



Climate warming in the Himalayas threatens biodiversity, ecosystem functioning and ecosystem services in the 21st century: is there a better solution?

Giri R Kattel^{1,2,3}

Received: 26 August 2021 / Revised: 29 March 2022 / Accepted: 1 April 2022 / Published online: 17 May 2022
© The Author(s) 2022

Abstract

Biodiversity losses can lead to global environmental crisis. Humans utilize biodiversity for a variety of ecosystem services. However, what drives biodiversity losses have become a critical question during the 21st century. Lately, the Hindu Kush Himalayan (HKH) region in Asia, one of the world's pristine habitats with the origin of majestic river systems including Brahmaputra, Indus, Mekong, and Yangtze, has witnessed rapid climatic warming. The unprecedented rates of climate warming in HKH has threatened biodiversity losses, ecosystem functioning and ecosystem services, and consequently the existence of mankind in the region. The Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlight the risks to humanity arising from unsustainable use of natural resources and loss of biodiversity worldwide under rapid climate warming condition. In addition, the growing economic transformation in HKH can have high environmental costs and biodiversity losses. By realizing this fact, the Convention on Biological Diversity addresses the key issues of biodiversity and ecosystem services in the HKH by liaising with the United Nations Framework Convention on Climate Change, Paris Agreement, and the Sustainable Development Goals (SDGs). Hence, the challenges of biodiversity losses, poor ecosystem functioning followed by reduced ecosystem services posed by climate warming and anthropogenic impacts needs to be addressed urgently by countries and multilateral agencies in HKH by identifying threatened ecosystem services and by providing better sustainability solutions. Here, I have outlined the current state of Himalayan biodiversity and ecosystem function and developed a framework for resilience management with an integrated approach of science and society to advance knowledge through learning. The resilience framework offers practical solutions comprising a robust and harmonized monitoring of climatic data, the use of multi-indicator approaches and modelling, and to make collaborated efforts among policy makers, implementers, and analysts to tackle evolving losses of biological diversity and reduction in ecosystem services in the HKH region.

Communicated by Anurag Chaurasia.

Extended author information available on the last page of the article

Keywords Climate warming. Hindu-Kush Himalayan region. Biodiversity. Ecosystem functioning. Ecosystem services. Resilience Framework. Resilience Management

Introduction

Biodiversity losses can lead to critical environmental crisis. About 9 million types of plants, animals, protists, and fungi, which inhabit the Earth have been influenced directly or indirectly by humans (Cardinale et al. 2012). However, a key question today is, how rapid climate warming intensifying the global biodiversity losses, and why the efforts to protect biodiversity have not been able to address properly (Betts et al. 2017). While the anthropogenic disturbances are thought to be the cause of habitat fragmentation and biodiversity losses worldwide, the decline of biodiversity in one of the world's least-disturbed habitats such as the Hindu Kush Himalayan (HKH) region has raised a question of the potential threat of climate warming in regional biodiversity during the 21st century.

The HKH region hosts 4 of 36 global biodiversity hotspots, 60 of the 200 global ecoregions, and 330 Important Bird and Biodiversity Areas (Kotru et al. 2020). The region is also a major source of some of the Asia's largest river systems and is regarded as the 'global biodiversity hotspot' (Fig. 1). The large glacier-fed river systems including the Indus, Ganges, Brahmaputra, Salween, Yangtze, Yellow, and Mekong originated from the Himalayan mountains support vast amount of ecosystem goods and services to more than one billion inhabitants residing in the downstream river basins (Chaudhari et al. 2018). However, the

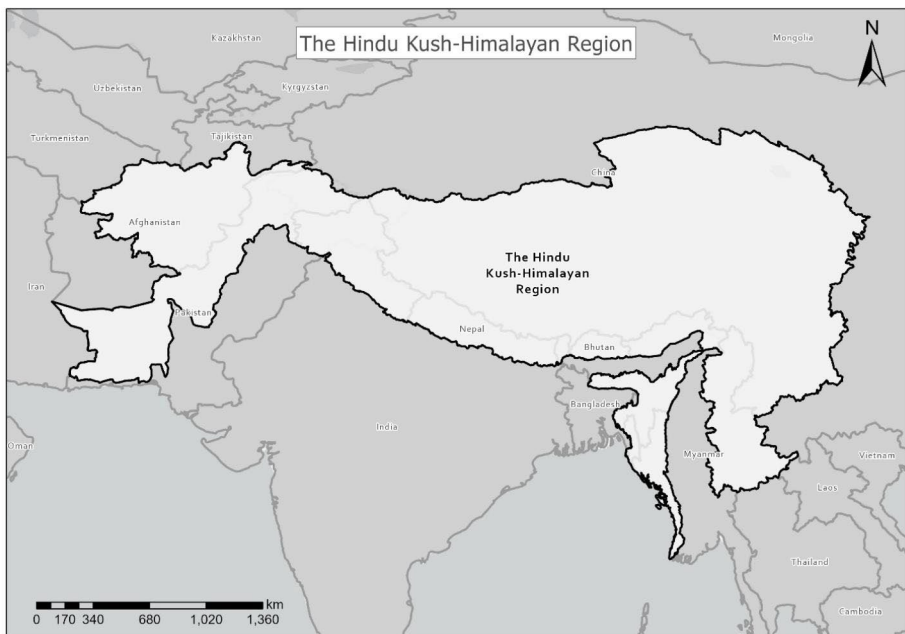


Fig. 1 The Hindu-Kush Himalayan (HKH) region in Asia.

Himalayas have been experiencing unprecedented warming at a rate greater than any time in the past (Shrestha et al. 2012). While the global mean temperature of the Himalayas over the past 100 years has increased at a rate of 0.74 °C, the regional temperature alone rose to an average 0.6 °C in every 25 years (Lamsal et al. 2017). Accelerated atmospheric aerosol thickness and black carbon emissions in the region during the 21st century have enhanced temperature rise further (Lau et al. 2010) leading to rapid snow melts (Ballesteros-Canovas et al. 2018). The snow shrinking not only has caused west-east and north-south gradients of climate variability, such as more from colder to drier, and wetter (monsoon-dominated) to warmer conditions (Bajracharya et al. 2015), but also has led to catastrophic snow avalanches, flash floods, landslides and erosions (Arora et al. 2016) causing significant natural and socioeconomic losses (Ballesteros-Canovas et al. 2018).

Today, the effects of climate warming in HKH have been observed as umbrella crisis causing all aspects of social, economic, political, and ecological and biodiversity impacts. While it is hard to distinguish natural and anthropogenic impacts of climate warming on biological diversity, but with rapidly changing life cycles and developing new physical traits and shifting habitat ranges and species distribution, changes in abundance, migration patterns, and frequency and severity of pest and disease outbreaks have become critical implications for biodiversity losses in HKH. Climate change and biodiversity losses together can have profound effects on ecosystem function. Biodiversity losses can erode the ability of ecosystems to withstand the effects of climate change. However, biodiversity has ability to stabilize ecosystems against climatic stressors (Pires et al. 2018). One of the unsolved questions today is therefore how climatic warming contributes to biodiversity losses, thereby to ecosystem function and, ecosystem services in HKH. As the interaction between climate warming and biodiversity losses is increasingly complex, at what condition climate warming can cause extreme damages to the Himalayan biodiversity is crucial to understand. Climate warming is suggested to alter mechanisms by which biodiversity affects ecosystem, and thereby influence the rates of functions (Pires et al. 2018). For instance, acute synchronous climate impacts can harm biodiversity. Timing and synchrony of climate impacts tested on approximately 30,000 species worldwide show that damages were observed to those species which were exposed to higher annual average temperature for an extended period (Sunday 2020). The rise of temperature and carbon dioxide levels together further changes hydrologic cycles (precipitation and evaporation) and an increased magnitude and frequency of extreme weather such as floods, cyclones, and droughts all have a profound negative impact on biodiversity (Habibullah et al. 2022). Direct response of individual organisms and populations to temperature and precipitation has shown that more temperature-sensitive functional groups such as dwarf shrubs, herbs, grasses, and bryophytes and lichens in the Himalayas have migrated northwards to cooler climate. Climate warming has also induced changes in the phenology, including the start of the growing season and spring greening of grasses and vegetation directly with the upward movement by 0.79 days a year in HKH (Shrestha et al. 2012). Higher plant diversity means the system has more energy stored, greater energy flow and higher community-energy-use efficiency across the trophic network. Hence, the effects of biodiversity on energy dynamics are crucial for different ecosystems (Buzhdygan et al. 2020). Climate warming also affect biodiversity indirectly weakening the ecosystem functioning by reducing the potential of biodiversity values (Benkwitt et al. 2020). Biodiversity losses affect ecosystem processes, reduced ecosystem productivity and performance (Balvanera et al. 2006). As ecosystem properties relate to ecosystem

services, biodiversity acts as a bridge between the two. Hence, the ecosystem services such as water quantity and quality, pollination, regulation of pests and human diseases, carbon storage and climate regulation, waste management all are the outcomes of the stability of ecosystem function and properties (Balvanera et al. 2006). However, with projected climate warming, and intensive anthropogenic impacts with increased land use change, extraction of resources including the harvest of organisms, wood, and agricultural commodities can result in significant loss of biodiversity and weaker ecosystem functioning together with reduced ecosystem services (Arneth et al. 2020). Climate warming across the elevational gradients has amplified land use effects, and the interplay between climate change and land use have further constrained biodiversity and ecosystem function and consequently lowered ecological resilience in the region (Peters et al. 2019). There also has been issues of mountain heterogeneity, observational data gap, model-based climate predictions and the uncertainties in HKH which profoundly influence the assessment of the impact of climate warming on biodiversity losses.

The Himalayas provides significant ecosystem services such as carbon sequestration, water storage, biodiversity maintenance, and food security to pastoral communities for over the millennia. For example, the Sikkim Himalaya alone contains 60% of global alpine plant families and 10% of global alpine genera (Ingty 2021). The presence of such diverse plant communities facilitates better utilization of resources with increased biomass use, as well as promote establishment and survival of other co-occurring species (Ingty 2021). Similarly, the oak forests in Bhutan Himalaya when managed under community-based forestry; agriculture; and a combination of forests and shrub land approach have become significant to generate a high-value socio-culturally based ecosystem services (Dorji et al. 2019). However, significant loss of ecosystem services in the Himalayas have been caused by reduction in habitats and biodiversity. The Shivapuri-Nagarjun National Park in the Nepal Himalaya has lost some of the important ecosystem services over the recent past with 74% reduction in the value of green-house gas sequestration, 60% reduction in the carbon storage, 94% reduction in the nature-based recreation, and 88% reduction in the water quality respectively (Peh et al. 2016).

