+ MODEL

Available online at www.sciencedirect.com

ScienceDirect

Advances in Climate Change Research xxx (xxxx) xxx

www.keaipublishing.com/en/journals/accr/

Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal

Sabarnee TULADHAR*, Binaya PASAKHALA, Amina MAHARJAN, Arabinda MISHRA

International Centre for Integrated Mountain Development (ICIMOD), 44703, Kathmandu, Nepal

Received 31 January 2020; revised 12 August 2020; accepted 31 December 2020

Abstract

Globally, mountains are often characterized as fragile and hazardous terrains, with vast areas covered by the cryosphere. The livelihoods of communities in the Hindu Kush Himalayan region are closely linked with the cryosphere. But over the past few decades, communities in the region have experienced multiple changes, including those driven by climat e change, with direct and immediate impacts on their lives and livelihoods. In this study, we explore linkages between the cryosphere and high-mountain livelihoods using a social–ecological system approach. It examines how the complex social–ecological system in villages in Langtang Valley, Nepal, has evolved in response to both cryospheric and socioeconomic changes. The local communities perceive gradual but significant changes in the cryospheric system, such as receding and thinning glaciers, changing snowfall patterns, changes in temperature and precipitation patterns, and a growing incidence of cryosphere-related hazards, such as avalanches and landslides. Communities in the Langtang Valley are also facing a number of socioeconomic changes, resulting in changing aspirations, particularly among the youth. The growing disconnection between society and the surrounding cryosphere, with direct impacts on the transfer and growth of local knowledge systems, are discussed. These simultaneous changes in the cryosphere and the socio-economic domain have also resulted in a homogenization of livelihood sources, with tourism emerging as the dominant source of livelihood. This has resulted in a dependence of the local population on food imported from outside the valley. A growing dependence on tourism for livelihoods, dependence on imports for food and other basic needs, and the lack of a risk reduction strategy might pose great risks for local lives and livelihoods in the long run. Interventions pertaining to diversifying livelihoods, harmonizing social capital, and hazard risk assessment are essential for strengthening linkages between cryosphere and the socioeconomic system.

Keywords: Cryosphere–livelihood linkages; Social–ecological systems; Climate change; High-mountain communities; Hindu Kush Himalaya; Langtang Valley

1. Introduction

Globally, mountains are often characterized as fragile and hazardous terrains with harsh environmental conditions, and occupied by economically and politically marginalized social groups (Jodha, 1992). Mountainous areas host diverse biological and cultural entities and provide multiple ecosystem services vital for more than half of humanity (Messerli and Ives, 1997). Vast parts of mountainous areas, particularly in the Hindu Kush Himalaya (HKH), are covered by the cryosphere − frozen water in the form of ice, glaciers, permafrost, and snow. The HKH region is home to 240 million people whose lives are intimately linked to cryospheric systems. Water from cryosphere melt in the region contributes to ten major river basins in Asia (Bajracharya et al., 2015), in which 1.9 billion people live.

The livelihoods of mountain communities in the HKH region are closely linked with the cryospheric system. The melting of the cryosphere supplies water for agriculture, pastoralism, drinking, hydropower generation, and recreation (Mukherjee et al., 2019; Xiao et al., 2015). It supplies moisture for the regeneration and growth of agricultural crops and vegetation, including medicinal and aromatic plants (Paudel and Andersen, 2013). Many mountain communities are

* Corresponding author.
E-mail address: sabarnee.tuladhar@icimod.org (TULADHAR S.).

https://doi.org/10.1016/j.accre.2020.12.004

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004

dependent on irrigation channels fed by glacier water and snowmelt streams (Nüsser and Schmidt, 2017). The snow- and glacier-covered mountains are revered as local deities by mountain communities (Allison, 2015). The cryosphere also plays a vital role in regulating micro-climates. It is influenced by the onset and intensity of the monsoon, and general circulation patterns (Moors and Stoffel, 2013) that have cascading effects on other ecosystems and livelihoods (Xu et al., 2009).

Over the past few decades, communities in the HKH region have experienced multiple changes in the cryosphere (Wang et al., 2019). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) and the Hindu Kush Himalayan Monitoring and Assessment Programme (HIMAP) report (Wester et al., 2019) have both indicated that temperature rise in the HKH exceeds the global average temperature rise. This increase in temperature has direct implications for glacier melt. Studies show that glaciers as well as the snow cover area in the region are shrinking, with few exceptions (Bajracharya et al., 2015; Gurung et al., 2011; Lutz et al., 2016; Kraaijenbrink et al., 2017; Bolch et al., 2019; IPCC, 2019). There has also been a reduction in the volume of annual snowfall and shifts in seasonal snowfall patterns in the region (Paudel and Andersen, 2011). Bolch et al. (2019) projected that the snow line in the HKH region will rise by several hundreds of metres and glaciers will lose significant mass by the end of the century.

The mountain communities will bear the immediate and severe impacts of changes in the cryosphere (McDowell et al., 2019; Rasul et al., 2019). The cryospheric changes result in hydro-ecological effects, such as the drying of springs and lakes (Manandhar et al., 2012) that have serious implications for water availability and food production, resulting water stress, and an increase in the costs of water collection and storage (McDowell et al., 2013). Rapid changes in the cryosphere increase the risk of disasters, such as floods, snow, ice, and rock avalanches, and landslides (IPCC, 2019). These not only damage property (agricultural land, houses, livestock, and cultural heritage) and infrastructure (hydropower plants, bridges, irrigation infrastructure, and roads), but also cost lives (Ashraf et al., 2012; Khanal et al., 2015; Watanbe and Rothacher, 1996). Their impacts increase economic burdens and can lead to psychological trauma, mental stress, and other health problems, especially in the elderly, women, and children (Ashraf et al., 2012), and ultimately also be a contributing factor to outmigration (Maikhuri et al., 2017). All those impacts will in turn adversely affect the livelihoods of mountain communities, particularly of poor and marginalized households (Mukherjee et al., 2019). The cryospheric changes and consequent hydrological change will also alter distribution range of mountain vegetation and wildlife (Lamsal et al., 2017; Xu et al., 2009).

Besides climate change, the HKH region has also witnessed social, cultural, and economic changes, which have created new livelihood opportunities as well as challenges (Wang et al., 2019). The nature of these changes and their impacts vary across the region. Globalization, changes in demography, governance systems, and institutions, and infrastructure development are the major social and economic drivers of changes in the mountains (Jodha, 2005; Wang et al., 2019). Increased connectivity, the growing influence of the state, market, and the international media, and the two-way flow of people have engendered new aspirations and interactions in communities in the HKH. On the other hand, some unique features of the mountains — traditional institutions and values, cultural practices, niche products, and social capital — that supported mountain communities for generations, have gradually disintegrated due to those factors and threaten the future development of the region (Bhatta et al., 2019; Jodha, 2005). Moreover, poverty and social marginalization are still serious issues in the region, and it is feared these will exacerbate with climate change, environmental degradation, and the weak governance system.

In the mountains, the cryosphere and socioeconomic systems closely interact. Such interactions between environment and human systems are complex, interdependent, and function through feedback mechanisms (Anderies et al., 2004; Berkes and Folke, 1998; Liu et al., 2007). The cryosphere influences stream flows, and the recharging of springs and lakes, which, in turn influences the ecology of local agricultural crops, forest vegetation, domestic animals and wildlife (Fountain et al., 2012; Xu et al., 2009). Agriculture, livestock rearing, and other livelihood practices, and the institutions, cultural beliefs, and practices of mountain communities have evolved through generations by adjusting and modifying local biophysical and social preconditions. For instance, customary institutions in the high mountains have historically operated and maintained irrigation networks by adapting to changes in glaciers (Nüsser and Schmidt, 2017). In addition to local preconditions, interactions between the systems are also influenced by external forces and shocks, such as globalization, or disasters (Vaidya et al., 2019; Wang et al., 2019).

The interactions between these two dynamic systems and feedbacks upon each other produce outcomes that vary spatially and need to be understood to avoid unexpected, perverse results (Liu et al., 2007). The system dynamic method is well-suited for understanding the complex interlinkages between the cryospheric and socioeconomic systems in the mountains. The system dynamics method is rooted in the theory of nonlinear dynamics and feedback and used for learning about complex systems (Sterman, 1994). Understanding of the complex interlinkages between cryospheric changes and socioeconomic changes, and their concomitant impacts on rural mountain livelihoods is critical to improving the adaptive capacities of local communities to climatic and social-ecological changes.

