CHAPTER 4

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Effects of a changing cryosphere on biodiversity and ecosystem services, and response options in the Hindu Kush Himalaya

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Chapter overview

KEY FINDINGS

The cryosphere of the Hindu Kush Himalaya (HKH) is an important source of water for maintaining ecosystem health, supporting biological diversity, and providing ecosystem services (*very high confidence*). This biodiversity-rich region – 40% of which is under protected area coverage – is characterised by interconnected and diverse ecosystems. Sixty percent of the region features seasonal cryosphere (snow, glacier, permafrost, and glacial lakes) – a major source of water and other ecosystem services (*very high confidence*).

However, multiple drivers of change, including climate change, are impacting the fragile HKH ecosystem and cryosphere, bringing cascading impacts on surrounding ecosystems and human wellbeing (*high confidence*). As a fragile ecosystem, the HKH is extremely sensitive to climate change. Widespread shrinking of the cryosphere – attributable to climate change – is resulting in glacier mass loss, snow cover reduction, shrinkage of permafrost area, changes in hydrology, and increased natural hazards and disasters (*high confidence*). Cascading impacts have been reported in most ecosystems, affecting most inhabitant species (*high confidence*). A visible range shift of species to higher elevations, ecosystem degradation and changes, decrease in habitat suitability, species decline and extinction, and invasion by alien species have been reported, both increasing the vulnerabilities of biodiversity and people and affecting their wellbeing (*high confidence*).

Future scenarios paint an alarming picture at the ecosystem and species levels – increased ecosystem vulnerability and lowered ecosystem services flows will result in disruptions to social–ecological resilience (*high confidence*). There is increasing documentation of the cascading effects of cryosphere loss on ecosystems, including ecosystem degradation and changes in species structure and composition. Predicted scenarios show more extreme events taking place, with increasing imbalances in ecosystem functions resulting in more acute societal vulnerability (*high confidence*).

POLICY MESSAGES

HKH ecosystems are complex and have specificities. Integrated approaches and regional interventions that minimise vulnerability – for ecosystems and human wellbeing – are required to address extreme events. The HKH region is characterised by large variations in ecosystems and cultures, and its local communities depend heavily on natural resources. Blanket approaches to minimising vulnerability will prove ineffective here. Nature-based solutions that consider customised interventions and are grounded in an ecosystems-based understanding could make for a possible, effective approach.

Stronger science on mountain ecosystems is needed to increase understanding of their complexities. Though climate science is gaining attention and investments in research are increasing, improving understanding of the complex interlinkages between climate change, cryosphere, ecosystems, and society needs urgent attention. Only then will designing and implementing interventions to increase resilience and develop adaptation capacity be possible.

The HKH region is a global asset. Conservation of its shared heritage requires regional cooperation. Considered the "Water Tower of Asia", the HKH contributes water and ecosystem services to a quarter of humanity. This shared heritage and its fragile ecosystems are facing regional challenges. Therefore, actions to address them also need to be regional in scale. South–South cooperation and implementation of the HKH Call to Action to sustain mountain environments and improve livelihoods could be promising ways forward.

CHAPTER SUMMARY

Global and regional drivers of biodiversity loss — such as land use change and habitat loss, pollution, climate change, and invasive alien species — are prevalent and increasing in the HKH (*high confidence*). For example, by 2100, the Indian Himalaya could see nearly a quarter of its endemic species wiped out (*medium confidence*). Although countries in the region already place a premium on functional ecosystems and ecosystem services – over 40% of all land in the HKH lies within protected area systems (*very high confidence*), ecosystems are in stress or are subject to risks – from a changing climate, varying government policies, and expanding markets (*high confidence*).

The HKH, also referred to as the "Third Pole", is an important repository of cryosphere outside the North and South poles (*very high confidence*). As the youngest mountain ecosystem, the HKH region is also significant in terms of the history of its formation, which has created geodiversity, multiple elevational gradients, and micro-climates (*very high confidence*). These variations enable diversity in vegetation zones that enrich biodiversity, including ecosystems diversity. The resulting ecosystem services provide direct services to 240 million people in the HKH region and support a further 1.65 billion people downstream (*very high confidence*). The region hosts significant ecoregions and global biodiversity hotspots, which form part of the 40% of area under formal protection. Such formal mechanisms reflect the commitment of the region's countries to conservation. They have helped ensure the protection of its fragile ecosystems and habitats, which host many charismatic species, and of the ecosystem services that contribute to the wellbeing of its people (*high confidence*).