In an effort to avoid the impact of climate warming on biodiversity and ecosystem function, in the 1990s, at the first Earth Summit in Brazil, vast majority of the world's nations declared a dismantle to the unsustainable actions of the Earth's ecosystems (Cardinale et al. 2012). The Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have highlighted risks to humanity arising from the unsustainable use of natural resources in the planet Earth. The discussions on how to define, design and implement long-term sustainability goals have become a central theme among the member countries of the United Nations. The Convention on Biological Diversity's post-2020 framework offers the important opportunity to address the interactions between climate change and biodiversity and assist in aligning these with the United Nations Framework Convention on Climate Change Paris Agreement and the Sustainable Development Goals (Arneth et al. 2020). Today, the framework for SDGs has become a universal agenda applicable to all countries, addressing poverty eradication and sustainable development, and integration of social, environmental, and economic dimensions of sustainability (Lucas et al. 2013). Lately, the idea of the 'safe operating space' for humanity in the planet Earth has taken a greater momentum in tackling the range of issues that prevent to meet the SDGs by 2030s. The safe operating space for humanity has reached

the critical level of the boundary where the three of the Earth-system processes: climate change, rate of biodiversity loss and interference with the nitrogen cycle have already transgressed their boundaries (Rockström et al. 2009). The threshold-based ecosystem services approach has been used to test the safe operating space for the humanity as part of the SDGs through the protection of global biodiversity and ecosystem functioning (Oliver et al. 2015). Given the global call from the international governing councils on loss and fragmentation of the Himalayan mountain habitats and upward movement of the plant and animal species over the recent century due to the rapid rate of climate warming, understanding of the structural, compositional, and functional dimensions of biodiversity and ecosystem functioning as well as ecosystem services are placed as the top priority (Arneeth et al. 2020). However, the HKH region receives limited attention in climate warming and biodiversity losses assessment. An international workshop on Biodiversity and Climate Change (BDCC-2018) held in Kharagpur, India was the first of its kind to focus on biodiversity losses in the HKH region and to recommend new strategies for adaptation and mitigation towards sustainable developments (Behera et al. 2019). Resilience management is the tenet of sustainable development with increased biodiversity, where ecosystem is able to maintain ecological stability, functioning and services following disturbances (Van Schmidt et al. 2021). With these perspectives, this study makes a comprehensive assessment of the current state of biodiversity, ecosystem function and ecosystem services in the HKH region, and develops a framework for resilience management, which offers a practical solution to tackle the sustainability of ecosystem services threatened by current climate warming in the HKH region.

Climatic warming and biodiversity losses in HKH region

Climate warming is likely to become one of the most substantial drivers of biodiversity losses in HKH in the 21st century. There are limited studies being available on climate related impacts on biodiversity losses in the region. Natural variability of climate change such as decreasing precipitation and increasing temperature have been reflected by the retreat of Himalayan glaciers in response to warming over the recent decades and posing severe threats to terrestrial diversity. For instance, advancement of vegetation phenology and greening have occurred under rapid climatic warming, while moisture stress causing plant growth, seedling survival, and vegetation browning (Sigdel et al. 2021). Montane floras are found highly sensitive to climate change, thus the species' response to warming in the high-altitude Himalayas is threatened by temperature rise. Greater temperature increases are expected at higher altitudes with anticipated impacts of climate warming on structure and functions of ecosystem in future (Behera et al. 2019). Ongoing warming has transformed plant assemblages. As high as 87% of 124 endemic species have experienced warming-driven geographical range shifts in the plant assemblages in the Sikkim Himalaya with species extinction (Telwala et al. 2013). Changes in species richness and beta diversity have strongly responded to climatic warming (Bhattacharjee et al. 2017), where the treeline ecotone species is highly sensitive to losses. Vegetation species such as *Betula utilis* (Himalayan birch) has shown tendency of shifts towards the Eastern Himalayas with declining trends towards the west (Hamid et al. 2018). Combined and interactive effects of photosynthetically active radiation (PAR) and CO₂ increase in the treeline ecotone have caused species redundancy, with a shift in dominance from deciduous *Betula utilis* (birch)

to evergreen Rhododendrons (Behera et al. 2019). Net ecosystem exchange (NEE) of sal forests in the lesser Himalayas has been reported due to the increased exposure to climate-induced wildfires (Behera et al. 2019). The impact of climate warming on aquatic biodiversity losses in HKH is reported even severe. For instance, changes to local (alpha) and regional (gamma) fish diversity across 38 sites of the Nepal's Kaligandaki-Narayani River (KNR) have showed a significant contraction in the mean abundance and species richness between the 1990 and 2010 s (Gillette et al. 2022). The cascading impacts of changes of water resources, farming systems and increasing prosperity of the Himalayan people under climatic warming trend have intensified biodiversity losses further (Dolezal et al. 2020). While there is an ongoing high risk of anthropogenic threats on Himalayan flora and fauna, climatic warming is projected to make the most severe and direct effects on biodiversity losses and reduced ecosystem services in HKH in future (Behera et al. 2019). Evidence suggests that biodiversity loss can affect ecosystem functions and services (Hector and Bagchi 2007). In an intermediate (21–40%) levels of species loss where about 5–10% plant productivity has been found lost (Hooper et al. 2012). Hence, climate warming in HKH has become inevitable phenomenon for biodiversity losses in HKH during the 21st century.

Conceptual framework of ecosystem function and ecosystem services

Ecosystem services are generated by ecosystem functions, which, in turn, are underpinned by biophysical structures and processes as classified by the Millennium Ecosystem Assess-

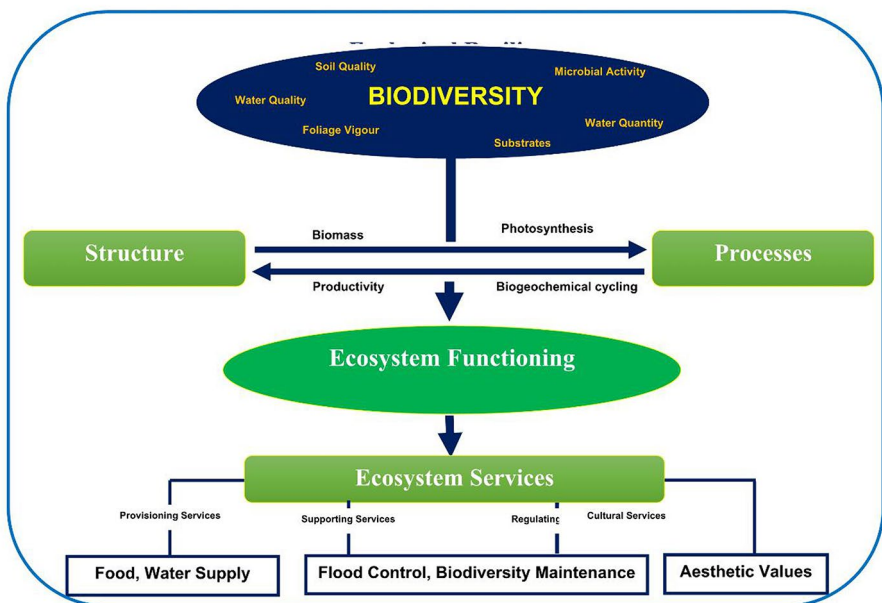


Fig. 2 Conceptual framework for Ecological Resilience Boundary from which biodiversity supports ecosystem structure, processes and consequently generate a range of ecosystem services.

ment (MA 2005). A resilient ecosystem has strong ecological boundary, where the naturally available soil, foliage, water, and sediment act as habitats or substrates for survival of variety of organisms and play a vital role for ecosystem functioning and generate services through ecosystem structure and processes (Fig. 2). The concept of resilient ecological boundary is complex, and often based on evolution of species interactions and dispersal within resourceful habitats. Any population loss from the boundary arises the question of persistent ecosystem. For example, resilient ecological boundary in lakes and rivers is based on healthy flow regime, physical habitat structure to act as refugia for species, sufficient thermal and light environments to regulate organismal metabolism, and ecosystem productivity, regulated chemicals and nutrients for better water quality and the biotic assemblage dynamics for ecosystem process and community structure (Baron et al. 2002). Biophysical processes determine the provision of ecosystem services which eventually be benefitted by humans (Fig. 2). The specific nature of interdependencies between the structure and diversity of biotic communities, the processes and the functioning of ecosystems remains however one of the most challenging and unresolved questions in ecology (Bastian 2013). A coherent and integrated approach for practical application of the concept of biodiversity, ecosystem structure and function in planning, management and decision making of regional and global ecosystems is still limited (Trabucchi et al. 2012).

Biodiversity plays a greater role in the ecological boundary concept, which was initially proposed as a 'safe operating space' for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes (Rockström 2009). Biodiversity underpins ecosystem function and that the provisioning of ecosystem services is essential for human well-being. When poverty and economic development have reciprocal relationships with biodiversity and the provision of important ecosystem goods and services, there is a growing demand of food, water, and biomass to sustain on-going population growth worldwide. Hence, research and policies in the sustainability of natural capital is vital for preservation of biodiversity and ecosystem services (Lucas et al. 2013). For example, in a coastal environment, a dynamic hydrologic cycle link terrestrial, freshwater and marine ecosystems, where humans get ecosystem services such as food and water security, flood protection, biodiversity maintenance and recreational activities (Apitz 2012).

The freshwater ecosystems in the Himalaya contributes as significant supporting services to terrestrial ecosystems, fisheries dynamics, pollution control, and to several other provisioning and cultural services including water supplies and tourism. Although, there are limited studies being carried out on ecosystem functioning and ecosystem services in the Himalayas, a long-term bio-geochemical assessment of lakes located as high as 5400 m a.s.l. at the Mt. Everest region suggests a persistent increase in the ionic content of water, a trend which appears to be closely linked to increasing temperature (Lami et al. 2010). In the lesser Himalayas, the water quality of lakes and reservoirs have reduced due to the disruption in phosphorus and nitrogen cycling caused by excessive inputs of nitrogen (TN) and phosphorous (TP) fertilizers and prolonged eutrophication (Walsh et al. 2016). Recent, climate warming has intensified harmful cyanobacterial blooms in the Himalayan lakes, which has led to loss of recreational and aesthetic values, negatively impacting on fisheries production, and in some cases lakeshore tourism. *Daphnia*, the cladoceran zooplankton (or water flea), is one of the key freshwater species in the Himalayan lakes, which are found to be highly sensitive to climate change. *Daphnia* such as *D. tibetana* has already been extinct in Nepal Himalaya since the 1980s possibly due to climate warming (Manca and Comoli

2004). *Daphnia* plays an important role in water recycling by removing the algae (Jeppesen et al. 2001; Kattel et al. 2018). Maintenance of strong interactions (regulating services) among fish, *Daphnia*, and algae (Fig. 3) is essential not only for high recreational fisheries, but also for intact Himalayan ecosystems for tourism development (cultural services). When *Daphnia* regulates algae by grazing water clarity is maintained and the ecosystem is well functioned. Hence, the maintenance of diversity of *Daphnia* populations in the Himalayan freshwater systems is crucial.

Ecosystem function and ecosystem services in Himalayas

The Himalayan ecosystem functioning is largely mediated by natural variability of temperature, soil type, nutrients, substrate quality, altitude, pH, light, water transparency, and minerals and conductivity. For example, soil-microbial interactions contribute to sustainability of agriculture by enhancing Oak leaf litter decomposition, nutrient release, and soil quality in rainfed wheat-paddy cropping system in the high altitude Himalayas in south Asia (Pant et al. 2017). Plant-soil interactions that include soil organic carbon, soil microbial carbon, soil microbial nitrogen, soil microbial phosphorous, and soil respiration, Leaf N, P, and leaf N/P ratios all are found to increase forest ecosystem processes and functioning where leaf traits and soil characteristics are strongly related to above- and below-ground ecosystem processes and biomass productivity (Rawat et al. 2020). The biodiversity and biomass of the forests of the Dachigam National Park (DNP) in the Indian Kashmir Himalaya suggest that pine forests (*Pinus wallichiana*) are the highest value forest type reported as an above