We acknowledge that complex interactions exist between the cryosphere, atmosphere, biosphere, hydrosphere, and lithosphere (Wang et al., 2019). However, it is beyond the scope of this study to analyse the interactions between all these spheres. This study focuses on services provided by the cryospheric system and analyses how changes in them have implications for the socioeconomic system of local communities in Langtang valley.

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004

2. Material and methods

2.1. Study site

Langtang Valley, a high mountain valley, is located in Gosaikunda rural municipality of Rasuwa district at 85°34′E and 28°12′N, about 60 km north of the capital Kathmandu. Its elevation ranges from 1300 m above sea level (m a.s.l.) to 7227 m a.s.l. at the peak of Mount Langtang Lirung. The valley is a glaciated catchment with clean and debris-covered glaciers. Permafrost and glaciers cover 46 km^2 of the valley (Bajracharya et al., 2014). The valley borders the Tibet Autonomous Region (TAR) of China to the north, Rasuwa district to the west and south, and Sindhupalchowk district to the east (Fig. 1).

The research was conducted in the five major settlement villages − Gompa Danda, Langtang, Mundu, Singdhum, and Kyangjing of Langtang Valley. There are 116 households over these five settlements, with a total population of 451 people. The valley is a largely homogenous community, as more than 80% of its population belongs to the Tamang ethnic group, practicing Buddhism (MoSTE, 2015). Traditionally, subsistence agriculture, pastoralism, and trade in medicinal herbs were the major livelihood options for the people. The villages are not accessible by road, and it takes at least two days' walk for the locals to reach the closest roadhead and market (at Syaphubesi) from their settlement. The government of Nepal, with the support of the Swiss government, had established a yak cheese factory in 1953 at Kyangjing to support local livelihoods. The area was declared part of the Langtang National Park in 1976, which had adverse impacts on the local people's traditional livelihood practices, particularly pastoralism and the trade in medicinal plants (McVeigh, 2004). However, with the expansion of tourism in Nepal, Langtang is developing as a tourist attraction due to its mountains and proximity to Kathmandu.

The valley was hit by a massive co-seismic avalanche, triggered by the huge earthquake of 25 April 2015 that devastated parts of Nepal. The earthquake triggered avalanches and landslides in numerous places, many accompanied by a tremendous blast of air (Kargel et al., 2016; Kunwar et al., 2019). In Langtang, the avalanche began from the southern slope of Mount Langtang Lirung and destroyed most of Langtang village and forest, along the path of air blast. The disaster claimed the lives of over 350 local inhabitants and tourists and over a hundred livestock animals (Kargel et al., 2016; MoSTE, 2015).

2.2. Data collection

The study uses the rapid rural appraisal (RRA) method, as the objective is to gain new insights, under time and budgetary constraints, into the complex and evolving linkages between a changing cryosphere and socioeconomic processes, in particular its effects on local livelihoods, rather than accurate and precise numbers. RRA is an appropriate method for learning about rural situations in an iterative and expeditious manner. It is defined as "any systemic activity designed to draw inferences, conclusions, hypotheses or assessments, including acquisition of new information in a limited period of time" (Grandstaff and Grandstaff, 1985).

For primary data collection, the techniques used were: unstructured interviews, key informant interviews (KIIs), group discussions, and direct observation. The data was collected from local villagers and key resource persons of the five settlements of Langtang valley during May June 2019. Interviews were carried out until there was data saturation (Saunders et al., 2018). Given the study area, and the homogenous nature of the community, a small sample size for the interviews was sufficient (Fusch and Ness, 2015). Twenty in-depth interviews were conducted, with nine female and eleven male participants, which included farmers, hotel owners, herders, a local shaman, porters, and members of mothers' group. A conscious effort was made to capture the voices of people belonging to different ages, genders, and occupations. The key informants for the study included local leaders, government officials, and researchers working in the area.

The interviews covered a wide range of topics, including livelihoods, community vitality, spirituality and religious beliefs, the importance of the cryosphere's contributions, the effect of the changes observed over time on livelihoods, ecosystems, and the impact of human activities on the cryosphere and the overall environment. Apart from the individual interviews, a group discussion was held with 21 participants from the study area. The discussion was around the community's way of life and the environment around them. A timeline mapping of major events including natural disasters, and mapping exercises regarding the livelihood calendar (Appendix Table A1) were carried out during the group discussion and individual interviews. For secondary data, research papers on the issue and published government data and statistics were used.

2.3. Method

The collected data was analysed using causal loop diagram (CLD) and system archetype to explore the dynamic, complex interlinkages within and between the cryospheric and socioeconomic systems in Langtang, Nepal. CLD is one of the diagrammatic tools used in system dynamics to capture the structure and feedbacks of the system (Sterman, 2000). Systems archetype is another diagnostic tool used for understanding behavioural patterns that emerge from the system to reveal insights into its structure and also detect potential problems (Braun, 2002; Kim and Anderson, 1998).

For the purpose, a conceptual model was mapped using the CLD technique with the help of Vensim® software. The study used CLD to understand direction and relationships between variables, but without quantifying their relationship. The causal links between, and influence of the independent variables (influencer) on dependent variables (influenced) are denoted by the arrows connecting them (Fig. 2). The variable from which the arrow originates is the independent variable

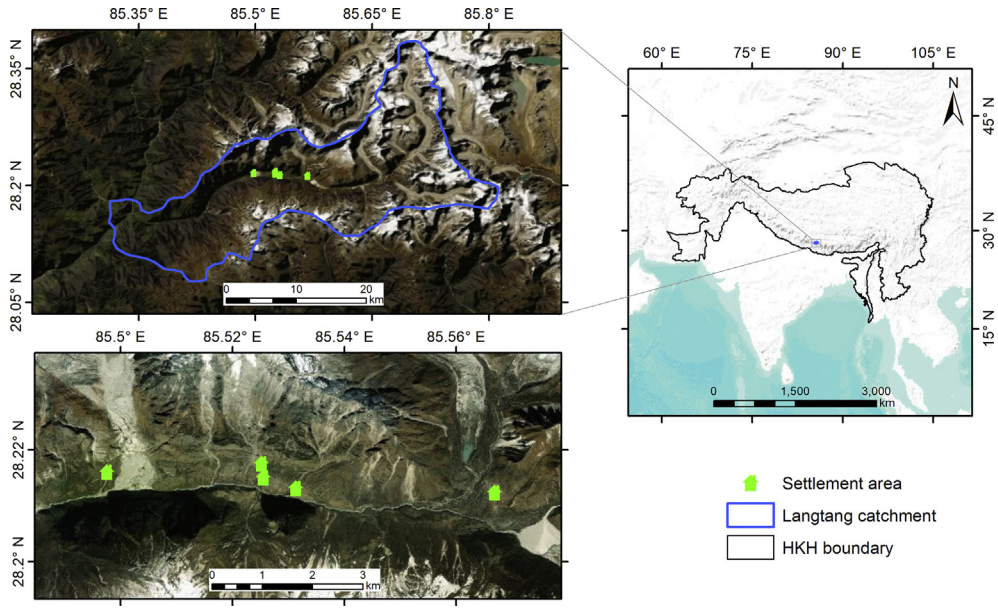


Fig. 1. Map of the study area.

and the variable to which the arrow points to is the dependent variable. The relationship between two variables may be positive or negative, indicated by positive (+) or negative (−) signs. They indicate how changes in the independent variable alter the dependent variable. The links and signs describe the structure of the system but not the behaviour of the variable. Reinforcing (positive) and balancing (negative) loops in the system are indicated by 'R' and 'B' respectively, inside a loop identifier, (↻), which circulates in the same direction as the corresponding loop.

The CLD models were based on authors' judgement and were validated with researchers working in the area, key informants, and secondary literature on the area. Follow-up research is underway for model simulation.

3. Results

3.1. Local livelihoods

Local livelihoods in Langtang valley revolve around three major sources, namely, farming, livestock rearing, and tourism. All the sources of livelihood are closely linked with the cryospheric system and their success is dependent on it. During winter (December−February), most people migrate to the district headquarters, Dhunche, or to Kathmandu and return to Langtang after February.