Despite these efforts, the HKH region and its biodiversity are threatened by a range of drivers of change. The rise in temperature and changes in precipitation patterns are discernible and have cascading impacts on HKH ecosystems and society (*medium confidence*). Even if global warming is limited to 1.5 °C, the HKH is likely to face serious impacts in terms of species loss, ecosystem structure, and productivity, resulting in lowered ecosystem services flows (*high confidence*). The HKH cryosphere and adjacent ecosystems – high-elevation rangelands, wetlands, and peatlands – are sources of ecosystem services to some of the world's most marginalised communities. The region's large and contiguous plant and animal habitats host fragile ecosystems that also support highland herding communities (*very high confidence*). About 67% of the HKH's ecoregions and 39% of the global biodiversity hotspots are still outside protected areas and exposed to different drivers of change (*very high confidence*).

Increasing vulnerability in high-elevation regions where the cryosphere is dominant is attributable to climate change, over-exploitation, air and water pollution, and invasion by alien species (*very high confidence*). Literature on the degradation of these vulnerable ecosystems record changes to a wide range of plant and animal community structures and productivity, including the productivity of medicinal plants. These have implications for the age-old cultures of herding communities dependent on highland ecosystems for their livelihoods and lowland communities whose water and energy (hydropower) needs are supported by the HKH cryosphere (*medium confidence*).

Climate change impacts have wide-ranging and cascading effects on the cryosphere and related ecosystems, biodiversity, and ecosystem services – including on nature-based trade and tourism, health, and culture. These changes, which also affect the subsistence livelihoods of HKH communities, are detrimental to the achievement of the Sustainable Development Goals (*high confidence*).

As the cryosphere changes, impacts on biodiversity at the ecosystem, genetic, and species levels mean an overwhelming majority of animal and plant species are negatively affected, sometimes to extinction (*high confidence*). There is increasing evidence of impacts on ecosystems and ecosystem services, changes in soil nutrient composition, changes in the phenology of plants, range shifts from lower to higher elevations, increase in invasive alien species, and changes in structural and population compositions in both plant and animal populations (*high confidence*). Observations on trade-offs have also been made: Some species in the eastern Himalaya are benefiting from warming temperatures and changes in precipitation levels, leading to higher growth and productivity. Furthermore, scenario analyses show these trends will increase in the future, with large implications on the wellbeing of people dependent on HKH resources (*medium confidence*).

While science on the cryosphere and related changes has strengthened considerably in recent years, understanding of the interactions between cryospheric components and consequent impacts on high-elevation ecosystems and biodiversity is limited (*very high confidence*). Adaptation options for mountain biodiversity remain poorly understood (*high confidence*). While these challenges are persistent and ever increasing, practices incorporating participatory approaches and community-led adaptation are also being reported (*high confidence*). Watershed, springshed, and landscape approaches are gradually being incorporated into adaptation, ecosystem restoration, and disaster risk reduction measures (*high confidence*). These approaches are heterogeneous and context-specific, varying greatly depending on the issues, conditions, and contexts at play.

Though cryosphere and biodiversity at the ecosystem, genetic, and species levels are highly interconnected, understanding on the links between cryosphere and biodiversity across the HKH is limited (*very high confidence*). In recent years, research into and knowledge on the impacts of climate change on the cryosphere have increased, but research into the impacts of cryospheric changes on ecosystems and species, including at the genetic level, is only slowly emerging. Documentation on ecosystems and species is sporadic, and largely available only for the higher taxa. Huge knowledge gaps – linkage gaps, impact gaps, and response gaps – persist (*very high confidence*). The HKH remains a data-deficit region, where long-term research that considers spatial and temporal scales remains lacking (*medium confidence*). There are few representative long-term research stations for environmental and biophysical studies. Additionally, there are major gaps in the social sciences and in holistic research that investigates the interconnectedness of cryosphere, biodiversity, and their different elements (*very high confidence*).