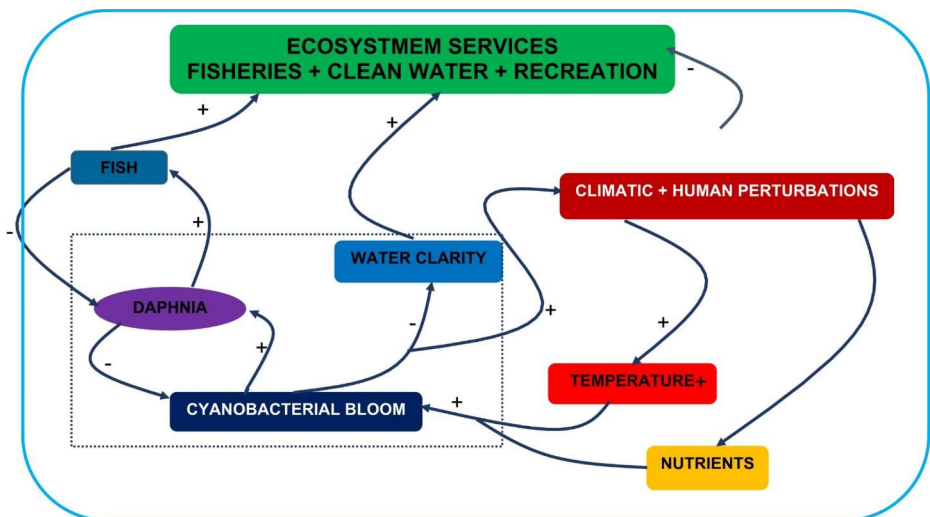


Fig. 3 Role of *Daphnia* in maintaining ecosystem services (regulating services) such as water purification/clarity (quality) and fisheries productivity in a lake system by controlling (reducing) cyanobacterial bloom or by being the fish diet. Within the dotted rectangle, an interaction between, *Daphnia*-cyanobacteria-and-water-clarity, has been shown. When *Daphnia* supports fish as a diet, there is an increase in fisheries production. When *Daphnia* reduces algae by grazing, water clarity increases. However, climate change and human disturbances including nutrient inputs in lake and river enhance cyanobacterial bloom.

ground, below ground and total biomass forest type, while scrub is the lowest value forest type in the region (Haq et al. 2020). *Pinus wallichiana* and *Quercus robur* tree species also stock the largest amounts of biomass for carbon sink, a significant ecosystem service product from ecosystem functioning in the region (Haq et al. 2020). Similarly, during the functioning of the lake ecosystem, the atmospheric temperature, lake surface area, suspended solids, bicarbonate and dissolved phosphorus all variables found strongly interacted with submerged macrophyte community to produce the important biomass as a part of lake ecosystem services in the Himalayan mountains (Lacoul and Freedman 2006). However, ecosystem functioning in the Himalayas is constantly threatened by climate change and other human disturbances causing alteration of ecosystem services. Under climatic warming, species adapted to or preferring relatively high temperatures are found to be distributed gradually toward higher altitudinal gradient, while the species adapted to or preferring relatively low temperatures are experiencing difficult to maintain ecological functioning (Li et al. 2016). For example, the baseline vegetation dynamics monitored in the Kashmir Himalayas from 1960 to 1990 showed considerable shifts in the ecosystem functioning and subsequent ecosystem services. The grasslands and tropical deciduous forests are found to be severely affected by recent climate warming. As a result, savannah, shrubland, temperate evergreen broadleaf forests, boreal evergreen forests and mixed forests mostly are found to be colonized across the cold desert/rock/ice land cover type areas in the region (Rashid et al. 2015).

It has been widely accepted that changes in temperature and precipitation including seasonal variations and intensity, have affected long-term water availability, and variability in cryosphere and evapotranspiration consequently influencing the Himalayan ecosystem functioning and ecosystem services. The monsoon (July–September) and the main snowpack (Nepal et al. 2014) accumulation or melt seasons (March–June) have altered timing of the contrasting hydrological regimes that collectively reflect on changes in the overall hydrology of the Himalayan watersheds (Hasson et al. 2019). The hydropower projects in Bhutan, China, India, Nepal, and Pakistan for example are some of the most important ecosystem services generated by the Himalayan river systems. Today, the reduction in the freshwater ecosystem functioning as a result of the reduced discharge, the region's hydropower potential is at extreme threat (Khatiwada et al. 2016). Highly dependent runoff patterns and unreliable seasonal flows with drier winter and shorter but intense monsoon pose potentially higher risks to water supplies to drinking water and hydropower reservoirs as well as crop irrigation in the region (Gautam et al. 2014).

Air pollution is also in rise in the Himalayas. No reliable documents are available in relation to air pollution and ecosystem functioning and ecosystem services, but persistent organic pollutants (POPs) transports across the south-north altitudinal transect (100–5200 m) in the central Himalayas show that more than 90% of POPs are trapped along the way due to gaseous deposition to soil/foliage and rainfall scavenging (Gong et al. 2019). Persistent Organic Pollutants and Polycyclic Aromatic Hydrocarbons (PAHs) are also found in waters, sediments, and soils of the high-altitude sites in the Sagarmatha National Park of the Nepal Himalaya (Guzzella et al. 2011) indicating its influence in the both aquatic and terrestrial ecosystem functioning and ecosystem services in the region. For example, the ecosystem of the Lesser Himalayan lake, Begnas Lake, in the Pokhara Valley, a dominant touristic district of Nepal, has shown a shift in trophic state and water quality due to inherent changes in the biogeochemical processes over the recent decades (Khadka and Ramanathan 2012), possibly altering ecosystem services generated by tourism industry.

The Himalayan cryosphere borders global hotspots for emissions of black carbon (BC), a carbonaceous aerosol with a short atmospheric life span and potentially impacts on glaciers and snow cover thereby ecosystem function and ecosystem services through the mix of organic carbon and water quality change (Gertler et al. 2016). Atmospheric BC absorbs radiation efficiently, leading to localized positive climate forcing, and in the meantime, the ultra-violet (UV) radiation can have direct consequences on both terrestrial and aquatic ecosystems (Bornman et al. 2019; Williamson et al. 2008). Solar UV-B radiation is known to affect the growth and performance of terrestrial plants and animals. The shorter wavelengths of the UV radiation (mostly in the UV-B range) may cause cellular damage, which can lead to changes in the morphology, physiology, and biochemistry of the organism. The structure, function, and diversity of terrestrial ecosystems in the HKH region are expected to be modified by the UV-B radiation causing massive forest dieback (Bornman et al. 2019; Xu et al. 2013) and possible loss of ecosystem services in the region. The BC may also be deposited on to snow and ice surfaces, thereby changing their albedo effects (Gertler et al. 2016). The high concentration of dissolved organic carbon caused by black carbon during the snowmelt absorbs potentially damaging UV-B radiation, resulting in photobleaching and release of more biologically available carbon in the freshwater system altering metabolism and ecosystem functioning (Williamson et al. 2008), and subsequently ecosystem services such as water quality in the region.

When ecosystems become sensitive to around threshold levels of certain key variables such as temperature, nutrients and light in the Himalayas, and if these thresholds are crossed, the ecosystems move into a new state, often with deleterious or potentially even disastrous consequences for the humanity in the long run (Rockström 2009; Szabó et al. 2020). Hence, knowing the state of biodiversity and ecosystem functioning and services and their contributions to human well-being is crucial (Balvanera et al. 2014). In the Himalayas, land, and water degradations due to climate change and human disturbances have consistently threatened the risk of threshold crossing, identifying the key ecosystem services that are threatened by climate change is urgently needed.

Key himalayan ecosystem services exposed to climate warming

Governments across the world are tasked with developing pathways to achieve nationally prioritized targets that incorporate social, economic, and environmental dimensions of sustainability. Building on progress made under the UN Millennium Development Goals, the Sustainable Development Goals (SDGs) are a globally agreed upon set of 17 goals, 169 nested targets, and over 200 associated indicators that set the agenda for addressing sustainable development challenges by 2030 (Wood et al. 2018). By sticking with these goals, the global community, more importantly the governments of Himalayan nations and the multi-lateral agencies working in the region should take an initiative and responsibility to assess and protect different ecosystem services that are threatened by climate change for the sake of future generations.

Provisioning services

The 2005 Millennium Ecosystem Assessment (MEA) identifies that water is an important provisioning ecosystem service (Carpenter et al. 2009). Water is exposed to severe climate change in the Himalayas and needs urgent management action plan. The sixth Sustainable Development Goal (SDG-6) for equal access to water and sanitation for all by 2030 have been adopted by some countries in the Himalayas. For example, the Melamchi Water Supply Project of the Government of Nepal has delivered water to the Kathmandu Valley to meet the SDG-6 (Bhattarai et al. 2020). Beside water, forests, other significant provisioning services, are becoming critical for resource-poor communities in the Himalayas. Forests provide woods, which are the main source of household energy (97%) in the region (Thorn et al. 2020). In Nepal alone, the community forest based ecosystem services supports more than 20% of the income of rural households (Acharya et al. 2020a) in which more than 65% of use *sal* tree (*Shorea robusta*) for trading as timber (Thorn et al. 2020) with an average USD 35 per cubic feet in *Siwalik* forests of northern India and southern Nepal (Acharya et al. 2020b). Forests and water in the HKH region collectively generate food, and incomes. The Koshi Tappu Wildlife Reserve of the Nepal Himalaya for example generates food equivalent to USD 16 million per year with the share of USD 982 per household (Sharma et al. 2015). Medicinal plants are an integral part of indigenous medical systems and livelihoods, and have long been collected, consumed, and conserved by indigenous populations in the Himalayan region (Khan et al. 2014; Kuniyal et al. 2014). Medicinal plants provide healthcare for up to 80% of the population (Saslis-Lagoudakis et al. 2014). In two of the far western high Himalayan districts, Baitadi and Dadelhdhura, of Nepal alone, 74 ethnomedicinal plant species have been recorded with important provisioning services in which 43 herbs, 15 trees, 10 shrubs and 6 climbers are potentially used for medical purposes (Kunwar et al. 2016). These plants are used for curing digestive, respiratory, urinary, blood circulatory and reproductive systems and skin related illnesses (Khan 2013).

Regulating services

Pollination, the mechanism behind the transfer of pollens from male flowers to the female flowers that lead to fertilization and reproduction, is an important regulating services of the Himalayan ecosystems. Pollinators are inextricably linked to human well-being through the maintenance of ecosystem health and function, wild vegetation reproduction, crop production and food (Potts et al. 2016). Wind, water, and invertebrate (bees, flies, butterflies, moths, wasps, beetles, and thrips), and vertebrate (birds, bats and other mammals and lizards) facilitate pollination and maintain ecosystem functioning in the region. Exposure to climate change and large-scale land-use intensifications such as monocultures with high use of chemicals have reduced the connectivity, abundance, and diversity of pollinators (Kovacs-Hostyanszki et al. 2017). Today, the flowering plants in the Himalaya have undergone severe pollen limitation (Jiang and Xie 2020) as a result of the reduction in the populations of eastern honeybee (*Apis cerana*) threatening regulating services (Potts et al. 2016). The Himalayan lakes and rivers have capacity to regulate surface and ground water through natural purification, where *Daphnia* sp. plays an important role (Fig. 3). But climate change in the high mountain system and wastewater pollution in the downstream river basins have reduced self-purification capacity of lakes and rivers (Rashid and Romshoo 2013). The

interconnected lake and river system in the region provides potentially significant flood and climate regulating services (Kummu et al. 2014). Wetlands, and river channels not only enhance retention of large amount of flood water in the lowland floodplains but also act as ecological nexus in the glaciated landscapes (Camargo and Cortesi 2019; Hauer et al. 2016; Jiang et al. 2020). However extreme variability of monsoonal patterns has threatened water storage and flood regulation capacities of lakes and rivers during the 21st century (Hirabayashi et al. 2013). Lakes and wetlands together with community and agro-forest ecosystems sequester carbon, alleviation poverty, and conserve biodiversity (Stringer et al. 2012). In the central Kashmir Himalaya of India, an integrated cropping of legumes, cereals and apple can mitigate climate impact by sequestering as high as 46 t ha^{-1} soil carbon (Zahoor et al. 2021). Many wetlands in the HKH region have been placed under national greenhouse gas (GHG) emissions assessment program due to their higher potential in carbon sequestration (Villa and Bernal 2018).