Barley, buckwheat, and potato are the major food crops grown in Langtang Valley. Farming here is dependent on snowmelt water. Farming activities usually start in March and end in October. Livestock rearing is both a vital source of income and of nutritional security for the local population. Yaks and their hybrid, horses, sheep, and mules are the major kinds of livestock bred by people in Langtang Valley. The milk, milk products, and the meat from yaks and their hybrid are vital sources of protein for the local population. The sale of yak milk to the cheese factory in Kyangjing is an important source of income to the locals. The hair and skin of yaks and sheep are used for clothing. Since the local community follows Buddhism, the slaughtering of animals is not permitted in the villages. Only the carcasses of yaks, their hybrids, and sheep that have died from natural causes are consumed as food.

In the past, the locals used horses mainly for carrying patients from villages to the nearest roadhead at Syaphubesi. With the growth in tourism in recent years, horses provide amenities as well as emergency services to the tourists. Sheep and mules are mainly used for the transportation of food and building materials.

Due to the local microclimatic conditions, the locals practise transhumance pastoralism for yaks, their hybrids, and sheep. Transhumance pastoralism is a labour-intensive livelihood strategy, as household members need to accompany the animals to winter and summer pastures and are away from home for most of the year. The cold habitat provided by the cryosphere is important for the survival of yaks, yak hybrids, and sheep.

Tourism is another important source of livelihood in Langtang, even more so after the 2015 disaster. The beautiful mountain peaks, glaciers, and the unique local culture are major attractions for tourists. Tourism in Langtang has two major seasons, from March to early June, and from October to December. At present, more than 90% of the households in the valley are involved in tourism-related activities. Tourism activities and services in Langtang include hotels and tea houses, guides, porters, and cooks. More than 1500 tourists visit Langtang National Park during the peak months (MoTCA, 2019).

Besides farming, pastoralism, and tourism, some households are also engaged in the collection of non-timber forest products (NTFPs), including *Ophiocordyceps sinensis*, a kind

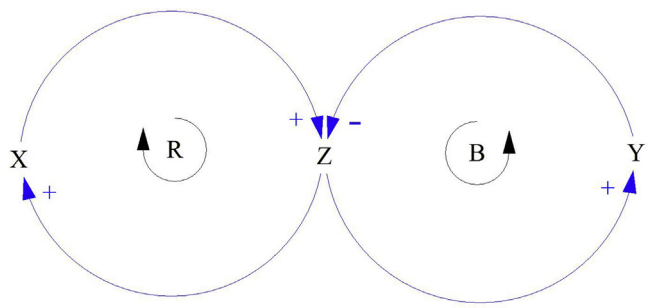


Fig. 2. Model of causal loop diagram used.

of fungus used in traditional medicine (known locally as *yarsha gumba*). The locals collect NTFPs mostly for domestic use rather than for trading. A few women in the valley are also engaged in creating handicrafts such as yak wool products. However, these practices were reported to be on the decline as most garments are now being imported from outside the valley. All these additional activities are usually carried out during the months when engagement in tourism, farming, and livestock rearing is low.

Remittances from household members who have migrated abroad have become another important source of income for the locals. People from here have migrated mostly to Europe, while a few people are in Gyirong, China, across the border. They had migrated for higher education, employment, or marriage.

In recent years, there has been rapid infrastructure development in the area. A road connecting Langtang and Syaphubesi is under construction but may take many years to complete. Non-governmental organizations (NGOs) have constructed a drinking water supply system and a micro-hydropower unit with a capacity of 120 kW, which supplies water and electricity to all five settlements. Telecommunications services are widely available in the valley. The only primary school in the valley was completely damaged during the 2015 earthquake, and its reconstruction was under way at the time of data collection. Consequently, most of the local children were being sent to Dhunche or Kathmandu for their education.

3.2. Impacts of a changing cryosphere

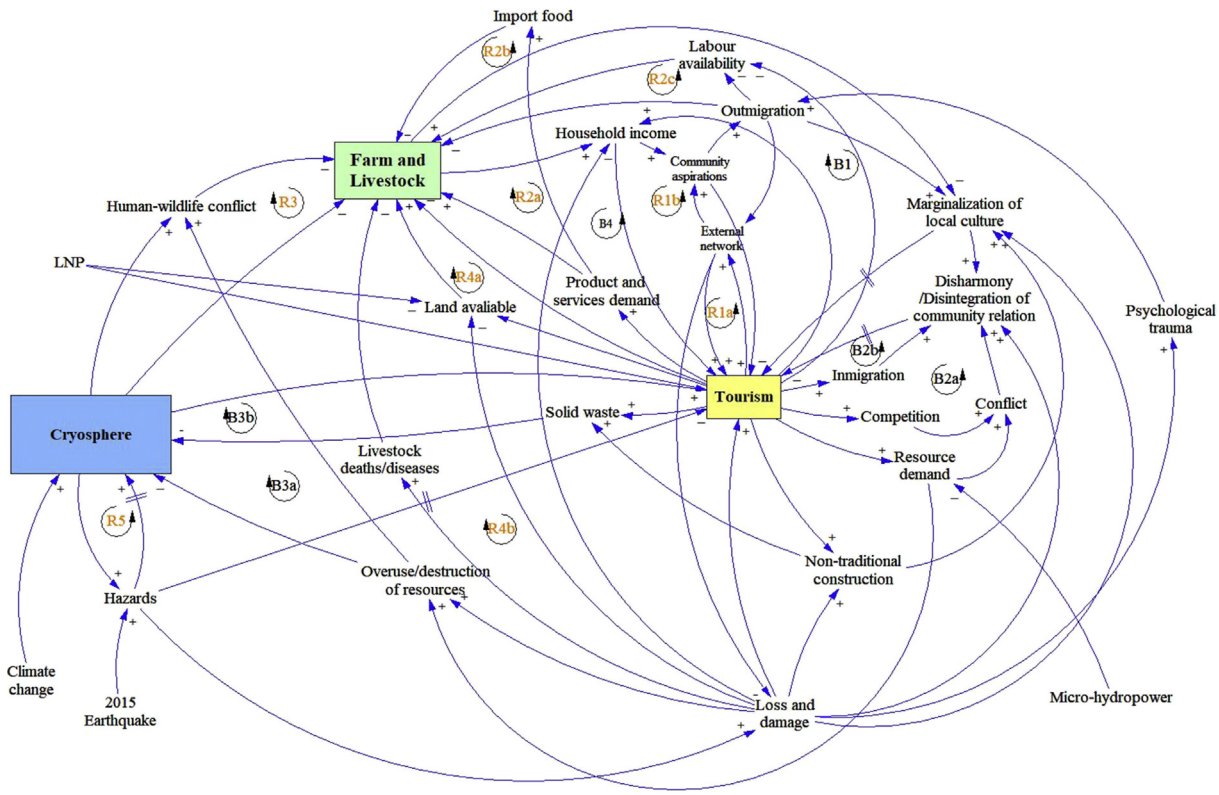
All the interviewees in Langtang (100%) were unequivocal about nearby glaciers having receded, particularly Khimsung and Yala glaciers. Khimsung glacier, they said, used to be brighter and closer to their houses but in recent years the glacier had become darker and retreated upward and displayed exposed bedrock. During a group discussion, the study team showed members of the local community photographs of the Yala glacier taken in 1982, 1996, 2008, and 2017. Seeing the changes in the glacier, all the participants stated that while they were aware about the shrinkage in the glacier, they but did not know that it had happened on such a large scale. The Yala glacier monitoring measurements from 2011 to 2017 show that the glacier has been rapidly losing mass, with an average annual mass balance of -0.81 ± 0.27 m w.e. per year (Acharya and Kayastha, 2019). It retreated 354 m since 1974, with an annual average retreat rate of 8 m per year (WGMS, 2020).

In general, the local community was less worried about changes in the glaciers and more concerned about changes in snowfall patterns. They were of the opinion that the existing glaciers would be sufficient to supply water for the next two generations and that it was futile to worry beyond that. The interviewees also reported that there has been a gradual decline in overall snowfall during the last 15 years, but an increased incidence of untimely, heavy snowfall. In the past, they had snowfall only in *Poush* (December–January) and *Magh* (January–February), but more recently snowfall had been occurring from *Falgun* (February–March) to *Baisakh* (April–May).