Policy interventions are currently limited to small pockets. These need to be scaled up if ecosystem-based adaptation is to be supported (*very high confidence*). As a contiguous ecosystem, the HKH faces cascading impacts that have regional implications. Therefore, regional cooperation among HKH countries needs to be prioritised, and investments in research capacity, data sharing, and the implementation of multidisciplinary approaches are needed for coordinated responses that are ultimately more effective (*very high confidence*).

KEY KNOWLEDGE GAPS

The cryosphere and biodiversity are highly interconnected at the species, genetic, and ecosystems levels, but understanding of this connectedness and the impacts of climate change on the same is limited.

Though permafrost is an important component and contributor to alpine ecosystems – rangelands, wetlands, and peatlands, the interactions between these systems and their interfaces remain under explored.

Climate-driven hazards and their cascading impacts on extinctions and range retractions, although already widespread, are poorly researched and reported. This is largely due to a failure to survey the distribution of species at a sufficiently fine resolution to enable detection of decline and attribute it to climate change.

Contents

4.1. Introduction

The Hindu Kush Himalayan (HKH) region is exceptionally rich in biodiversity[1] at the ecosystem, species, and genetic levels (Allen et al., 2010; Chaudhary et al., 2022; Rana et al., 2022; Xu et al., 2019). This rich biodiversity is the result of high levels of climatic variability, rugged topography, and altitude variations (Sathyakumar et al., 2020; Zomer & Oli, 2012). The Hindu Kush Himalaya is one of the youngest mountain ranges on Earth, the formation of which commenced some 60 million years ago with the start of the collision between the Indian Plate and the Eurasian Plate, which resulted in twisted strata of biogeography, extreme variabilities in topography, and variations in vegetation (Jaegar, 2021; Sathyakumar et al., 2020; Xu et al., 2019). The dominant land cover of the region is characterised by high-elevation grassland (38.23%), bare rocks and soil (30.69%), forests (14%), snow and glacier areas (4%), and water bodies and riverbeds (2%) (Uddin et al., 2021). The major ecosystems include tropical and subtropical rainforests; temperate broadleaf, deciduous, and temperate coniferous forest; high-elevation cold shrub or steppe; and cold desert (Chen, 2002). The cryosphere, which consists of ice, snow, glacier, permafrost, and glacial lakes, is an important part of the HKH as it has the largest accumulation of ice and snow outside the polar regions (Bolch et al., 2019). The HKH is the source of 12 major river basins (Amu Darya, Helmand, Indus, Tarim, Ganges, Interior Tibetan Plateau, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, and Yellow) and hosts four global biodiversity hotspots (the Himalaya, South-West China Mountains, Indo-Burma, and Central Asia Mountains) offering ideal habitats for endemic and rare species (Wu et al., 2013) (Figure 4.1).

The region contains 575 protected areas (Chaudhary et al., 2022), 12 of the Global 200 Ecoregions (Olson & Dinerstein, 2002), 335 Important Bird and Biodiversity Areas (IBAs), and 348 Key Biodiversity Areas (Donald et al., 2019). These ecosystems support a high level of biodiversity and provide a congenial environment for a range of flora and fauna often endemic to the region (Myers et al., 2000). Mountains are considered as ideal places to study species richness because of large environmental gradients over short distances at small spatial scales. The spatial pattern of species richness in mountains can be generally grouped into three types: (1) a monotonic decline; (2) high richness at lower elevations and decline at higher elevations; and (3) a "hump-shaped" distribution with high richness at intermediate elevations (Liang et al., 2020). Climatic factors are the dominant drivers of these observed spatial patterns. HKH is home to a significant share of the global plant and animal diversity, in particular the Himalaya, Indo-Burma, and southwest China biodiversity hotspots (Allen et al., 2010). Among the most charismatic and iconic species found in high-elevation HKH ecosystems are the snow leopard (*Panthera uncia*), Tibetan brown bear (*Ursus arctos pruinosus*), giant panda (*Ailuropoda melanoleuca*), red panda (*Ailurus fulgens*), semi-domesticated yak (*Poephagus grunniens*), and Marco Polo sheep (*Ovis ammon polii*).