Supporting services

Biodiversity can indicate the ecosystem services (e.g. the capacity or the service to provide suitable living conditions for plants and animals), hence the effects of species loss or changes in species composition determine maintenance of ecosystem services (Bastian

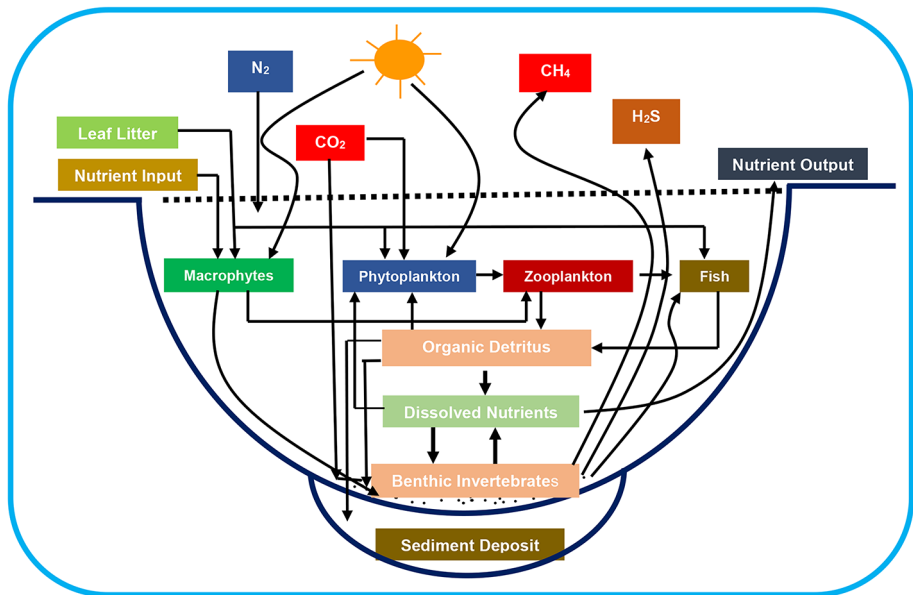


Fig. 4 Framework for supporting ecosystem services (nutrient recycling) of benthic macroinvertebrates in the Himalayan stream ecosystem. Under the sunlight, the ecosystem functions. Primarily the temperature and light influence macrophyte and phytoplankton growth, which then support benthos and fish. The benthos transforms organic detritus from sedimentary storage into dissolved nutrients that can be mixed into open waters and used again by macrophytes and phytoplankton to enhance primary productivity in the system. Meantime, several other drivers involve such as the dynamics of carbon-di-oxide (CO_2), hydrogen sulphide (H_2S), methane (CH_4) and nitrogen (N_2).

2013). The terrestrial and aquatic ecosystems of the Himalayas provide many important supporting services including nutrient recycling, soil respiration and stream metabolism while maintaining the biodiversity (Li et al. 2020). The benthic invertebrates in the region are estimated to provide more than 50% supporting services by processing riparian leaf-litter inputs to headwater streams. Benthic invertebrates release bound nutrients into solution by their feeding activities, excretion, and burrowing into sediments. Bacteria, fungi, algae, and aquatic angiosperms utilize dissolved nutrients and speed up microbial activity and growth. Benthic microbes, algae, and rooted macrophytes are utilized by herbivorous and omnivorous benthic invertebrates. Predatory benthic invertebrates control prey size and numbers, as well as they themselves supply food for both aquatic and terrestrial consumers (e.g., fishes, turtles, and birds) as well as transferring nutrients to open water and adjacent riparian zones (Covich et al. 1999) (Fig. 4). However, climate change and riparian deforestation cause stream channel narrowing, increases water velocity, and lowers bed roughness and alters nitrogen and phosphorus processing, dissolved organic matter processing and net stream metabolism ultimately reducing benthic stream ecosystem functioning and supporting services (Sweeney et al. 2004) in the region.

Cultural services

Mountain regions meet an increasing demand for pleasant landscapes, offering many cultural ecosystem services to both their residents and tourists (Schirpke et al. 2016). Many national parks and conservation areas of the Himalayas are protected that not only protects biodiversity but also provides important cultural services through recreation and environmental education for visitors, promotes sustainable livelihood for local communities. National parks can well address the relationship between protection and rational utilization of natural resources and consider the demands of the local community for fundamental livelihood. Cultural ecosystem services in the Himalaya are estimated in a ‘bundle’ of biodiversity and natural history-type services for knowledge such as bird watching, religious such as pilgrimage, aesthetic or recreational such as boating, rafting, swimming, hiking, fishing, off-road driving, skiing and paragliding (Ament et al. 2017). Most importantly, the region is regarded as sacred, spiritual place for Hinduism, Buddhism, Jainism, and Sikhism. For example, the Mt Kailash (6714 m) and the Lake Mansarovar are worshipped by devotees of different religions such as Hindu, Buddhist, Bon, and Jain, who travel to the site from across the globe. The Kailash Sacred Landscape (KSL) program of the International Center for Integrated Mountain Development (ICIMOD) estimates USD 2.9 million per year average use value of its cultural services to the visitors and the households of the KSL area (Nepal et al. 2018). The nature-based tourism industry in the HKH supports people in the region, as a complement of this, the mountain people actively design and protect landscapes, as well as circulate, and consume resources, create a social space for themselves through various means by making a place of attraction for tourists.

Critically threatened himalayan ecosystem services

The vast storage of water as a form of ice or snow in highly extended geographical terrain of the HKH region regulates flow of ten large river systems that secure food and water

directly to the 200 million people in the HKH and indirectly to the 1.3 billion people living downstream river basins (Xu et al. 2009). Some of the historically important regions, for instance, the Gangetic Plain, the Indus Delta, the Bangladesh floodplains, the Yangtze, the Yellow and the Mekong Delta, for global and regional food and water security, however are severely impacted by climate warming over the past 100 years (Zomer and Sharma 2009). The rise in temperatures has caused rapid glacier melts in the upstream HKH with reduction in the 50% of total runoff in the eastern Karakoram, and the western Himalayas (Zomer and Sharma 2009) and 70% less runoff in the Ganges, Indus, Tarim, and Kabul river basins alone (Xu et al. 2009) during the dry seasons. However, during the summer-monsoon seasons, glacier melts in the Himalaya–Karakoram mountain ranges temporarily increasing summer meltwater run-off but continuously reducing the ice-storage volume causing severe water resources and water-related hazards as well as streamflow patterns in the region (Nie et al. 2021). As a result, there is uncertainty in future runoff due to variations in precipitation (Immerzeel et al. 2020). It is likely that future glacier runoff increases in early summer but decreases in late summer. By the end of 2100 one-third of glaciers might experience runoff decreases greater than 10% due to glacier mass loss in at least one month of the melt season (Huss and Hock 2018). Lately, the food security of the Indus River in Pakistan that depend on snowmelt has been profoundly affected by the poorly managed irrigation system (Xu et al. 2009). Humans have modified natural landscapes in a way the most river basins cannot sustain under the pressure of growing populations and water use (Green et al. 2015). Withdrawal of groundwater has expanded agricultural and domestic use wide across the HKH region and subsequently exceeded recharge capacity limiting the water availability for the groundwater dependent ecosystems (Glazer and Likens 2012).

Direct discharge of solid waste and liquid wastewater into the river systems beyond the capacity of waste assimilation of the river themselves has intensified water insecurity further under climate warming in the region (Bhattarai et al. 2020). The reduction in the environmental flow and water pollution together have triggered basin wide food and water insecurity in a variety of ways. For example, moisture availability in the atmosphere of the HKH that governs physiology, metabolic and reproductive processes, phenology, and the geographic distribution of wild native plants and cultivated crops all have been significantly altered (Sigdel et al. 2020; Xu et al. 2009) causing major regional food insecurity.

Constant warming in the central Himalayas for example, has been reported to a threshold crossing of the moisture regime followed by the shift in treelines (Sigdel et al. 2018) affecting the biomass production of grasslands and tropical deciduous forests in the region. Most savannah, shrubland, temperate evergreen broadleaf, boreal evergreen and mixed forests are found to be colonized under cold high-altitude environments of the HKH due to the rapid warming (Rashid et al. 2015). The other biodiversity and ecosystems, critically threatened, but less investigated in the HKH region under climate warming, are the functional characteristics of species (i.e., their traits) in agroecosystems. Functional traits of plants, such as (morphology, phenology, physiology) influence ecosystem functioning directly by mediating changes in biotic controls (e.g., competition) and indirectly through responses to changes in local environment (e.g., microclimates or disturbance regimes). Functional traits indicate the response of species to the environment and their fitness or capacity to generate ecosystem services (Wood et al. 2015). When climate warming is making profound implications for food and water securities in the HKH region, management of the key ecosystem services with consideration of functional traits on time is utmost necessity.

From the perspective of the symbiotic relationship between tourism and the environment, people in the HKH region are greatly benefitted from the cultural ecosystem services over many years (Waite et al. 2003) and has become crucial for socio-economic development (Godwin 1996). Protection of biodiversity in the HKH region therefore offers sustainability of livelihoods in the region through promotion of cultural services. However, a constant exposure to both direct and indirect impacts of climate change such as the nature and quality of natural environments on which mountain tourism depends (i.e., climate-induced biophysical change) has constantly threatened nature-based tourism industry by reducing the perceived cultural ecosystem services such as attractiveness of the protected areas (Scott et al. 2007). Hence, how the environment is perceived that influences the use of environment as a resource, and how a person perceives the environment as a consequential effect for sustainable development, holds considerable significance of critical ecosystem services in the HKH region (Xu and Fox 2014).

Is there a better solution?

When the ecosystems provide necessary structure and processes that underpin ecosystem functions, and it potentially have the capacity to deliver services, but in the meantime, the society constantly face management challenges of ecosystems for the delivery of services sustainably. The integration of ecosystems and associated variables and management actions

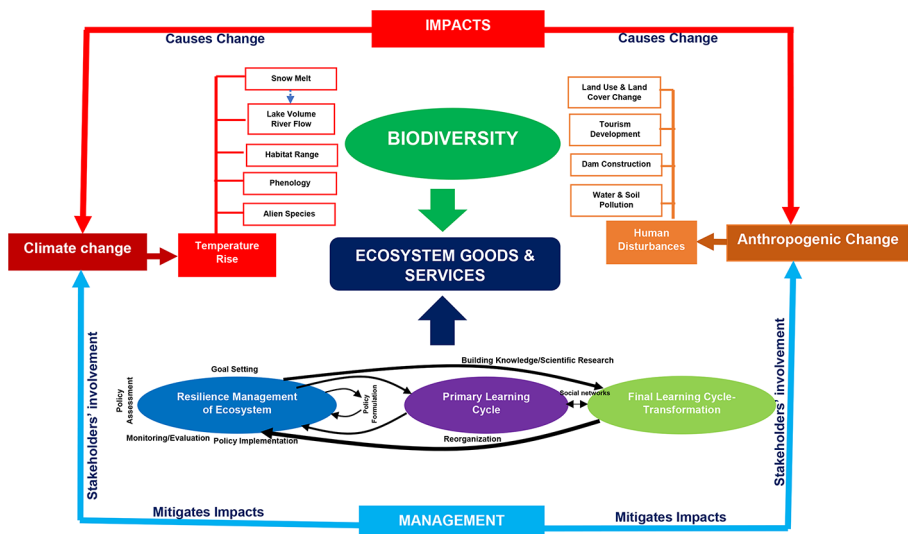


Fig. 5 A framework for impacts of climate change and anthropogenic disturbances on biodiversity (upper half) and resilience management (lower half) of diagram shaping ecosystem goods and services in the HKH region. Impact and management usually have trade-off, biodiversity generates key ecosystem services (ES), while climate warming and anthropogenic impacts cause changes in biodiversity through various ways such as snowmelt and land use. Resilience management plays a significant role to maintain the condition of biodiversity in the region, as resilience management maximizes ecosystem services including the goal setting, learning through building knowledge of science, and better policy implementation. Scientists identify change, and stakeholders involve resolve in decision making.

can frame spatially explicit, quantitative assessments of impacts that influences changes in biodiversity and ecosystems, ecosystem services and benefits. Such integrated framework connects biodiversity and ecosystems with ecosystem services values and benefits human wellbeing by making a sustainable flow of goods and services. However, the complex interactions of biological diversity and ecosystems and their exposure to both climate change and human disturbances can lead to the series of cascading impacts altering the delivery of ecosystem goods and services to the society.