The interviewees related this untimely snowfall with the occurrence of avalanches, which had also increased over the last ten years. Local communities here distinguish between two forms of avalanches: *khari*, which is the sliding of dense snowpack with rocks, and *khaiyu*, which is a suspension of snow in the air. According to them, *khaiyu* are less devastating than *khari*. They regard the avalanche after the 2015 earthquake as an instance of *khari*. Other *khari* had occurred in 1997, 2011 (near Singdhum), and 2019 (near Mundu). The *khari* in 1997 killed only livestock, the one in 2011 killed two people, and there were no casualties in 2019. Local communities recount that *khaiyu* have caused helicopter crashes, the death of animals, and damage to a few hotels.

Untimely snowfall has also been reported to cause crop failure. For instance, the farmers sowed potato seeds in late Chaitra (mid-April) but snowfall and the melting of snow in *Baisakh* (April–May) washed away the sowed seeds in recent years. The untimely, heavy snowfall also resulted in water and food shortages, particularly for yaks, resulting in the mass deaths of the animals in 2014, 2018, and 2019. The locals believe that the untimely and heavy snowfall in March 2015 was responsible for the avalanche and snow blast triggered by the 2015 earthquake. The meteorological data and digital elevation models (DEMs) confirm that the accumulation of anomalous snowfall between October 2014 and April 2015 largely contributed to the avalanche (Fujita et al., 2017). The disaster had buried the new part of Langtang village, destroyed the old Langtang village (by the air blast), and killed over two-thirds of the livestock population. It also led to significant loss of life leading to loss of traditional knowledge and skills regarding religious rituals, agriculture, herding, carpentry, and crafts. This had immense adverse impacts on their livelihood and culture. After the earthquake, the villagers had been forced to build new settlements in former farming lands and on the site of the old Langtang village. The 2015 earthquake also resulted in the deaths of 40 tourists from 14 countries. Tourist arrivals had still not reached pre-2015 levels at the time of data collection.

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004



Note: ➡: direction of influence; '+': positive effect; '−': negative effect; ◯: loop; R: reinforcing loop; B: balancing

Fig. 3. Cryosphere and society linkages in Langtang.

3.3. Cryosphere and society: linkages, drivers, and feedbacks

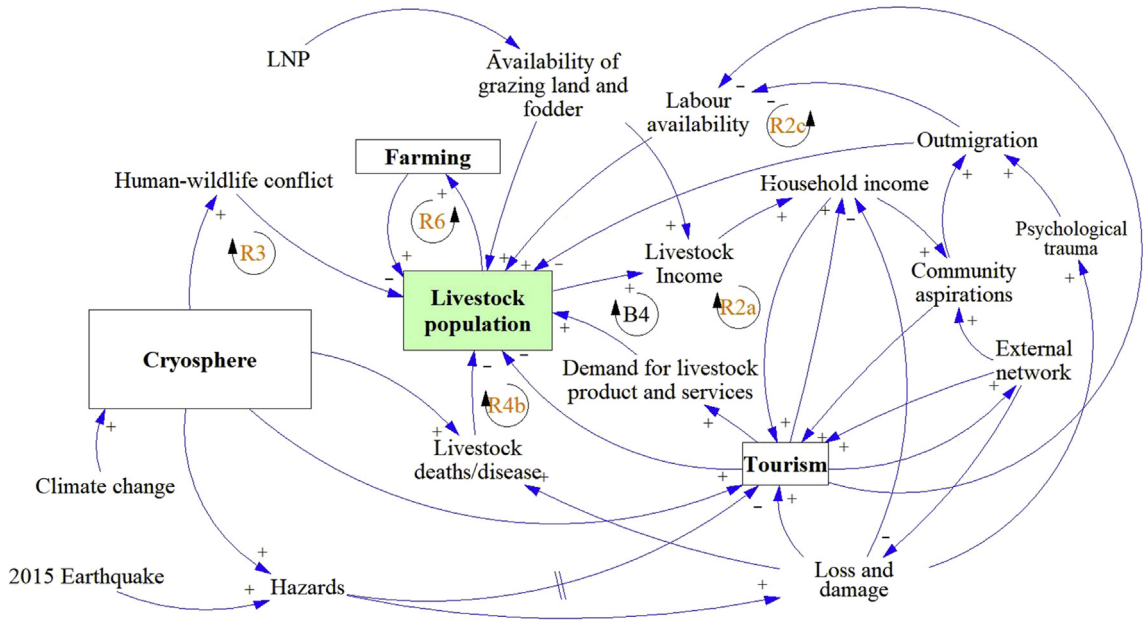
There is a complex interaction between the two dynamic systems (the cryospheric and the socioeconomic systems) in Langtang, which produces a series of feedbacks. While the two systems are constantly influencing various components within, they are also influenced by external factors such as climate change and globalization. These influences have both positive and negative effects on Langtang's system. Fig. 3 depicts the complex interlinkages between the various components of the two systems in Langtang Valley. The feedbacks (Table A2) and causal links (Table A3) in the system show several prominent trends – the growing tourism economy, the declining trend in high mountain farming and livestock rearing, increasing outmigration, and the growing disconnect between the local society and the cryosphere. These feedbacks and their drivers are explored from a socioeconomic point of view by dividing the system into three livelihood-based subsystems: the livestock rearing sub-system, the farming subsystem, and the tourism sub-system.

3.3.1. Livestock rearing sub-system

Traditionally, agriculture and livestock rearing used to be the main sources of livelihood for the local community (McVeigh, 2004). However, this study's findings show that the proportion of households engaged in livestock rearing has declined to 30% of the total number of households. The examination of the CLD shows that there are five reinforcing loops driven by four factors that are causing this decline (Fig. 4).

The first driver of change has been the climate change observed in the area – changes in snowfall and rainfall patterns and increases in temperature (Shea et al., 2015). Untimely, heavy snowfall – along with the gradual decline in overall snowfall in recent years – has been causing fodder and water shortages for livestock for weeks, resulting in the death of a large number of animals. Moreover, untimely heavy snowfall has also contributed to avalanches and landslides killing a large number of animals – over a thousand are reported to have been killed in the 2015 disaster. Interviewees also reported an increase in the occurrence of disease in livestock with increases in temperature.

The second driver has been a decline in the local labour force available for livestock rearing. The 2015 disaster killed a number of people with traditional knowledge and skills of herding. At the same time, a large number of local residents have been shifting to tourism, as it is viewed as more lucrative and less labour intensive than livestock rearing. Additionally, the interaction of locals with foreign tourists visiting the area has influenced the aspirations of the local people, particularly of the youth. The changes in



Note: → : direction of influence; '+': positive effect; '−': negative effect; ↻ : loop; R: reinforcing loop; B: balancing loop

Fig. 4. Livestock sub-system of Langtang Valley.

aspirations and the creation of external networks (through the foreign tourists) has resulted in an increasing trend of out-migration of local youth, causing labour shortages in the valley.

With the growth of tourism in Langtang, locals have shifted from sheep to mules for the transportation of goods. The shift was also partly in response to fodder and labour shortages for sheep herding. Additionally, with the growing modernization and tourism in the area, the demand for packaged foods, bottled water, building materials, and other products increased, whereas sheep were traditionally used only for carrying salt, medicinal plants, and wares (McVeigh, 2004).

There are also a few balancing factors, such as the demand for yak products and the transportation of goods, that have encouraged households to continue livestock rearing. However, the reinforcing factors have a stronger influence than the balancing ones.