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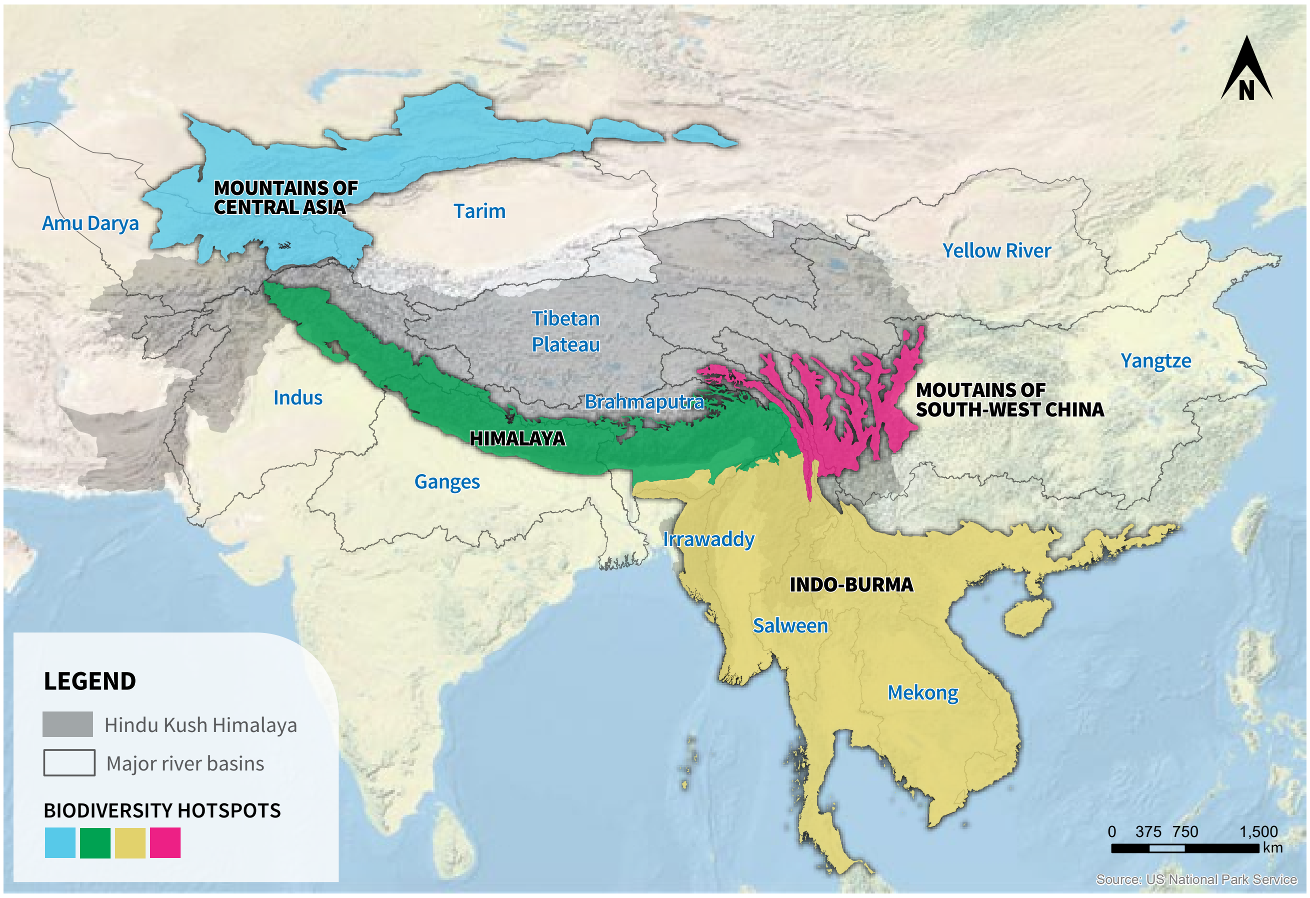
[1] "Biodiversity" is the diversity of life on earth at ecosystem, species, and genetic levels (CBD, 1992).