How biodiversity plays a central role in the maintenance of ecosystem goods and services in the HKH region when it is exposed to increased climate warming and human disturbances can be observed through a complexity of climate change and anthropogenic impacts as well as the efforts being made by humans to overcome problems in biodiversity loss in the mountains. There are already inevitable consequences being made by climate change on variable water resources, plant phenology, soil moisture, invasive species, and habitat range. Increased water extraction, agriculture cultivation, and tourism development have further made serious threats to Himalayan biodiversity. For example, snow melt has altered the pattern of downstream water volume causing inundation during summer, and dehydration during dry season consequently affecting irrigation and agriculture productivity as well as performance of wetland ecosystems. The proposed resilience management framework in the HKH (Fig. 5) identifies the cause and effects, and shows the linkages between biodiversity and ecosystem services, and utilizes the knowledge that has been gained through learning and to set up goals and implement the agenda. The ecosystem of the HKH region urgently needs resilience management.

Today, resilience management has become one of the important agenda for global sustainability and development programs including the Himalayas (Boltz et al. 2019; Jones et al. 2021). Thus, the way how ecosystem functions and responds to disturbance in the HKH region (ecological resilience) needs to be well understood to achieve sustainable goals of regional supply and demand of ecosystem goods and services. Resilience is the buffering capacity or the ability of an ecosystem to absorb perturbations, or the magnitude of disturbance that can be absorbed before an ecosystem changes its structure and function by changing the variables and processes that control behaviour (Holling 2001). Resilience is also two-dimensional metric systems, in which the resistance of ecological changes in response to a disturbance and the recovery after a disturbance (Calder and Shuman 2019). Following exposure to climate change if biodiversity can return to an equilibrium state or a recovery or ‘engineering resilience’. However, biodiversity can also resist climate change and maintains ecosystem functions, potentially through internal reorganization or ‘adaptive capacity’ and be able to generate services sustainably. Both mechanisms have a trade-off. Hence, resilience management defends the system being changed as well as speeds up the system recovery from a disturbance (Adger 2000). Resilience is also the process of developing a broader management plan that protects biodiversity (Oliver et al. 2015) while delivering ecosystem services to the society (Ma et al. 2019). Active maintenance of diversity for ecological functioning by keeping homeostatic feedbacks and avoiding threshold crossings, and increasing the capacity of the system to cope with change through learning and adaptation is significant during resilience management (Allen et al. 2011).

For example, when climate warming triggers alien species in the HKH region, removing invasive plants could be an important agenda for resilience management. However, while rooting out invasive plants, the action may also degrade soil property as well as endan-

gers native wildlife habitats. Hence, resilience management is the use of better strategy and application of policies together with educating local community forest users, forest ecologists and resource managers as a part of broader Himalayan biodiversity conservation and management program for sustainability of ecosystem services in the region. When the demand for sustainable food security and ecosystem services in the face of rapid climate change and biodiversity losses increases, an advanced thinking of resilience management is urgently needed in the HKH region.

With the implementation of new technologies in resilience management, it is also important to have a framework that clearly characterizes the effect on resilience by assessing a range of disruptions affecting the system (Marchese et al. 2020). For instance, diversifying cropping systems in the HKH region can improve resilience of agriculture management practices which has the potential to reduce risk from being collapsed due to climate change related threats and ultimately increases food security in the region (Bowles et al. 2020). However, potentially other impacts of this approach should also be considered at a time of resilience management. Crop choice can have a significant effect on when the HKH region experiences prolonged drought hazard. Crops such as wheat, soybean, and rice are 'C3 plants' which fix CO₂ through 3-carbon compound, phosphoglyceric acid, need to be carefully chosen at a time of drought so that their resilience can be maximized positively. As wheat, soybean and rice have lower water use efficiencies compared to typical dryland crops such as millet or sorghum, any failures to choose a right crop for plantation would lead to reduced resilience (Agnew and Woodhouse 2010). While doing this, the scientific bodies, policy makers and local stakeholders including the farmers groups should work collaboratively.

Similarly, lately the frequency and magnitude of flash floods, debris flow and land slide episodes have increased in many Himalayan countries like India, Pakistan, Afghanistan, Bhutan, and Nepal (Mohanty et al. 2019). Providing sound adaptive flood management strategies to communities and lake and river systems with the ability to anticipate and withstand short-lived extremes (i.e., flood and drought) as well as being able to adapt to long-term shifts in flow patterns is significant (Quincey et al. 2018). Adaptive management is particularly an important part of resilience management in the Himalayas, because it focuses on learning, reducing uncertainty and monitoring of the environmental change (Allen et al. 2011). Ethnic communities in the Himalayas are adapted to severe environmental change over the millennia. Their life experiences, spiritual considerations, family, kinship, and oral history are significant for learning while working for resilience management (Ford et al. 2020). For instance, a resilient flood management approach would not only include structural measures, such as building better levees and dams in the river to achieve stability and predictability of the system but also incorporating local people's knowledge and participation in decision making for sustainability of regulating services of the river and lake ecosystems in the HKH region is important (Sung et al. 2018). Increased climate warming and flood episodes has also elevated river runoff when the biodiversity and ecosystem services are threatened by increased water brownification in the region. Lowland lakes are impacted by exacerbated cyanobacterial growth and increased toxin levels. Food web management can be an important resilience management approach to control harmful cyanobacteria (Urrutia-Cordero et al. 2016). Community participation through research and management of freshwater systems such as the removal of non-native fish that feed on native planktivorous fish would improve water clarity by increasing large zooplankton

populations (Jeppesen et al. 2001) and secure supply of drinking water resources against the negative impacts of climate warming on the lake and river systems in the region.

As the temperature has risen together with changes in precipitation and extreme weather patterns, the biodiversity and ecosystem composition and dynamics, particularly the species with small, but highly specialized population size in the Himalayas are shifting upward, and those cannot shift or adapt to a new environment are threatened to be extinct (Montoya and Raffaelli 2010). For instance, with climate warming cold-adapted species are expected to decline in the lower altitudes, while warm-adapted species increase through upward habitat shifts (Oliver et al. 2015). Resilience management in the Himalayan biodiversity and ecosystem services is potentially significant for limiting the decline of cold-adapted species through identifying the species-specific habitat preference and range shifts. For instance, species not making a range-shift are found more endangered while those shifts along with climate warming are found least vulnerable (Bernardo 2014). Climate warming has affected phenology and functional traits with shift in the start of the growing season and spring greening of grasses and vegetation (Shrestha et al. 2012) as well as fitness or capacity of plants to generate ecosystem services (Wood et al. 2015). Reduced moisture availability in the atmosphere has also affected metabolic and reproductive processes (Sigdel et al. 2020; Xu et al. 2009). Rapid expansion of invasive alien plant species such as *Ageratina Adenophora* L., *Ageratum conyzoides* L., *Ageratum houstonianum* Mill., *Amaranthus spinosus* L., *Bidens pilosa* L., *Erigeron karvinskianus* DC., *Lantana camara* L., *Parthenium hysterophorus* L., *Senna occidentalis* (L.) Link., *Senna tora* L. Roxb. and *Xanthium strumarium* L.) in Nepal and Indian Himalaya has posed severe threats to the biodiversity and stability (resilience) of native ecosystems mainly scrublands and subtropical needle-leaved forests (Thapa et al. 2018). Hence, resilience management should be placed as an utmost priority for species preferring to cold temperature by securing their habitats in the HKH region (McVittie and Faccioli 2020).

Countries across the Himalayas have begun to address issues associated with climate warming, biodiversity losses and resilience management. National and local governments have been working closely with non-governmental organizations such as International Centre for Integrated Mountain Development (ICIMOD), International Union for Nature Conservation (IUCN) and World Bank on transboundary ecological resilience issues. Several biodiversity conservation and management issues, such as wildlife trade, forest fires, migration of animals, watershed restoration, corridor and connectivity development, and transboundary protected area management, are transnational in nature, and have been widely discussed for resilience management. For instance, ICIMOD has conceptualized and operationalized the Kailash Sacred Landscape Initiative (KSLCDI) to its 8 member Himalayan nations between 2011 and 2017 to strengthen relationships between governments of China, India, and Nepal and to mainstream sustainable biodiversity and ecosystem management practices into local and national policies and plans for inclusive socioeconomic development. The initiative has greatly benefitted biodiversity conservation through successful adoption of innovative livelihoods; ecosystem management; access and benefit sharing; long-term environmental and socioecological monitoring; and regional cooperation, and knowledge management (Kotru et al. 2020). Rapid increase of impoundments under intensified climate warming in the Himalayan river systems has threatened aquatic and terrestrial diversity. Watershed-scale planning for hydroelectricity and fish passage development in the region are considered significant (Gillette et al. 2022). In lesser Himalayas such as,

Chitwan National Park, Bardiya National Park, and Koshi Tappu Wildlife Reserve of Nepal, and Jaldapara and Manas national parks of India are refuges for many endemic fish species such as trout barb (*Raiamus bola*) and Hamilton's baril (*Opsarius bendelesis*). Local governments together with stakeholders should require put extra efforts in minimizing water pollution, mining, and sustainable resource harvests in such protected areas (Gillette et al. 2022). On spot sustainability efforts are thought to minimize external inputs to the systems and channelization of internal resources including human, social, and ecological capacity. Strengthening communities' skills and capacities through participatory and collaborative research approaches and co-learning mechanisms together with stakeholders is considered significant for agrobiodiversity conservation-oriented policies and future sustainability in the HKH (Shakya et al. 2019). It appears that there have been positive outcomes of the regional vegetation conservation efforts from GOs and NGOs in the HKH. As the community participation plays a central role for forest management and conservation in HKH, but sometimes, active management can lead to unsustainable biodiversity conservation. For instance, monoculture of *Shorea robusta*, an important timber species in Nepal, through active community management has reduced biodiversity and sustainability. While encouraging community participation in forest management, maintenance of multiple species during thinning and pruning processes and awareness programs should also be placed, which would provide a regeneration ground for a multiple-species and improve sustainability (Paudel and Sah 2015). For effective biodiversity conservation program in the HKH, a simplified cost-benefit analysis is thought to be important to maximize ecosystem services. For instance, a continued biodiversity protection measures placed in government policies can preserve carbon stock, and its high value ecosystem services in mitigating climatic warming in the region (Peh et al. 2016).

Further, mapping and valuing of ecosystem services are becoming important in the HKH region for understanding and standardizing the outputs needed to meet the requirement of the specific policy and tackle the challenge of ecosystem services distribution posed by climate change and anthropogenic disturbances in the region. Incorporating the integrated model in resilience management framework has been found significant to overcome the challenge of sustainable use of ecosystems in Europe (Maes et al. 2012). For instance, mapping water purification services needs a series of maps that illustrate how ecosystem services cascade and used as a frame to map water purification services at a regional scale. In the case of watershed resilience management, each HKH watershed should be regarded as a unit for resilience management with an aim to estimate contribution of biodiversity and ecosystem function to water purification over a certain timeframe. Using various indicator values together with numerical modeling, water purification services in the region can be estimated and mapped (Grizzetti et al. 2016; Karki et al. 2020).

The important aspect of the framework presented in Fig. 5 is to bring the local stakeholders' knowledge and skills in a decision-making process. Such stakeholders are usually the representatives of the scientific community, policy makers and end users of natural resources. A triple-loop learning framework (Pahl-Wostl 2009) of resilience management for a transformation of the entire structural system is suggested by stakeholders to bring a change in regulatory frameworks and practices of governance in risk management. In a triple-loop learning framework, usually three management components are practiced. After the primary learning loop, where the knowledge is advanced through scientific research, the outcomes are usually shared with various stakeholders in the final learning loop (Fig. 5).