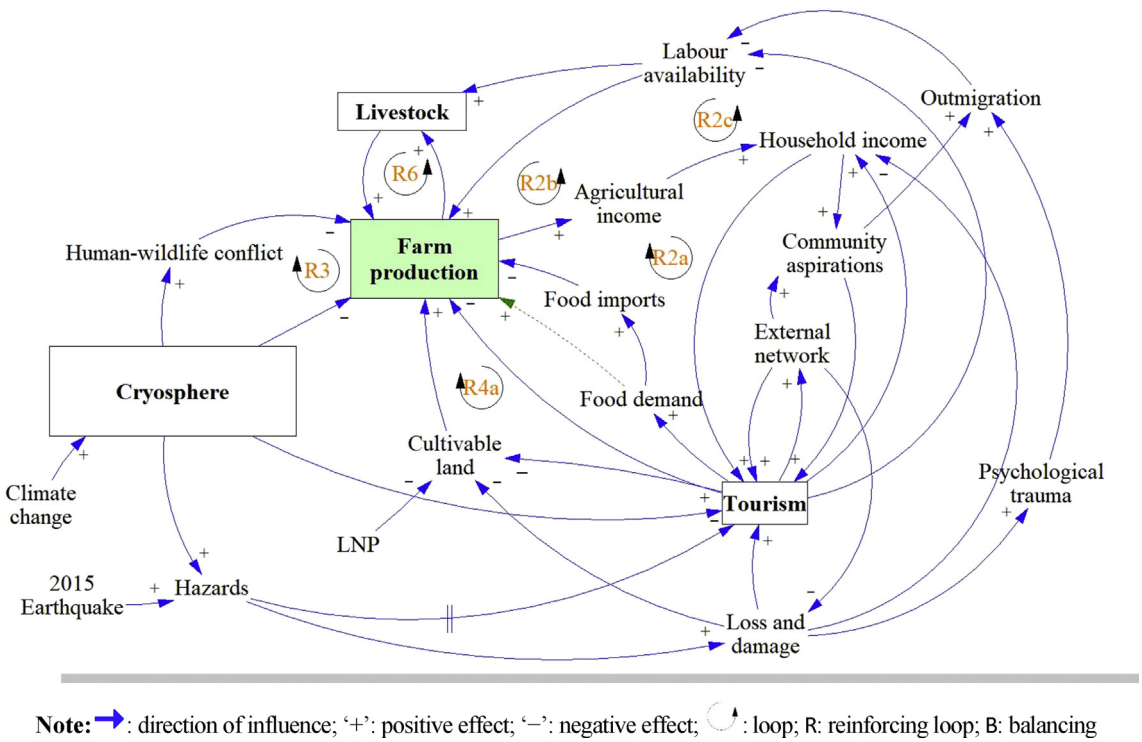
3.3.2. Farming sub-system

The number of households involved in crop farming has declined, with large parcels of farming land abandoned, particularly after the 2015 earthquake. Less than 10% of the total number of households in the valley reported engaging in farming. The highland farming system in the Langtang village has declined due to six reinforcing cryospheric and socio-economic loops (Fig. 5). There are no balancing loops we could identify.

Changes in the cryosphere due to climate change have had a seriously negative impact on highland farming. The changes in precipitation patterns and temperature have increased the incidence of disease and pests in crops, and of crop failure. Households still engaged in farming have shifted from traditional food crops such as barley and buckwheat to vegetables, such as leafy vegetables, cabbage, radish, carrot, coriander, garlic, and mustard. The climatic conditions in Langtang are not suitable for most vegetables, but advancements in agricultural technologies have made growing vegetables possible. We observed this decline in traditional foods ourselves during our field trip, as they were rarely offered by the hotels in their menu. The only occasion the study team was offered a local dish was by a local woman while visiting her home for an interview. The reduction in farm production has been substituted by imported foods such as rice and *dal* (lentils), which were not grown locally.

Changes in the cryosphere and the rise in average temperatures gradually expanded the habitat of wild boars up to Langtang settlements. Before the 2015 earthquake, the walls surrounding the agricultural fields were effective in preventing wild animals from entering. Following the disaster, the walls had been either completely destroyed, or their height reduced by damage and hence not enough to prevent the wild animals from entering, resulting in an increase in the incidence of crop foraging and losses. Lastly, climatic changes, including that related to the 2015 avalanche, had increased the perception of risk attached with continuing agricultural practices.

The changes in farming were further exacerbated by three major reinforcing socioeconomic factors – tourism, out-migration, and the decline in livestock. The growth of tourism is the most influential socioeconomic driver in the Langtang system. Although the number of tourists has grown, the demand for traditional food items or local products has not grown accordingly. The hotels and tea



Note: ➡: direction of influence; '+': positive effect; '−': negative effect; ↻: loop; R: reinforcing loop; B: balancing

Fig. 5. Farming sub-system of Langtang valley.

houses import food items based on their assumptions about the preferences of visiting tourists. This has further discouraged farming.

Another factor reinforcing the decline in farming is the lack of labour availability. The loss of life in the 2015 disaster, particularly of elders with traditional knowledge about farming, decreased the overall available labour force. As with livestock rearing, many households prioritized investing their limited human and financial resources in tourism after the 2015 earthquake and avalanche, particularly setting up tea houses. More farmers find farming less profitable than tourism. This finding of ours is supported by that of Ojha et al. (2017). Besides profitability, local people believe that engaging in tourism helps them to build their external social networks, which played an important role in recovering from the 2015 disaster. The outmigration of local youth for higher studies and work has also reduced the availability of labour.

Additionally, livestock manure is the only source of soil nutrients/fertilizer available in Langtang. Yaks and their hybrids were used for ploughing. The decline in the livestock population and of households involved in livestock rearing, discussed above, has had a negative effect on Langtang's highland farming practices.

At present, there are no balancing loops active in the system that can reduce the negative influences of the reinforcing loops. An increased demand for local food products could be an important balancing factor, but this has been limited due to the practice of importing food. Based on this trend, we can expect an exponential decline of the highland farming system in villages in Langtang Valley in the future.

3.3.3. Tourism sub-system

Tourism has emerged as the most important livelihood subsystem in Langtang, with direct and indirect influences on the other two sub-systems and on the Langtang system overall. Based on the CLD of Langtang's tourism sub-system, this study has identified seven reinforcing loops and five balancing loops. Most of the strong reinforcing loops that are actively driving changes in tourism here are caused by socioeconomic changes that are in turn triggered by the cryospheric changes (Fig. 6). Tourism, which had been steadily rising as an occupation in the past few decades, accelerated after the massive earthquake in 2015. The locals have realized the risks associated with farming and livestock breeding due to the changes in the cryosphere. They view the tourism business as relatively less risky and more profitable.

With growing tourism, the exposure of locals to external networks also expanded. Consequently, many locals migrated or opted out of farming and livestock-based occupations. Moreover, the households that were engaged in tourism prior to the 2015 disaster received more support from their external networks than other households. This experience further lured others to shift to tourism.

The growth of tourism also led to previously cultivable land being converted to built-up areas. This is because the government does not allow locals to expand their cultivable or built-up areas, nor to purchase new land for private uses, since Langtang villages are located inside a national park. There was also a delinking between the growth in tourism and the demand for local food crops. All these reinforcing factors were strong enough to transform the tourism sub-system from a

secondary source to being the primary source of employment and income.

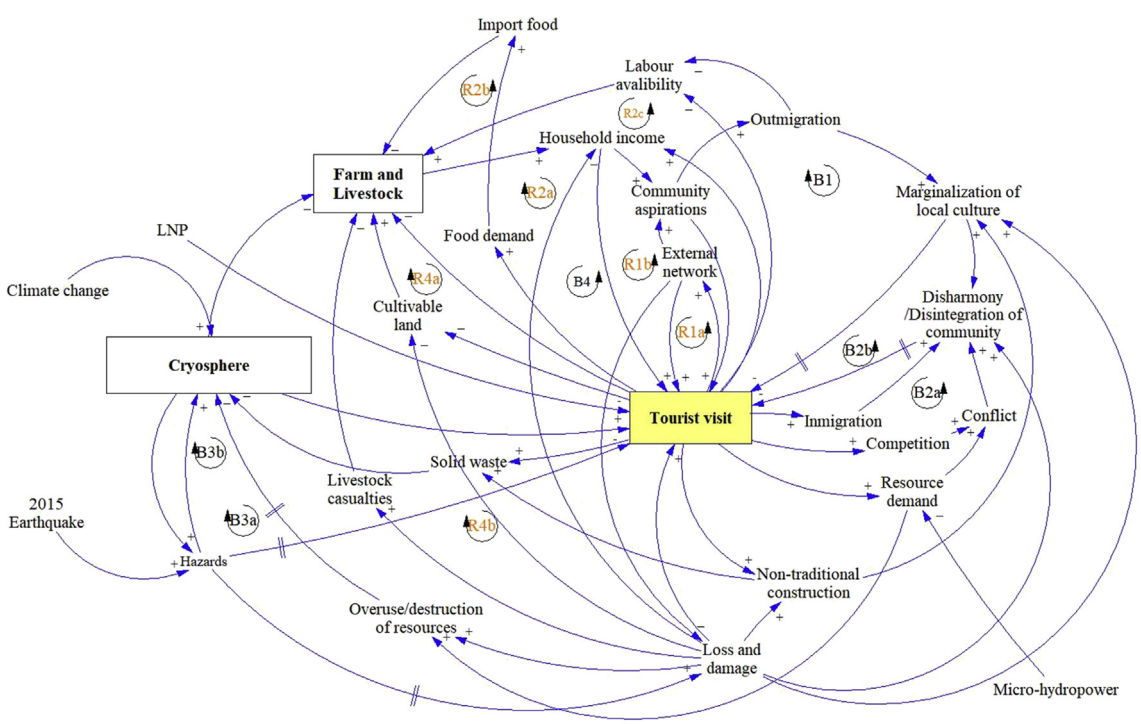
There are also many balancing loops in operation that could damage or even destroy tourism in Langtang, despite the existence of reinforcing loops that promote it. This study has identified five cryospheric and socioeconomic balancing factors (Table A2).