FIGURE 4.1 RIVER BASINS AND GLOBAL BIODIVERSITY HOTSPOTS IN THE HINDU KUSH HIMALAYA



Source: US National Park Service

4.2. Drivers of change

Biodiversity and ecosystem services in the region are threatened by a range of drivers of change. Among them are climate change, land use and land cover change, increasing human footprints, and invasive species (Wang et al., 2019). The region has been modified and altered by humans for thousands of years (Ives & Messerli, 1989) through interventions such as cattle and crop farming, and cultural practices (Chen et al., 2015; Gurung, 2004; Pandit & Kumar, 2013). HKH has also experienced significant changes in climate during the past decades, with the region subject to higher variabilities and changes in temperature and precipitation. The mean temperature is increasing significantly across the HKH, and warming is likely to be higher in the region in the future with the higher elevations experiencing more warming than the lower (Krishnan et al., 2019). Likewise, changes in precipitation patterns, too, are highly likely, particularly in higher elevation areas (Bolch et al., 2019) (see Chapter 2 for more details).

In the HKH, climate change impacts on the cryosphere are well established – evident in the rapid retreating of glaciers, shrinking of mountain ice, thawing of permafrost, and changing patterns in snow cover (Bolch et al., 2019). The outcome has been a shrinking cryosphere due to losses in glacier mass, snow cover, and permafrost area as well as changes in hydrology and an increase in natural hazards and disasters (IPCC, 2019). The rate of warming is slightly higher than the global average in the HKH cryosphere, with significant impacts on streams and river flows (Lutz et al., 2016) (see Chapter 3), and ecosystems and species of the region (Gaire et al., 2022; Shrestha et al., 2015; Singh & Samant, 2020). Even a 1.5°C temperature rise in the HKH would seriously impact most ecosystems, including forest, rangeland, and wetlands, because of changes in species abundance, composition, and productivity (Mayewski et al., 2020; Negi et al., 2012). The non-climatic anthropogenic drivers of change such as land use and land cover change, invasive species, solid waste and atmospheric pollution, habitat degradation, and over-exploitation of resources are exacerbating the impacts of climate change on ecosystems and their services (Xu et al., 2019). The interactions between the various drivers of change amplifies the impacts on biodiversity and people (Wang et al., 2019).

While our knowledge about the physical science of the cryosphere and changes in it have developed considerably in recent years, our understanding of the interactions between components of the cryosphere (such as glaciers, ice, snow, permafrost, and glacial lakes), and their impacts on high-elevation biodiversity is very limited. This chapter assesses the scientific literature on the impacts of the changing cryosphere on biodiversity and ecosystem services in the HKH as well as response options. It focuses on the observed impacts at the ecosystems and species level and discusses the response options reported in the literature. In doing so, the chapter highlights the key knowledge gaps and provides recommendations for better understanding the impacts as well as adaptation actions to enhance socio-ecological resilience. The assessment adopted the 'state-of-the-art' method proposed by Grant & Booth (2009) to conduct a review of relevant literature. The method focused on specific subject matter to gain a holistic understanding of the issue at hand. Deploying Scopus, we used specific keywords related to the cryosphere (snow, glaciers, permafrost, lakes, and ice), biodiversity (such as species, ecosystem, genetic, and alpine), region (HKH), and language. Relevant literature was selected through a quick scanning of the title and abstract. We also carefully reviewed the *HKH assessment* report (Wester et al., 2019) and the recent IPCC Cross-Chapter Paper on Mountains (Adler et al., 2022).