The adoption of those outcomes in the management policy following the series of learning cycles can be significant for biodiversity and ecosystem services management in the HKH region. However, complex ecosystem interactions under ongoing environmental change, and institutional governance constrains the implementation of policies. Tackling those constraints through regular restructuring or reorganization, monitoring and evaluation and policy reassessment using an integrated approach of planning and implementation is essential, as this increases resilience and adaptive capacity of biodiversity and ecosystem, which are then being able to generate sustainable ecosystem services to the society of the HKH region.

Box 1 Climate warming and biodiversity losses in HKH: practical solutions for resilience management

Impact	Biodiversity consequences	Practical solution
<p><u>Direct impact:</u> Average rate (0.74 °C) of temperature rise in past 100 years, and average rate (0.6 °C) of regional temperature rise in past 25 years, together with changing pattern of precipitation directly causing biodiversity losses</p>	<p>Rapid retreat of glaciers, extreme floods and droughts and changing hydrological cycles Northward migration of plant and animals; treeline shift of plant species such as dwarf shrubs, herbs, and grasses, bryophytes, and lichens; advancement of vegetation phenology and greening</p>	<p>Extensive collection, and robust and harmonized monitoring of climate related data Use of diversified methods to understand causal mechanisms species response to climate change</p>
<p><u>Indirect impact:</u> Climatic warming affecting biodiversity losses indirectly via mobilizing soil moisture, water nutrients, and pH</p>	<p>Variation in soil moisture regime; and stress on plant growth, seedling survival, and vegetation browning Increased acidification, nutrients, and CO₂ levels with highly productive, decomposed environments leading to poor biodiversity, and ecosystem services including reduced water quality, altered pollination, pest regulation</p>	<p>Incorporation of integrated models to overcome the challenge; and use of multi-indicator value approach to identify the status of regional biodiversity Development of numerical modeling approaches for predicting future biodiversity losses caused by direct and indirect impacts</p>
<p>Mixed impact: Combined and modulated effects of climate warming and anthropogenic disturbances</p>	<p>Reduced biodiversity and poor ecosystem functioning Lowering of both ecological resilience and ecological resistance</p>	<p>Collaboration among policy makers and scientists and to ensure that scientific evidence would speak to diverse needs of mountain people Implementation of new technologies, such as diversification of cropping systems to improve agro-biodiversity resilience</p>

The development of a framework in Fig. 5 would offer some of the key practical solutions for combating the challenges posed by the impact of climate warming on biodiversity and sustainability in the HKH region and is summarized in Box 1.

The direct impact of climate warming such as the retreat of Himalayan glaciers causing extreme flood, drought, and northward migration and phenology of biota, for which a robust and harmonized monitoring of climate data and the use of diversified approaches is essential for building ecological resilience (Jones et al. 2021). The indirect impact of climate warming on biodiversity losses in HKH is not well understood, but the consequences of reduced pH values, and enriched nutrients are intensified by climate change, which should be resolved through multi-indicator values (bio-geochemical indicators) and modelling approaches. More importantly, the combined effect of climate warming and anthropogenic disturbance including the land use change is thought to be severe on biodiversity losses, which strongly modulate ecosystem functioning, and lower ecological resilience and resistance. For this, strong collaboration among policy makers, implementers, and analysts is needed to ensure that evidence-based research would be the only, and best solution for ecological resilience management in the HKH region.

Conclusions

The Himalayan biodiversity generates some of the most essential ecosystem services including food production, water supply, pollination, climate regulation and intrinsic values to more than one billion people residing in the HKH region by maintaining the ecosystem functioning over the millennia. However, unprecedented climate warming during the 21st century has threatened the HKH biodiversity and ecosystem services and the regional prosperity for the mankind. Today, the endemic biota, their ability to adapt to change, and the role of indigenous knowledge of the local people in combating the climate change impacts over the millennia has become threatened. Resilience management offers practical solutions to tackle the rapidly evolving biodiversity and ecosystem services crises in the Himalayas. Resilience management, when implemented as a series of learning cycles, can have an ability to identify the crises and help prepare to defend, as well as reorganize the threats of biodiversity and ecosystem functioning through collaboration amongst various stakeholders including the scientists and decision makers. Evaluation of rapidly changing ecosystem services using sophisticated models such as the integration of biodiversity response to climate change, benchmark of ecological thresholds and the stability of ecosystem functioning and incorporation of those models in resilience management framework is essential for meeting the SDGs of the HKH countries by 2030.

Acknowledgements I would like to acknowledge Longshan Professorship and the talent grant (#1511582101011) at Nanjing University of Information Science and Technology (NUIST), and global talent scholar program at Tsinghua University (Beijing). I would also like to extend gratitude to the editor of Biodiversity and Conservation, and five other anonymous reviewers, whose comments significantly improved the quality of the manuscript. Dr. Himalaya Singh kindly assisted to draw the Hindu-Kush Himalayan (HKH) regional map (Fig. 1) in ArcGIS.

Author contribution NA.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions

Data Availability NA.

Declarations

Conflict of Interest NA.

Animal Research (Ethics) NA.

Consent to participate (Ethics) NA.

Consent to Publish (Ethics) NA.

Plant Reproducibility NA.

Clinical trials Registration NA.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Acharya RP, Maraseni T, Cockfield G (2020a) Assessing the financial contribution and carbon emission pattern of provisioning ecosystem services in Siwalik forests in Nepal: Valuation from the perspectives of disaggregated users. *Land Use Policy* 95
- Acharya RP, Maraseni TN, Cockfield G (2020b) An Ecosystem Services Valuation Research Framework for Policy Integration in Developing Countries: A Case Study from Nepal. *Sustainability* 12(19)
- Adger WN (2000) Social and ecological resilience: are they related? *Prog Hum Geogr* 24:347–364
- Agnew C, Woodhouse P (2010) Climate Change Resilience and Adaptation: Perspectives from a Century of Water Resources Development. *Environ Soc* 1(1):156–183
- Allen CR, Cumming GS, Garmestani AS, Taylor PD, Walker BH (2011) Managing for resilience. *Wildl Biology* 17(4):337–349
- Ament JM, Moore CA, Herbst M, Cumming GS (2017) Cultural Ecosystem Services in Protected Areas: Understanding Bundles, Trade-Offs, and Synergies. *Conserv Lett* 10(4):440–450
- Apitz SE (2012) Conceptualizing the role of sediment in sustaining ecosystem services: Sediment-ecosystem regional assessment (SEcoRA). *Sci Total Environ* 415:9–30
- Arneeth A, Shin YJ, Leadley P, Rondinini C, Bukvareva E, Kolb M, Midgley GF, Oberdorff T, Palomo I, Saito O (2020) Post-2020 biodiversity targets need to embrace climate change. *Proc Natl Acad Sci U S A* 117(49):30882–30891
- Arora M, Kumar R, Singh RD, Malhotra J, Kumar N (2016) Analysis of unusual meteorological conditions that led to recent floods in Bhagirathi basin (Uttarakhand Himalayas). *Hydrological Sciences Journal*:1–6
- Bajracharya SR, Maharjan SB, Shrestha F, Guo W, Liu S, Immerzeel W, Shrestha B (2015) The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. In: *International Journal of Water Resources Development*. vol 2. p 161–173
- Ballesteros-Canovas JA, Trappmann D, Madrigal-Gonzalez J, Eckert N, Stoffel M (2018) Climate warming enhances snow avalanche risk in the Western Himalayas. *Proc Natl Acad Sci U S A* 115(13):3410–3415
- Balvanera P, Pfisterer AB, Buchmann N, He JS, Nakashizuka T, Raffaelli D, Schmid B (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecol Lett* 9(10):1146–1156

- Balvanera P, Siddique I, Dee L, Paquette A, Isbell F, Gonzalez A, Byrnes J, O'Connor MI, Hungate BA, Griffin JN (2014) Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps. *Bioscience* 64(1):49–57
- Baron JS, Poff NL, Angermeier PL, Dahm CNG, Peter H, Hairston NGJ, Jackson RBJ, Carol A, Richter, Brian D, Steinman AD (2002) Meeting ecological and societal needs for freshwater. *Ecol Appl* 12(5):1247–1260
- Bastian O (2013) The role of biodiversity in supporting ecosystem services in Natura 2000 sites. *Ecol Ind* 24:12–22
- Behera MD, Behera SK, Sharma S (2019) Recent advances in biodiversity and climate change studies in India. *Biodivers Conserv* 28(8–9):1943–1951
- Benkwitt CE, Wilson SK, Graham NAJ (2020) Biodiversity increases ecosystem functions despite multiple stressors on coral reefs. *Nat Ecol Evol* 4(7):919–926
- Bernardo J (2014) Biologically grounded predictions of species resistance and resilience to climate change. *Proc Natl Acad Sci U S A* 111(15):5450–5451
- Betts MG, Wolf C, Ripple WJ, Phalan B, Millers KA, Duarte A, Butchart SHM, Levi T (2017) Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* 547(7664):441–444
- Bhattacharjee A, Anadón J, Lohman D, Doleck T, Lakhankar T, Shrestha B, Thapa P, Devkota D, Tiwari S, Jha A, Siwakoti M, Devkota N, Jha P, Krakauer N (2017) The Impact of Climate Change on Biodiversity in Nepal: Current Knowledge, Lacunae, and Opportunities. *Climate* 5(4)
- Bhattarai KK, Pant LP, FitzGibbon J (2020) Contested governance of drinking water provisioning services in Nepal's transboundary river basins. *Ecosystem Services* 45
- Boltz F, LeRoy Poff N, Folke C, Kete N, Brown CM, St. George Freeman S, Matthews JH, Martinez A, Rockström J (2019) Water is a master variable: Solving for resilience in the modern era. *Water Security* 8
- Bormann JF, Barnes PW, Robson TM, Robinson SA, Jansen MAK, Ballare CL, Flint SD (2019) Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems. *Photochem Photobiol Sci* 18(3):681–716
- Bowles TM, Mooshammer M, Socolar Y, Calderón F, Cavigelli MA, Culman SW, Deen W, Drury CF, Garcia y Garcia A, Gaudin ACM, Harkcom WS, Lehman RM, Osborne SL, Robertson GP, Salerno J, Schmer MR, Strock J, Grandy AS (2020) Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America. *One Earth* 2(3):284–293
- Buzhdygan OY, Meyer ST, Weisser WW, Eisenhauer N, Ebeling A, Borrett SR, Buchmann N, Cortois R, De Deyn GB, de Kroon H, Gleixner G, Hertzog LR, Hines J, Lange M, Mommer L, Ravenek J, Scherber C, Scherer-Lorenten M, Scheu S, Schmid B, Steinauer K, Strecker T, Tietjen B, Vogel A, Weigelt A, Petermann JS (2020) Biodiversity increases multitrophic energy use efficiency, flow and storage in grasslands. *Nat Ecol Evol* 4(3):393–405
- Calder WJ, Shuman B (2019) Detecting past changes in vegetation resilience in the context of a changing climate. *Biol Lett* 15(3):20180768
- Camargo A, Cortesi L (2019) Flooding water and society. *Wiley Interdisciplinary Reviews: Water*, 6(5)
- Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS, Naeem S (2012) Biodiversity loss and its impact on humanity. *Nature* 486:59–67
- Carpenter SR, Mooney HA, Agard J, Capistrano D, Defries RS, Diaz S, Dietz T, Duraiappah AK, Oteng-Yeboah A, Pereira HM, Perrings C, Reid WV, Sarukhan J, Scholes RJ, Whyte A (2009) Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc Natl Acad Sci U S A* 106(5):1305–1312
- Chaudhari S, Felfelani F, Shin S, Pokhrel Y (2018) Climate and anthropogenic contributions to the desiccation of the second largest saline lake in the twentieth century. *J Hydrol* 560:342–353
- Covich A, Palmer MA, Crowl TA (1999) The Role of Benthic Invertebrate Species in Freshwater Ecosystems Zoobenthic species influence energy flows and nutrient cycling. *Bioscience* 49:119–127
- Dolezal J, Jandova V, Macek M, Mudrak O, Altman J, Schweingruber FH, Liancourt P, Bonser S (2020) Climate warming drives Himalayan alpine plant growth and recruitment dynamics. *J Ecol* 109(1):179–190
- Dorji T, Brookes J, Facelli J, Sears R, Norbu T, Dorji K, Chhetri Y, Baral H (2019) Socio-Cultural Values of Ecosystem Services from Oak Forests in the Eastern Himalaya. *Sustainability* 11(8)
- Ford JD, King N, Galappaththi EK, Pearce T, McDowell G, Harper SL (2020) The Resilience of Indigenous Peoples to Environmental Change. *One Earth* 2(6):532–543
- Gautam BR, Li F, Ru G (2014) Climate change risk for hydropower schemes in Himalayan region. *Environ Sci Technol* 48(14):7702–7703
- Gertler CG, Puppala SP, Panday A, Stumm D, Shea J (2016) Black carbon and the Himalayan cryosphere: A review. *Atmos Environ* 125:404–417