Members of the local community acknowledge that glacier- and snow-covered mountains, the local culture, and local ecosystems are the main attractions for tourists visiting Langtang Valley. However, some of the things that contribute to the local cultural identity and appeal have been increasingly ignored by the community. The traditional architecture has been replaced with new buildings made of concrete, with modern amenities. The community has not gathered together and celebrated annual festivals such as Langshisha and Dhupa Chhiju for the last few years, as they used to. An elder of the community reported that the community used to come together and organise events and prayers in the past but now people prefer to remain within the confines of their homes. Community traditions, culture, and community vitality in the area had weakened resulting in a loss of social capital.

The growth in the number of tourists also increased the demand for natural resources such as water and fuelwood. People did not report water shortages but they indicated a scarcity of fuelwood, and the degradation of the nearby dense forests into becoming a sparse forest. With the decline in forest cover, the locals also reported a decrease in the sightings of wildlife such as the Himalayan *tahr*, the Himalayan *monal*, and the snow leopard. With the growing tourism business, solid waste was becoming a major environmental problem in the area. Plastic bottles, wrappers, and beer and whisky bottles were littered along the trekking routes near the villages. Locals too dump the growing solid waste into the Langtang river or nearby streams. Mules used for transporting goods leave behind a trail of dung. The environmental degradation might decrease the appeal of this region, reducing its ability to draw tourists.

In order to cater the needs of tourists, many local hoteliers have hired cooks and other staff from other parts of Nepal. An increasing number of migrants into the valley may negatively affect the traditional culture, and knowledge in the area. The influx of immigrants into a society that historically does not have any experience of coping with immigrants may create disharmony. An increase in the competition for tourists, limited available resources, and the inability to cope with the rapid social changes taking place might cause conflict and disharmony in the Langtang community. Some local respondents also shared the feeling of inequality among local inhabitants due to the differences in aid and support received by the agro-pastoral income-based households, and those deriving income from tourism. Ignoring social capital and local culture, which could have been a strong reinforcing factor for the growth of tourism, may contribute to its decline.

The receding of glaciers and the reduction in snow cover in the mountains also pose a serious threat to tourism in the long term. Climate change is likely to cause an increase in the frequency of cryosphere-related hazards such as rockfalls and



Note: → : direction of influence; '+': positive effect; '−': negative effect; ◯ : loop; R: reinforcing loop; B: balancing

Fig. 6. Tourism sub-system of Langtang valley.

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004

avalanches, and changes in the hydrological regime. Interestingly, the locals were hesitant to report any hazardous incidents to the media and the governmental agencies, out of the fear that tourists would then refrain from visiting Langtang. They also had doubts about the capacity of the government agencies to respond to or mitigate these disasters.

The reinforcing loops for the tourism sub-system are very strong currently. This has resulted in unsustainable sociocultural changes, leading to an increasing number of households shifting to tourism. There are balancing loops present, but have not come into effect yet due to their delayed nature. In the long run, the latter will become stronger than the reinforcing loops and might cause significant damage to tourism in the region.

4. Discussion

This study shows that livelihoods in Langtang are closely linked with the surrounding cryosphere system. As with other mountainous areas of the Nepalese Himalaya, the local community in Langtang are experiencing the impacts of climate change (Manandhar et al., 2011, 2012). In the mountains, snow is an important source of moisture and nutrition (Paudel and Andersen, 2011) for agriculture and pastoralism. Which is why members of the local community were particularly concerned about the untimely snowfall in recent years rather than the rapid receding of glaciers, as the former have induced landslides and avalanches. The huge avalanche triggered by the 2015 earthquake is perceived as an immediate impact of the changing cryosphere, whereas locals understand that the impacts of the disappearance of glaciers will be felt some time into the future.

Natural hazards are not new to mountain communities in the HKH region, but climate change, including cryospheric changes, have increased the frequency of hazardous extreme events here (Vaidya et al., 2019; Wang et al., 2019). In response to changes in snowfall patterns, mountain communities have responded autonomously by adopting adaptation measures such as changes in crops and cropping patterns. However, they lack the resources to mitigate the growing number of disasters triggered by the changes in the cryosphere (Rasul et al., 2019).

The three CLDs of Langtang's livelihood sub-systems demonstrate a clear trend of a decline in farming and livestock rearing, while tourism shows exponential growth. These trends are an outcome of the multiple, strong reinforcing loops mainly triggered by climate change, outmigration, labour shortages, and globalization. Due to a shift from a subsistence economy to a market economy, traditional livelihood practices across the HKH region have declined over the years (Wang et al., 2019). Globalization and an increase in connectivity have helped tourism and labour migration to flourish in the HKH, which have diversified livelihoods and increased households' cash incomes (Nepal and Nepal, 2004; Padoa-Schioppa and Baietto, 2008). Infrastructure and services development such as water supply and telecommunications, along with the diversification of sources of income, can help communities minimize the systemic threats caused by changes in climate and the cryosphere (Fu et al., 2012).

When analysing the behavioural patterns of the livelihood systems, a two-system archetype – of growth and underinvestment, and the generation of accidental adversaries – emerges (Braun, 2002). In earlier times, both farming and tourism-based households began with a win−win situation, with both parties striving for economic betterment. For this situation to continue, the interdependence of the two sets of households is critical, whereby one sector provides inputs, materials, or generates demand for another sector and there is less competition in shifting from one sector to another. The farming and livestock sectors could provide the tourism sector with local food and culture; and the tourism sector in turn generates greater demand for agricultural products and the maintenance of traditional culture. However, such a complementary system has not evolved in many rural areas of the region, including in Langtang.

Despite the positive impacts of tourism on mountain livelihoods, it has given rise to serious issues relating to social harmony, traditional culture, and the environment (Aryal et al., 2018). Instead of boosting traditional food crops, the tourism sector created demand for imported food items, with adverse impacts on farming and livestock rearing households, and on the local culture. This will in turn likely lead to a decline in tourism in the future, and hence the accidental adversaries archetype.

Additionally, the growing tourism industry needs investments to build on and sustain its growth. However, the local community has not invested in the management of local resources and the ecosystem, maintenance and preservation of the community, in local traditions and culture, agriculture, and livestock rearing, all of which are especially important for tourism in high-mountain regions. The lack of investment in these environmental and socioeconomic facets of the system will ultimately disrupt the growth trends in tourism, and nudge it into decline, hence illustrating the growth and underinvestment system behaviour.

It is clear that, without proper intervention, all the three important livelihood sources, community and cultural vitality, and the ecosystem in Langtang are headed on the path of decline. There are five issues that require intervention for strengthening linkages between cryosphere and the socioeconomic system of Langtang. First, the trend of the community adopting homogenous livelihoods needs to be addressed. There needs to be a rediversification and close integration of different livelihood sources in order to build the economic resilience of households, and in turn the local community. One way of achieving this is by promoting the demand for traditional crops such as buckwheat and barley and livestock products in the tourism sector.

The second issue that needs to be addressed is the decline in local ecosystems. The locals are aware of the importance of the ecosystem's contributions to their livelihoods, but have largely ignored the hazard of overharvesting finite resources. Along with resource management, it is equally important to address the issue of waste management.

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004

Third, the decline in local traditions and culture needs immediate attention and a redressal mechanism, to ensure the continuation of a vibrant tourism sector. Awareness needs to be generated about the importance of nature and culture for a community dependent on tourism.

The fourth issue is the decline in social capital. The decline in local traditions and culture also reflect a decline in social capital. Community bonding has declined in the past decade as a result of the socioeconomic changes and cryospheric disservices. Mountain communities such as in Langtang valley are heavily dependent on their social capital and structure to cope with shocks. Hence, there is a strong need to rebuild community vitality to augment their resilience, particularly in a context of an increasing occurrence of hazards and shocks due to a changing climate.