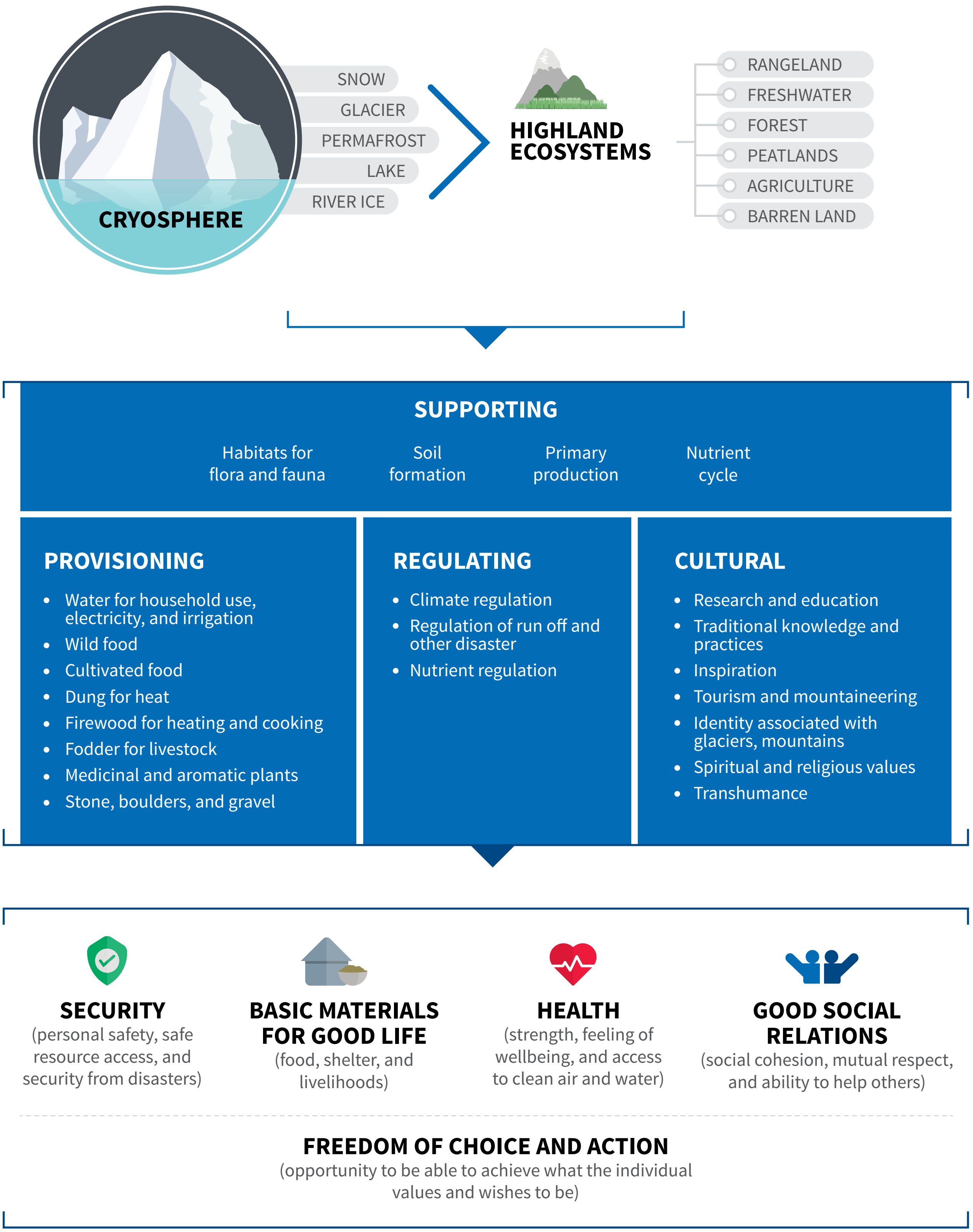
4.3. Cryosphere and ecosystem services

The biodiversity of the HKH provides a wide range of ecosystem services and contributes, thereby, to the wellbeing of the people living in the region and beyond. The major ecosystems that are spatially connected to the cryosphere are rangeland, freshwater (rivers and wetlands), high-elevation peatlands, and barren land (gravel, stones, and boulders) but the cryosphere also indirectly contributes to other ecosystems in lowland areas such as forest and agriculture. All these ecosystems provide a wide variety of services. However, this chapter will primarily focus on high-elevation ecosystems that are directly linked to the cryosphere (see Figure 4.2).

The major provisioning services reported in the HKH region are water for household use, irrigation, and electricity; wild and domesticated food, firewood, and forage; medicinal plants; and materials such as stones, minerals, metal ore, coal, gravel, and boulders (Chaudhary et al., 2017; Murali et al., 2017). Countries of the HKH region are heavily dependent on these services. For example, about 80% of the population of Nepal is dependent on forests and agriculture for their livelihoods while around 26–39% of the country's Gross Domestic Product comes from agriculture, forestry, and fisheries (Government of Nepal & UNDP Nepal, 2010). Similarly, the economy and culture are intricately linked to forests. The Bhutanese economy depends significantly on natural resources such as wood, non-timber forest products, minerals, agricultural land, and water. Tourism, festivals, and trekking, which are important for the country's economy and cultural practices, too, are largely dependent on natural ecosystems (Sears et al., 2017). Among the other provisioning services from the high-elevation ecosystems are minerals, coals, metal ores, and salt (Govil et al., 2021).