- Gillette DP, Edds DR, Jha BR, Mishra B (2022) Thirty years of environmental change reduces local, but not regional, diversity of riverine fish assemblages in a Himalayan biodiversity hotspot. *Biological Conservation*, 265
- Glazer AN, Likens GE (2012) The water table: the shifting foundation of life on land. *Ambio* 41(7):657–669
- Godwin H (1996) In pursuit of ecotourism. *Biodivers Conserv* 5:277–291
- Gong P, Wang X, Pokhrel B, Wang H, Liu X, Liu X, Wania F (2019) Trans-Himalayan Transport of Organochlorine Compounds: Three-Year Observations and Model-Based Flux Estimation. *Environ Sci Technol* 53(12):6773–6783
- Green PA, Vörösmarty CJ, Harrison I, Farrell T, Sáenz L, Fekete BM (2015) Freshwater ecosystem services supporting humans: Pivoting from water crisis to water solutions. *Glob Environ Change* 34:108–118
- Grizzetti B, Lanzanova D, Liqete C, Reynaud A, Cardoso AC (2016) Assessing water ecosystem services for water resource management. *Environ Sci Policy* 61:194–203
- Guzzella L, Poma G, De Paolis A, Roscioli C, Viviano G (2011) Organic persistent toxic substances in soils, waters and sediments along an altitudinal gradient at Mt. Sagarmatha, Himalayas, Nepal. *Environ Pollut* 159(10):2552–2564
- Habibullah MS, Din BH, Tan SH, Zahid H (2022) Impact of climate change on biodiversity loss: global evidence. *Environ Sci Pollut Res Int* 29(1):1073–1086
- Hamid M, Khuroo AA, Charles B, Ahmad R, Singh CP, Aravind NA (2018) Impact of climate change on the distribution range and niche dynamics of Himalayan birch, a typical treeline species in Himalayas. *Biodivers Conserv* 28(8–9):2345–2370
- Haq SM, Calixto ES, Kumar M (2020) Assessing Biodiversity and Productivity over a Small-scale Gradient in the Protected Forests of Indian Western Himalayas. *Journal of Sustainable Forestry*:1–20
- Hasson Su, Saeed F, Böhner J, Schluessner C-F (2019) Water availability in Pakistan from Hindukush–Karakoram–Himalayan watersheds at 1.5°C and 2°C Paris Agreement targets. *Advances in Water Resources* 131
- Hauer FR, Locke H, Dreitz VJ, Hebblewhite MH, Lowe WH, Muhlfeld CC, Nelson CR, Proctor MF, Rood SB (2016) Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscape. *Sci Adv* 2:e1600026
- Hector A, Bagchi R (2007) Biodiversity and ecosystem multifunctionality. *Nature* 448(7150):188–190
- Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S (2013) Global flood risk under climate change. *Nat Clim Change* 3(9):816–821
- Holling CS (2001) Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4(5):390–405
- Hooper DU, Adair EC, Cardinale BJ, Byrnes JE, Hungate BA, Matulich KL, Gonzalez A, Duffy JE, Gamfeldt L, O'Connor MI (2012) A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* 486(7401):105–108
- Huss M, Hock R (2018) Global-scale hydrological response to future glacier mass loss. *Nat Clim Change* 8(2):135–140
- Immerzeel WW, Lutz AF, Andrade M, Bahl A, Biemans H, Bolch T, Hyde S, Brumby S, Davies BJ, Elmore AC, Emmer A, Feng M, Fernandez A, Haritashya U, Kargel JS, Koppes M, Kraaijenbrink PDA, Kulkarni AV, Mayewski PA, Nepal S, Pacheco P, Painter TH, Pellicciotti F, Rajaram H, Rupper S, Sinisalo A, Shrestha AB, Viviroli D, Wada Y, Xiao C, Yao T, Baillie JEM (2020) Importance and vulnerability of the world's water towers. *Nature* 577(7790):364–369
- Ingty T (2021) Pastoralism in the highest peaks: Role of the traditional grazing systems in maintaining biodiversity and ecosystem function in the alpine Himalaya. *PLoS ONE* 16(1):e0245221
- Jeppesen E, Leavitt P, De Meester L, Jensen JP (2001) Functional ecology and palaeolimnology: using cladoceran remains to reconstruct anthropogenic impact. *Trends Ecol Evol* 16(4):191–198
- Jiang T, Su B, Huang J, Zhai J, Xia J, Tao H, Wang Y, Sun H, Luo Y, Zhang L, Wang G, Zhan C, Xiong M, Kundzewicz ZW (2020) Each 0.5°C of Warming Increases Annual Flood Losses in China by More than US\$60 Billion. *Bull Am Meteorol Soc* 101(8):E1464–E1474
- Jiang X, Xie Y (2020) Meta-analysis reveals severe pollen limitation for the flowering plants growing in East Himalaya-Hengduan Mountains region. *BMC Ecol* 20(1):53
- Jones L, Constan A, Matthews M, Verkaart N (2021) S Advancing resilience measurement. *Nature sustainability*
- Karki S, Stewardson MJ, Webb JA, Fowler K, Kattel GR, Gilvear DJ (2020) Does the topology of the river network influence the delivery of riverine ecosystem services? *River Res Appl* 37:1–14
- Kattel G, Zhang K, Yang X (2018) Application of subfossil cladocerans (water fleas) in assessing ecological resilience of shallow Yangtze River floodplain lake systems (China). *Science China Earth Sciences*
- Khadka UR, Ramanathan AL (2012) Major ion composition and seasonal variation in the Lesser Himalayan lake: case of Begnas Lake of the Pokhara Valley, Nepal. *Arab J Geosci* 6(11):4191–4206
- Khan SM (2013) Medicinal flora and ethnoecological knowledge in the Naran Valley, Western Himalaya, Pakistan. *Journal of Ethnobiology and Ethnomedicine* 9

- Khan SM, Page S, Ahmad H, Harper D (2014) Ethno-ecological importance of plant biodiversity in mountain ecosystems with special emphasis on indicator species of a Himalayan Valley in the northern Pakistan. *Ecol Ind* 37:175–185
- Khatiwada K, Panthi J, Shrestha M, Nepal S (2016) Hydro-Climatic Variability in the Karnali River Basin of Nepal Himalaya. *Climate* 4(2)
- Kotru RK, Shakya B, Joshi S, Gurung J, Ali G, Amatya S, Pant B (2020) Biodiversity Conservation and Management in the Hindu Kush Himalayan Region: Are Transboundary Landscapes a Promising Solution? *Mountain Research and Development* 40(2)
- Kovacs-Hostyanszki A, Espindola A, Vanbergen AJ, Settele J, Kremen C, Dicks LV (2017) Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecol Lett* 20(5):673–689
- Kummu M, Tes S, Yin S, Adamson P, Józsa J, Koponen J, Richey J, Sarkkula J (2014) Water balance analysis for the Tonle Sap Lake-floodplain system. *Hydrol Process* 28(4):1722–1733
- Kuniyal CP, Bisht VK, Negi JS, Bhatt VP, Bisht DS, Butola JS, Sundriyal RC, Singh SK (2014) Progress and prospect in the integrated development of medicinal and aromatic plants (MAPs) sector in Uttarakhand, Western Himalaya. *Environ Dev Sustain* 17(5):1141–1162
- Kunwar RM, Baral K, Paudel P, Acharya RP, Thapa-Magar KB, Cameron M, Bussmann RW (2016) Land-Use and Socioeconomic Change, Medicinal Plant Selection and Biodiversity Resilience in Far Western Nepal. *PLoS ONE* 11(12):e0167812
- Lacoul P, Freedman B (2006) Relationships between aquatic plants and environmental factors along a steep Himalayan altitudinal gradient. *Aquat Bot* 84(1):3–16
- Lami A, Marchetto A, Musazzi S, Salerno F, Tartari G, Gullizzoni P, Rogora M, Tartari GA (2010) Chemical and biological response of two small lakes in the Khumbu Valley, Himalayas (Nepal) to short-term variability and climatic change as detected by long-term monitoring and paleolimnological methods. *Hydrobiologia* 648(1):189–205
- Lamsal P, Kumar L, Shabani F, Atreya K (2017) The greening of the Himalayas and Tibetan Plateau under climate change. *Glob Planet Change* 159:77–92
- Lau WKM, Kim M-K, Kim K-M, Lee W-S (2010) Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. *Environmental Research Letters* 5(2)
- Li F, Shah D, Pauls S, Qu X, Cai Q, Tachamo Shah R (2016) Elevational Shifts of Freshwater Communities Cannot Catch up Climate Warming in the Himalaya. *Water* 8(12)
- Li S, Zhang H, Zhou X, Yu H, Li W (2020) Enhancing protected areas for biodiversity and ecosystem services in the Qinghai–Tibet Plateau. *Ecosystem Services* 43
- Lucas P, Kok M, Nilsson M, Alkemade R (2013) Integrating Biodiversity and Ecosystem Services in the Post-2015 Development Agenda: Goal Structure, Target Areas and Means of Implementation. *Sustainability* 6(1):193–216
- MA (2005) *Ecosystems and Human Well-Being: Current State and Trends*. Island Press, Washington, DC
- Ma A, Lu X, Gray C, Raybould A, Tamaddoni-Nezhad A, Woodward G, Bohan DA (2019) Ecological networks reveal resilience of agro-ecosystems to changes in farming management. *Nat Ecol Evol* 3(2):260–264
- Maes J, Egoh B, Willemsen L, Liquete C, Vihervaara P, Schägner JP, Grizzetti B, Drakou EG, Notte AL, Zulian G, Bouraoui F, Luisa Paracchini M, Braat L, Bidoglio G (2012) Mapping ecosystem services for policy support and decision making in the European Union. *Ecosyst Serv* 1(1):31–39
- Manca M, Comoli P (2004) Reconstructing long-term changes in *Daphnia*'s body size from subfossil remains in sediments of a small lake in the Himalayas. *J Paleolimnol* 32:95–107
- Marchese D, Jin A, Fox-Lent C, Linkov I (2020) Resilience for Smart Water Systems. *Journal of Water Resources Planning and Management* 146(1)
- McVittie A, Faccioli M (2020) Biodiversity and ecosystem services net gain assessment: A comparison of metrics. *Ecosystem Services* 44
- Mohanty A, Hussain M, Mishra M, Kattel DB, Pal I (2019) Exploring community resilience and early warning solution for flash floods, debris flow and landslides in conflict prone villages of Badakhshan, Afghanistan. *Int J Disaster Risk Reduct* 33:5–15
- Montoya JM, Raffaelli D (2010) Climate change, biotic interactions and ecosystem services. *Philos Trans R Soc Lond B Biol Sci* 365(1549):2013–2018
- Nepal M, Rai R, Das S, Bhatta L, Kotru R, Khadayat M, Rawal R, Negi G (2018) Valuing Cultural Services of the Kailash Sacred Landscape for Sustainable Management. *Sustainability* 10(10)
- Nepal S, Flügel W-A, Shrestha AB (2014) Upstream-downstream linkages of hydrological processes in the Himalayan region *Ecological Processes* 3: 1–16
- Nie Y, Pritchard HD, Liu Q, Hennig T, Wang W, Wang X, Liu S, Nepal S, Samyn D, Hewitt K, Chen X (2021) Glacial change and hydrological implications in the Himalaya and Karakoram. *Nat Reviews Earth Environ* 2:91–106