Lastly, there is a strong need for hazard risk assessment and management. Presently, there is a tendency to not report or underreport the occurrence of natural hazards in fear of deterring tourists from visiting. Together with slow onset changes, there has been, as has been stated, an increase in the frequency and intensity of hazards triggered by climate change. Thus, rather than ignoring it, there is an urgent need for members of the community to come together and tackle these climate change-driven issues with the support of the local government and other relevant stakeholders. The locals expect the growing trend of tourism to continue and over time to move into goal-seeking behaviour in which there will be a steady flow of tourists and sustained tourism industry in the area. Although the reinforcing loops are presently strong and actively influencing the socioeconomic and cryosphere system, there are equally strong balancing loops in action caused by cryospheric changes, the growth of the tourism industry, unsustainable resource demand, increasing pollution, and the marginalization of local community and culture. At present, the effects of the balancing loops are not that obvious, as they will occur with a substantial delay. But once they take effect, we expect a sharp decline in the number of tourist arrivals and in the income from tourism.

5. Conclusions

This study explores the linkages between the cryosphere and high-mountain livelihoods through the social–ecological system approach and examines how the complex linkages in a village in Langtang Valley has evolved in response to both cryospheric and socioeconomic changes. Local communities have observed gradual but significant changes in the cryospheric system, such as receding glaciers, changing snowfall patterns, growing incidence of hazards, and changes in temperature and precipitation. Though the local community has contributed little to the changing cryosphere, they face the impacts of such changes most directly and severely. The study shows that the cryosphere and livelihoods of people are closely interlinked; any change in the cryosphere has immediate impacts on local lives and livelihoods. This was experienced by the local community in 2015, when the huge earthquake triggered an avalanche and snow blast. This disaster resulted in a huge loss of life, livelihoods, and damage to infrastructure in Langtang valley.

As a result of changes in both the cryospheric system and the socioeconomic system, there is an increasing disconnect between them. The livelihoods of local people are slowly concentrating in the tourism sector, unlike the diversified livelihoods that prevailed in the past. A number of cyrospheric and socioeconomic factors are responsible for this gradual shift in livelihoods. This homogenization of livelihoods in a fragile and vulnerable mountain community might make the overall social-ecological system in Langtang more vulnerable over the long run for instance during the COVID-19 pandemic. The loss of traditional knowledge of crop farming, livestock breeding, and herding can have long-term impacts. Traditional knowledge is transferred and built upon from one generation to another, but with the younger generation giving up farming altogether, this knowledge system may be lost altogether. Local communities used to observe the cryosphere closely as their livelihoods were dependent on it, but with the decline in traditional livelihoods, the interest in the cryosphere has also declined.

Among the cryospheric changes, the changes in snowfall patterns and intensity is of immediate concern for the local community, as its impacts are immediate and can be severe. Local communities perceive that changing snowfall patterns, particularly heavy snowfall in the warmer months (April–May), are the major cause of both disruption to local livelihoods and of cryospheric hazards such as avalanches. Locals feel that the incidence of hazards has increased over the last decade, particularly of *khari*, the sliding of snowpack with rocks. However, there is presently no system in place of hazard risk assessment and management, which poses great risks for local lives and livelihoods.

Finally, we propose five areas for intervention – pertaining to livelihoods, the damage to local ecosystems, the decline in traditions, in social capital, and hazard risk assessment – for building resilience of the socioeconomic system of Langtang.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

We extend our sincere thanks to two anonymous reviewers and editor for their constructive comments. We also benefited from discussions and comments from Anna Sinisalo (GRID-Arendal) and Sharad Joshi (ICIMOD). We would also like to acknowledge Amrit Thapa (ICIMOD) and Prashant Thapaliya (ICIMOD) for preparing the map and Nagraj Adve for language editing. This study was supported by the Cryosphere Initiative at the International Centre for Integrated Mountain Development (ICIMOD). The initiative is supported by Ministry of Foreign Affairs, Government of Norway and the Swiss Agency for Development and

Cooperation. Also, core funds of ICIMOD supported the study. The views and interpretations in this publication are those of the authors and are not attributable to the ICIMOD.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2020.12.004.

References

Acharya, A., Kayastha, R.B., 2019. Mass and energy balance estimation of Yala glacier (2011−2017), Langtang valley, Nepal. Water 11 (1), 6. https://doi.org/10.3390/w11010006.

Allison, E.A., 2015. The spiritual significance of glaciers in an age of climate change. WIREs Clim. Change 6 (5), 493−508. https://doi.org/10.1002/wcc.354.

Anderies, J.M., Janssen, M.A., Ostrom, E., 2004. A framework to analyze the robustness of social–ecological systems from an institutional perspective. Ecol. Soc. 9 (1), 18. https://doi.org/10.5751/ES-00610-090118.

Aryal, S., Cockfield, G., Maraseni, T.N., 2018. Globalisation and traditional social-ecological systems: understanding impacts of tourism and labour migration to the transhumance systems in the Himalayas. Environ. Develop. 25, 73−84.

Ashraf, A., Naz, R., Roohi, R., 2012. Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan ranges of Pakistan: implications and risk analysis. Geomat. Nat. Hazards Risk 3 (2), 113−132. https://doi.org/10.1080/19475705.2011.615344.

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., et al., 2014. Glacier status in Nepal and decadal change from 1980 to 2010 based on Landsat data. ICIMOD, Kathmandu. https://lib.icimod.org/record/29591.

Bajracharya, S.T., Maharjan, B.S., Shrestha, F., et al., 2015. The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. Int. J. Water Resour. Dev. 31 (2), 161−173. https://doi.org/10.1080/07900627.2015.1005731.

Berkes, F., Folke, C. (Eds.), 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge.

Bhatta, L.D., Shrestha, A., Neupane, N., et al., 2019. Shifting dynamics of nature, society and agriculture in the Hindu Kush Himalayas: perspectives for future mountain development. J. Mt. Sci. 16 (5), 1133−1149. https://doi.org/10.1007/s11629-018-5146-4.

Bolch, T., Shea, J.M., Liu, S., et al., 2019. Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In: Wester, P., Mishra, A., Mukherji, et al. (Eds.), The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Springer, Cham, pp. 209−255. https://doi.org/10.1007/978-3-319-92288-1_7.

Braun, W., 2002. The system archetypes. System.

Fountain, A.G., Campbell, J.L., Schuur, E.A.G., et al., 2012. The disappearing cryosphere: impacts and ecosystem responses to rapid cryosphere loss. Biosci. 62 (4), 405−415. https://doi.org/10.1525/bio.2012.62.4.11.

Fu, Y., Grumbine, R.E., Wilkes, A., et al., 2012. Climate change adaptation among Tibetan pastoralists: challenges in enhancing local adaptation through policy support. Environ. Manag. 50, 607−621. https://doi.org/10.1007/s00267-012-9918-2.

Fujita, et al., 2017. Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal. Nat. Hazards Earth Syst. Sci. 17, 749−764. www.nat-hazards-earth-syst-sci.net/17/749/2017/doi:10.5194/nhess-17-749-2017.

Fusch, P.I., Ness, L.R., 2015. Are we there yet? Data saturation in qualitative research. Qual. Rep. 20 (9), 1408−1416.

Grandstaff, T., Grandstaff, F., 1985. Report on rapid rural appraisal activities. International Conference on RRA. September. Khon Kaen University, Thailand.

Gurung, D.R., Giriraj, A., Aung, K.S., et al., 2011. Snow-cover mapping and monitoring in the Hindu Kush-Himalayas. ICIMOD, Kathmandu.

IPCC, 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York. https://www.ipcc.ch/report/ar5/wg2/.

IPCC, 2019. Special Report on the ocean and cryosphere in a changing climate. https://www.ipcc.ch/srocc/chapter/chapter-2/.

Jodha, N.S., 1992. Mountain perspectives and its utility: a framework for development strategies. Himal. Rev. XX-XXIII, 11−24.

Jodha, N.S., 2005. Economic globalisation and its repercussions for fragile mountains and communities in the Himalayas. In: Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Eds.), Global Change and Mountain Regions: An Overview of Current Knowledge. Springer, Dordrecht, Netherlands, pp. 583−591.

Kargel, J.S., Leonard, G.J., Shugar, D.H., et al., 2016. Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. Sci.ence 351 (6269). https://doi.org/10.1126/science.aac8353.

Khanal, N.R., Mool, P.K., Shrestha, A.B., et al., 2015. A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from Nepal and the transboundary area. Int. J. Water Resour. Dev. 31 (2), 219−237. https://doi.org/10.1080/07900627.2014.994116.

Kim, D.H., Anderson, V., 1998. Systems archetype basics. Pegasus Communications Inc., Waltham, Mass.

Kraaijenbrink, P.D.A., Bierkens, M.F.P., Lutz, A.F., et al., 2017. Impact of a 1.5°C global temperature rise on Asia's glaciers. Nature 549, 257−260. https://doi.org/10.1038/nature23878.

Kunwar, R.R., Aryal, D.R., Karki, N., 2019. Dark tourism: a preliminary study of Barpak and Langtang as seismic memorial sites of Nepal. J. Hospit. Tourism Educ. 9, 88−136. https://doi.org/10.3126/jthe.v9i0.23683.

Lamsal, P., Kumar, L., Atreya, K., 2017. Historical evidence of climatic variability and changes, and its effect on high-altitude regions: insights from Rara and Langtang, Nepal. Int. J. Sust. Develop. World Eco. 24 (6), 471−484. https://doi.org/10.1080/13504509.2016.1198939.

Liu, J., Dietz, T., Carpenter, S.R., et al., 2007. Complexity of coupled human and natural systems. Science 317 (5844), 1513−1516. https://doi.org/10.1126/science.1144004.

Lutz, A., Immerzeel, W.W., Bajracharya, S.R., et al., 2016. Impact of climate change on the cryosphere, hydrological regimes and glacial lakes of the Hindu Kush Himalayas: a review of current knowledge. ICIMOD Research Report 2016/3. ICIMOD, Kathmandu.

Maikhuri, R.K., Nautiyal, A., Jha, N.K., et al., 2017. Socio-ecological vulnerability: assessment and coping strategy to environmental disaster in Kedarnath Valley, Uttarakhand, Indian Himalayan Region. Int. J. Disaster Risk Reduct. 25, 111−124. https://doi.org/10.1016/j.ijdrr.2017.09.002.

Manandhar, S., Pandey, V.P., Kazama, F., 2012. Hydro-climatic trends and people's perceptions: case of Kali Gandaki River Basin, Nepal. Clim. Res. 54, 167−179. https://doi.org/10.3354/cr01108.

Manandhar, S., Vogt, D.S., Perret, S.R., et al., 2011. Adapting cropping systems to climate change in Nepal: a cross-regional study of farmers' perception and practices. Reg. Environ. Change 11, 335−348. https://doi.org/10.1007/s10113-010-0137-1.

McDowell, G., Ford, J.D., Lehner, B., et al., 2013. Climate-related hydrological change and human vulnerability in remote mountain regions: a case study from Khumbu, Nepal. Reg. Environ. Change 13 (2), 299−310. https://doi.org/10.1007/s10113-012-0333-2.

McDowell, G., Huggel, C., Frey, H., et al., 2019. Adaptation action and research in glaciated mountain systems: are they enough to meet the challenge of climate change? Global Environ Change. 54, 19−30. https://doi.org/10.1016/j.gloenvcha.2018.10.012F.

McVeigh, C., 2004. Himalayan herding is alive and well: the economics of pastoralism in the Langtang Valley. Nomadic Peoples 8 (2), 107−124. https://doi.org/10.3167/082279404780446023.

Messerli, B., Ives, J.D., 1997. Mountains of the World: A Global Priority. Parthenon, New York.

Moors, E.J., Stoffel, M., 2013. Changing monsoon patterns, snow and glacial melt, its impacts and adaptation options in northern India: synthesis. Sci. Total Environ. 468−469 (1), S162−S167. https://doi.org/10.1016/j.scitotenv.2013.11.058.

MoSTE (Ministry of Science, Technology and Environment, Government of Nepal.), 2015. Nepal earthquake 2015: rapid environmental assessment. Kathmandu. Kathmandu.

MoTCA (Ministry of Culture, Tourism and Civil Aviation. Government of Nepal), 2019. Nepal tourism statistics 2018. Kathmandu.

Mukherji, A., Sinisalo, A., Nüsser, M., et al., 2019. Contributions of the cryosphere to high mountain communities in the Hindu Kush Himalaya: a review. Reg. Environ. Manag. https://doi.org/10.1007/s10113-019-01484-w.

Nepal, S.K., Nepal, S.A., 2004. Visitor impacts on trails in the Sagarmatha (Mt Everest) national Park, Nepal. Ambio 33, 334−340.

Nüsser, M., Schmidt, S., 2017. Nanga Parbat revisited: evolution and dynamics of sociohydrological interactions in the Northwestern Himalaya. Ann. Assoc. Am. Geogr. 107 (2), 403−415. https://doi.org/10.1080/24694452.2016.1235495.

Ojha, H.R., Shrestha, K.K., Subedi, Y.R., et al., 2017. Agricultural land underutilisation in the hills of Nepal: investigating socio-environmental pathways of change. J. Rural Stud. 53, 156−172.

Padoa-Schioppa, E., Baietto, M., 2008. Effects of tourism pressure on herd composition in the Sherpa villages of Sagarmatha national Park (Everest, Nepal). Int. J. Sus. Dev. World 15, 412−418.

Paudel, K.P., Andersen, P., 2011. Monitoring snow cover variability in an agropastoral area in the Trans Himalayan region of Nepal using MODIS data with improved cloud removal methodology. Remote Sens. Environ. 115 (5), 1234−1246. https://doi.org/10.1016/j.rse.2011.01.006.

Paudel, K.P., Andersen, P., 2013. Response of rangeland vegetation to snow cover dynamics in Nepal Trans Himalaya. Climatic Change 117, 149−162. https://doi.org/10.1007/s10584-012-0562-x.

Rasul, G., Pasakhala, B., Mishra, A., et al., 2019. Adaptation to mountain cryosphere change: issue and challenges. Clim. Dev. 12 (4), 297−309. https://doi.org/10.1080/17565529.2019.1617099.

Saunders, B., Sim, J., Kingstone, T., et al., 2018. Saturation in qualitative research: exploring its conceptualization and operationalization. Qual. Quantity 52 (4), 1893−1907. https://doi.org/10.1007/s11135-017-0574-8.

Shea, J.M., Wagnon, P., Immerzeel, W.W., et al., 2015. A comparative high-altitude meteorological analysis from three catchments in the Nepalese Himalaya. Int. J. Water Res. Develop. 31 (2), 174−200.

Sterman, J.D., 1994. Learning in and about complex systems. Syst. Dynam. Rev. 10 (2–3), 291−330. https://doi.org/10.1002/sdr.4260100214.

Sterman, J.D., 2000. Business dynamics: systems thinking and modeling for a complex world. Irwin/McGr, Boston.

Vaidya, R.A., Shrestha, M.S., Nasab, N., et al., 2019. Disaster risk reduction and building resilience in the Hindu Kush Himalaya. In: Wester, P., Mishra, A., Mukherji, A., et al. (Eds.), The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Springer, Cham, pp. 389−419.

Wang, Y., Wu, N., Kunze, C., et al., 2019. Drivers of change to mountain sustainability in the Hindu Kush Himalaya. In: Wester, P., Mishra, A., Mukherji, A., et al. (Eds.), The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Springer, Cham, pp. 17−56.

Watanbe, T., Rothacher, D., 1996. The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya. Mt. Res. Dev. 16, 77−81 (c).

Wester, P., Mishra, A., Mukherji, A., et al. (Eds.), 2019. The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Springer, Cham.

WGMS, 2020. Global glacier change bulletin No. 3 (2016−2017). In: Zemp, M., Gärtner-Roer, I., Nussbaumer, S.U., et al. (Eds.), ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service. Zurich, Publication Based on Database Version. https://doi.org/10.5904/wgms-fog-2020-08.

Xiao, C.D., Wang, S.-J., Qin, D.-H., 2015. A preliminary study of cryosphere service function and value evaluation. Adv. Clim. Change Res. 6 (3–4), 181−187. https://doi.org/10.1016/j.accre.2015.11.004.

Xu, J., Grumbine, R.E., Shrestha, A., et al., 2009. The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. Conserv. Biol. 23 (3), 520−530. https://doi.org/10.1111/j.1523-1739.2009.01237.x.

Please cite this article as: TULADHAR, S., et al., Unravelling the linkages of cryosphere and mountain livelihood systems: A case study of Langtang, Nepal, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2020.12.004