In addition to the contributions to society and economy, the provisioning of freshwater from glaciers, snow, ice, and permafrost also play a

FIGURE 4.2 MAJOR SERVICES PROVIDED BY ALPINE ECOSYSTEMS



SUPPORTING

- Habitats for flora and fauna
- Soil formation
- Primary production
- Nutrient cycle

PROVISIONING

- Water for household use, electricity, and irrigation
- Wild food
- Cultivated food
- Dung for heat
- Firewood for heating and cooking
- Fodder for livestock
- Medicinal and aromatic plants
- Stone, boulders, and gravel

REGULATING

- Climate regulation
- Regulation of run off and other disaster
- Nutrient regulation

CULTURAL

- Research and education
- Traditional knowledge and practices
- Inspiration
- Tourism and mountaineering
- Identity associated with glaciers, mountains
- Spiritual and religious values
- Transhumance

SECURITY
(personal safety, safe resource access, and security from disasters)

BASIC MATERIALS FOR GOOD LIFE
(food, shelter, and livelihoods)

HEALTH
(strength, feeling of wellbeing, and access to clean air and water)

GOOD SOCIAL RELATIONS
(social cohesion, mutual respect, and ability to help others)

FREEDOM OF CHOICE AND ACTION
(opportunity to be able to achieve what the individual values and wishes to be)

Source: Scopus-based literature review by the authors (2021). The dataset is available on request.

critical role in the function, growth, and survival of biodiversity at high elevations (Mukherji et al., 2015). As part of the ecosystem function, nutrients such as nitrogen, phosphorous, potassium, calcium, manganese, and sulphur are supplied, which are required for metabolic activity in organisms at higher elevations as well as nutrients cycling and soil formation (Su et al., 2019). The availability of such nutrients forms the basis of primary production, which determines vegetation types (Tian et al., 2019). This activity is largely supported through the flow of ecosystem services, including water. In the HKH, sources of water also play a significant role in the energy sector, especially hydropower. Permafrost and frozen ground, moreover, regulate and determine the types, composition, structure, and distribution pattern of ecosystems (Kaplan & New, 2006).

Alpine ecosystems are unique in terms of their role in regulating climate and nutrients, and disaster risk reduction as well as providing habitats and food for flora and fauna. Called supporting services, cryosphere components are important for the sustainability of biodiversity. The cryosphere strongly affects ecosystems in terms of structure, composition, and functions, which provide habitats for a range of flora, fauna, and micro-organisms (O'Connor et al., 2020). There are diverse ice-associated organisms, including bacteria, fungi, microalgae, unicellular animals, birds, and mammals, which photosynthesise, forage, reproduce, and grow in cryosphere habitats and form unique food chains (Su et al., 2019). As such, the HKH cryosphere supports high biodiversity including diverse micro-organisms, plants, and animals such as the snow leopard (Lambeck, 1997; Mukherji et al., 2019).