- Oliver TH, Heard MS, Isaac NJB, Roy DB, Procter D, Eigenbrod F, Freckleton R, Hector A, Orme CDL, Petchey OL, Proenca V, Raffaelli D, Suttle KB, Mace GM, Martin-Lopez B, Woodcock BA, Bullock JM (2015) Biodiversity and Resilience of Ecosystem Functions. *Trends Ecol Evol* 30(11):673–684
- Pahl-Wostl C (2009) A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Glob Environ Change* 19(3):354–365
- Pant M, Negi GCS, Kumar P (2017) Macrofauna contributes to organic matter decomposition and soil quality in Himalayan agroecosystems, India. *Appl Soil Ecol* 120:20–29
- Paudel S, Sah JP (2015) Effects of Different Management Practices on Stand Composition and Species Diversity in Subtropical Forests in Nepal: Implications of Community Participation in Biodiversity Conservation. *J Sustainable Forestry* 34(8):738–760
- Peh KSH, Thapa I, Basnyat M, Balmford A, Bhattarai GP, Bradbury RB, Brown C, Butchart SHM, Dhakal M, Gurung H, Hughes FMR, Mulligan M, Pandeya B, Stattersfield AJ, Thomas DHL, Walpole M, Merriman JC (2016) Synergies between biodiversity conservation and ecosystem service provision: Lessons on integrated ecosystem service valuation from a Himalayan protected area, Nepal. *Ecosyst Serv* 22:359–369
- Peters MK, Hemp A, Appelhans T, Becker JN, Behler C, Classen A, Detsch F, Ensslin A, Ferger SW, Frederiksen SB, Gebert F, Gerschlauser F, Gutlein A, Helbig-Bonitz M, Hemp C, Kindeketa WJ, Kuhnelt A, Mayr AV, Mwangomo E, Ngereza C, Njovu HK, Otte I, Pabst H, Renner M, Roder J, Rutten G, Schellenberger Costa D, Sierra-Cornejo N, Vollstadt MGR, Dulle HI, Eardley CD, Howell KM, Keller A, Peters RS, Ssymank A, Kakengi V, Zhang J, Bogner C, Bohning-Gaese K, Brandl R, Hertel D, Huwe B, Kiese R, Kleyer M, Kuzakov Y, Nauss T, Schleuning M, Tschapka M, Fischer M, Steffan-Dewenter I (2019) Climate-land-use interactions shape tropical mountain biodiversity and ecosystem functions. *Nature* 568(7750):88–92
- Pires APF, Srivastava DS, Marino NAC, Macdonald AA, Figueiredo-Barros P, Farfalla VF (2018) Interactive effects of climate change and biodiversity loss on ecosystem functioning. *Ecology* 99:1203–1213
- Potts SG, Imperatriz-Fonseca V, Ngo HT, Aizen MA, Biesmeijer JC, Breeze TD, Dicks LV, Garibaldi LA, Hill R, Settele J, Vanbergen AJ (2016) Safeguarding pollinators and their values to human well-being. *Nature* 540(7632):220–229
- Quincey D, Klaar M, Haines D, Lovett J, Pariyar B, Gurung G, Brown L, Watson C, England M, Evans B (2018) The changing water cycle: the need for an integrated assessment of the resilience to changes in water supply in High-Mountain Asia. *Wiley Interdisciplinary Reviews: Water* 5(1)
- Rashid I, Romshoo SA (2013) Impact of anthropogenic activities on water quality of Lidder River in Kashmir Himalayas. *Environ Monit Assess* 185(6):4705–4719
- Rashid I, Romshoo SA, Chaturvedi RK, Ravindranath NH, Sukumar R, Jayaraman M, Lakshmi TV, Sharma J (2015) Projected climate change impacts on vegetation distribution over Kashmir Himalayas. *Clim Change* 132(4):601–613
- Rawat M, Arunachalam K, Arunachalam A, Alatalo JM, Kumar U, Simon B, Hufnagel L, Micheli E, Pandey R (2020) Relative contribution of plant traits and soil properties to the functioning of a temperate forest ecosystem in the Indian Himalayas. *Catena* 194
- Rockström J (2009) A safe operating space for humanity. *Nature* 461:472–461
- Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research* 45(7)
- Saslis-Lagoudakis CH, Hawkins JA, Greenhill SJ, Pendry CA, Watson MF, Tuladhar-Douglas W, Baral SR, Savolainen V (2014) The evolution of traditional knowledge: environment shapes medicinal plant use in Nepal. *Proc Biol Sci* 281(1780):20132768
- Schirpke U, Timmermann F, Tappeiner U, Tasser E (2016) Cultural ecosystem services of mountain regions: Modelling the aesthetic value. *Ecol Indic* 69:78–90
- Scott D, Jones B, Konopek J (2007) Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: A case study of Waterton Lakes National Park. *Tour Manag* 28(2):570–579
- Shakya B, Shrestha A, Sharma G, Gurung T, Mihin D, Yang S, Jamir A, Win S, Han X, Yang Y, Choudhury D, Schneider F (2019) Visualizing Sustainability of Selective Mountain Farming Systems from Far-eastern Himalayas to Support Decision Making. *Sustainability* 11(6)
- Sharma B, Rasul G, Chettri N (2015) The economic value of wetland ecosystem services: Evidence from the Koshi Tappu Wildlife Reserve, Nepal. *Ecosyst Serv* 12:84–93
- Shrestha UB, Gautam S, Bawa KS (2012) Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS ONE* 7(5):e36741
- Sigdel SR, Pandey J, Liang E, Muhammad S, Babst F, Leavitt SW, Shen M, Zhu H, Salerno F, Piao S, Camarero JJ, Peñuelas J (2021) No benefits from warming even for subnival vegetation in the central Himalayas. *Sci Bull* 66(18):1825–1829

- Sigdel SR, Wang Y, Camarero JJ, Zhu H, Liang E, Penuelas J (2018) Moisture-mediated responsiveness of treeline shifts to global warming in the Himalayas. *Glob Chang Biol* 24(11):5549–5559
- Sigdel SR, Zhang H, Zhu H, Muhammad S, Liang E (2020) Retreating Glacier and Advancing Forest Over the Past 200 Years in the Central Himalayas. *J Geophys Res: Biogeosciences* 125(9):1–14
- Stringer LC, Dougill AJ, Thomas AD, Spracklen DV, Chesterman S, Speranza CI, Rueff H, Riddell M, Williams M, Beedy T, Abson DJ, Klintonberg P, Syampungani S, Powell P, Palmer AR, Seely MK, Mkwambisi DD, Falcao M, Siteo A, Ross S, Kopolu G (2012) Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands. *Environ Sci Policy* 19–20:121–135
- Sunday JM (2020) The pace of biodiversity change in a warming climate. *Nature*
- Sung K, Jeong H, Sangwan N, Yu DJ (2018) Effects of Flood Control Strategies on Flood Resilience Under Sociohydrological Disturbances. *Water Resour Res* 54(4):2661–2680
- Sweeney BW, Bott TL, Jackson JK, Kaplan LA, Newbold JD, Standley LJ, Hession WC, Horwitz RJ (2004) Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proc Natl Acad Sci U S A* 101(39):14132–14137
- Szabó Z, Buczkó K, Haliuc A, Pál I, Korponai J, Begy R-C, Veres D, Luoto TP, Zsigmond AR, Magyari EK (2020) Ecosystem shift of a mountain lake under climate and human pressure: A move out from the safe operating space. *Science of The Total Environment*
- Telwala Y, Brook BW, Manish K, Pandit MK (2013) Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. *PLoS ONE* 8(2):e57103
- Thapa S, Chitale V, Rijal SJ, Bisht N, Shrestha BB (2018) Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. *PLoS ONE* 13(4):e0195752
- Thorn JPR, Thornton TF, Helfgott A, Willis KJ (2020) Indigenous uses of wild and tended plant biodiversity maintain ecosystem services in agricultural landscapes of the Terai Plains of Nepal. *J Ethnobiol Ethnol* 16(1):33
- Trabucchi M, Ntshotsho P, O'Farrell P, Comin FA (2012) Ecosystem service trends in basin-scale restoration initiatives: a review. *J Environ Manage* 111:18–23
- Urrutia-Cordero P, Ekvall MK, Hansson LA (2016) Local food web management increases resilience and buffers against global change effects on freshwater. *Sci Rep* 6:29542
- Van Schmidt ND, Oviedo JLO, Hruska T, Huntsinger L, Kovach TJ, Kilpatrick A, Miller NL, Beissinger SR (2021) Assessing impacts of social-ecological diversity on resilience in a wetland coupled human and natural system. *Ecol Soc* 26(2):3
- Villa JA, Bernal B (2018) Carbon sequestration in wetlands, from science to practice: An overview of the biogeochemical process, measurement methods, and policy framework. *Ecol Eng* 114:115–128
- Watt G, Lane R, Head L (2003) The boundaries of nature tourism. *Annals of Tourism Research* 30(3):523–545
- Walsh JR, Carpenter SR, Vander Zanden MJ (2016) Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proc Natl Acad Sci U S A* 113(15):4081–4085
- Williamson CE, Dodds W, Kratz TK, Palmer MA (2008) Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. *Front Ecol Environ* 6(5):247–254
- Wood SA, Karp DS, DeClerck F, Kremen C, Naeem S, Palm CA (2015) Functional traits in agriculture: agrobiodiversity and ecosystem services. *Trends Ecol Evol* 30(9):531–539
- Wood SLR, Jones SK, Johnson JA, Brauman KA, Chaplin-Kramer R, Fremier A, Girtvetz E, Gordon LJ, Kappel CV, Mandle L, Mulligan M, O'Farrell P, Smith WK, Willemsen L, Zhang W, DeClerck FA (2018) Distilling the role of ecosystem services in the Sustainable Development Goals. *Ecosyst Serv* 29:70–82
- Xu F, Fox D (2014) Modelling attitudes to nature, tourism and sustainable development in national parks: A survey of visitors in China and the UK. *Tour Manag* 45:142–158
- Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang Y, Wilkes A (2009) The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conserv Biol* 23(3):520–530
- Xu J, Zhang Q, Li X, Ge X, Xiao C, Ren J, Qin D (2013) Dissolved organic matter and inorganic ions in a central Himalayan glacier—insights into chemical composition and atmospheric sources. *Environ Sci Technol* 47(12):6181–6188
- Zahoor S, Dutt V, Mughal AH, Pala NA, Qaisar KN, Khan PA (2021) Apple-based agroforestry systems for biomass production and carbon sequestration: implication for food security and climate change contemplates in temperate region of Northern Himalaya, India. *Agroforest Syst* 95(2):367–382
- Zomer R, Sharma E (2009) A need for mountain perspectives: Impacts of climate change on ecosystem services in the greater Hindu Kush – Himalaya region. *IOP Conference Series: Earth and Environmental Science* 6(30): 302040–302041

Authors and Affiliations

Giri R Kattel^{1,2,3}

✉ Giri R Kattel
gkattel@unimelb.edu.au

¹ School of Geographical Sciences, Nanjing University of Information Science and Technology (NUIST), Nanjing, China

² Department of Hydraulic Engineering, Tsinghua University, Beijing, China

³ Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia