed by organisms during decay (Buchanan and Levine 1999). The CO_2 emitted from wood combustion or decay in the forest can be offset by the carbon absorption in the forest. By saving a part of the biomass, sustainable forest management can aim to offset the emissions of the whole supply chain (Pierobon et al 2015).

Thus, there are trade-offs between sequestering carbon stocks in forests and the climatic benefits obtained by sustainable forest harvesting and using wood products to displace fossil carbon emissions (Pingoud et al 2010). In this case, if the park regulations allow 30 m^3 of wood to be cut, considering a wood density of 670 kg m^{-3}, and if 70% of the harvested wood is used to produce wooden planks, then this corresponds to 14 tons of wood available for building. Assuming a carbon content of 50% of the total biomass (IPCC 2006), 7 tons of carbon are stored in the total available woody biomass. Unlike the carbon that it is released during combustion, the carbon stored in wood that is used as a building material will be stored for the entire lifespan of the building, which in this context is greater than 100 years.

Conclusions

In this study, an LCA of building materials used in Sherpa houses in Sagarmatha National Park and its buffer zone was performed to evaluate the contribution of each material to the building's GWP, using as the unit of analysis 1 m^2 of wall. Findings indicate that construction of walls in semimodern and modern houses built of commercial materials such as cement, polystyrene, and glass wool, which are gradually replacing traditional houses built of locally available materials, have 4 to 5 times greater impacts on global warming. Although the construction of modern buildings generates high GWP, their walls are more thermally efficient than those of semimodern and traditional buildings. This helps reduce energy consumption for space heating and consequently reduces GWP. In fact, when taking heating into consideration, after only 5 years the total emissions of the traditional building equal those of the modern building. In 25 years, the total GWP of a traditional building will be 20% higher than that of a modern building; in 100 years, it will be 26% higher.

The study also identified possible ways to reduce CO_{2eq} emissions during the life span of building materials. High amounts of CO_{2eq} are generated during the production and transportation of the materials, especially insulation materials. This suggests that CO_{2eq} can be reduced by adopting traditional manufacturing techniques using locally available materials, which have high value in terms of environmental protection. Among the locally available materials, the use of wood combined with sustainable forest management practices, which have an impact on carbon stocks in biomass and on the annual supply of wood products, should be encouraged. Up to 7 tons of carbon can be stored in the woody biomass available for building construction.

This study is relevant to the general debate on sustainable mountain development, especially on the role that communities' knowledge can play in it. Although traditional knowledge and locally developed bottom-up solutions are often proposed in juxtaposition with top-down technologically based ones, the results of this study show that both traditional building types and modern ones can contribute, in different ways, to a more sustainable use of environmental resources. Appropriate solutions thus require a balanced mix of tradition and modernity, which cannot be generalized but must be locally defined to allow for the high specificity and delicate equilibrium of mountain ecosystems. In this context, LCA can be a valuable support to decision-making when it is important to choose the best technology and material to minimize the environmental impact of building construction.

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Supplemental material

FIGURE S1 Location of Sagarmatha National Park and its buffer zone. (Map by Salerno F, Flury B, Thakuri S, Basani M, Maskey RM, Khanal S, Sapkota A, Bhuju D, Jha P, Bhochhibhoya S. 2009. Management-Oriented Environmental Research in Sagarmatha National Park and Buffer Zone. HKKH Technical Paper, Kathmandu Nepal, courtesy of the authors)
FIGURE S2 Material flows for traditional, semimodern, and modern buildings.
TABLE S1 Primary data collected for the material needed to build 1 m^2 of wall. Where relevant, type of building is indicated in parentheses.
TABLE S2 Emissions per 1 m^2 of building material.

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