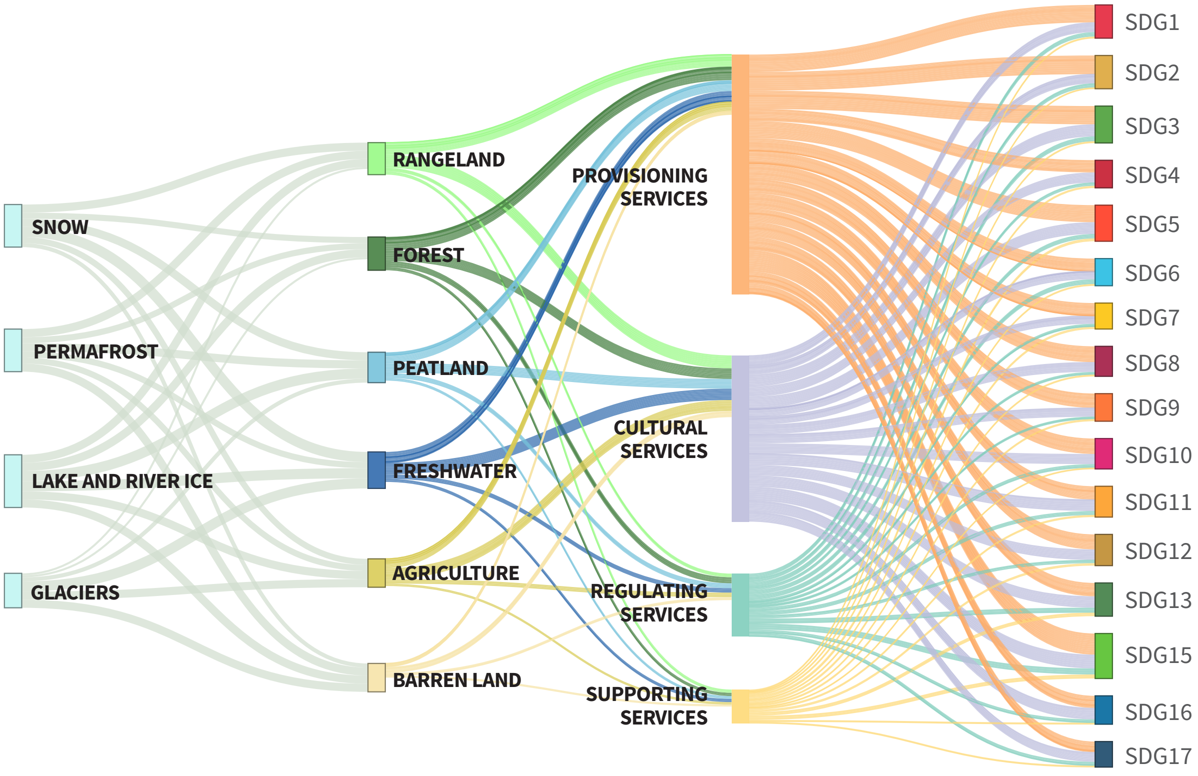
Cultural services are important in the HKH in terms of wellbeing, social capital, and the economy. Some of the major cultural services in the region are transhumance system, tourism and mountaineering, inspiration, social cohesion, spirituality and religious values, traditional ecological knowledge and practices, indigenous local knowledge and practices, and research and education (Chaudhary et al., 2017; Chettri et al., 2021; Kandel et al., 2021; Tuladhar et al., 2021). People regard some high mountains with snow, lakes, and rivers as the physical manifestations of God (Winters, 2022). The interactions between the cryosphere and biodiversity also provide opportunities for research as these cultural services, in the form of beliefs and practices, provide opportunities to advance science, shape contemporary and traditional knowledge about the high-elevation regions, and directly and indirectly contribute to the conservation of biodiversity at all levels.

4.4. Cryosphere services and sustainable development goals

Figure 4.3 provides a conceptual overview of the flows of ecosystem services from the cryosphere towards the sustainable development goals (SDGs).

Services from the cryosphere substantially contribute towards SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (health and wellbeing), SDG 6 (clean water and sanitation), SDG 7 (clean energy), SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and communities), SDG 12 (sustainable consumption and production), SDG 13 (climate action), and SDG 15 (life on land).

FIGURE 4.3 **LINKS BETWEEN CRYOSPHERE, HIGHLAND ECOSYSTEMS, ECOSYSTEM SERVICES, AND SUSTAINABLE DEVELOPMENT GOALS**



SDG1: NO POVERTY
SDG2: ZERO HUNGER
SDG3: GOOD HEALTH AND WELLBEING
SDG4: QUALITY EDUCATION
SDG5: GENDER EQUALITY
SDG6: CLEAN WATER AND SANITATION
SDG7: AFFORDABLE AND CLEAN ENERGY
SDG8: DECENT WORK AND ECONOMIC GROWTH
SDG9: INDUSTRY, INNOVATION, AND INFRASTRUCTURE
SDG10: REDUCED INEQUALITIES
SDG11: SUSTAINABLE CITIES AND COMMUNITIES
SDG12: RESPONSIBLE CONSUMPTION AND PRODUCTION
SDG13: CLIMATE ACTION
SDG15: LIFE ON LAND
SDG16: PEACE JUSTICE, AND STRONG INSTITUTIONS
SDG17: PARTNERSHIP FOR THE GOALS

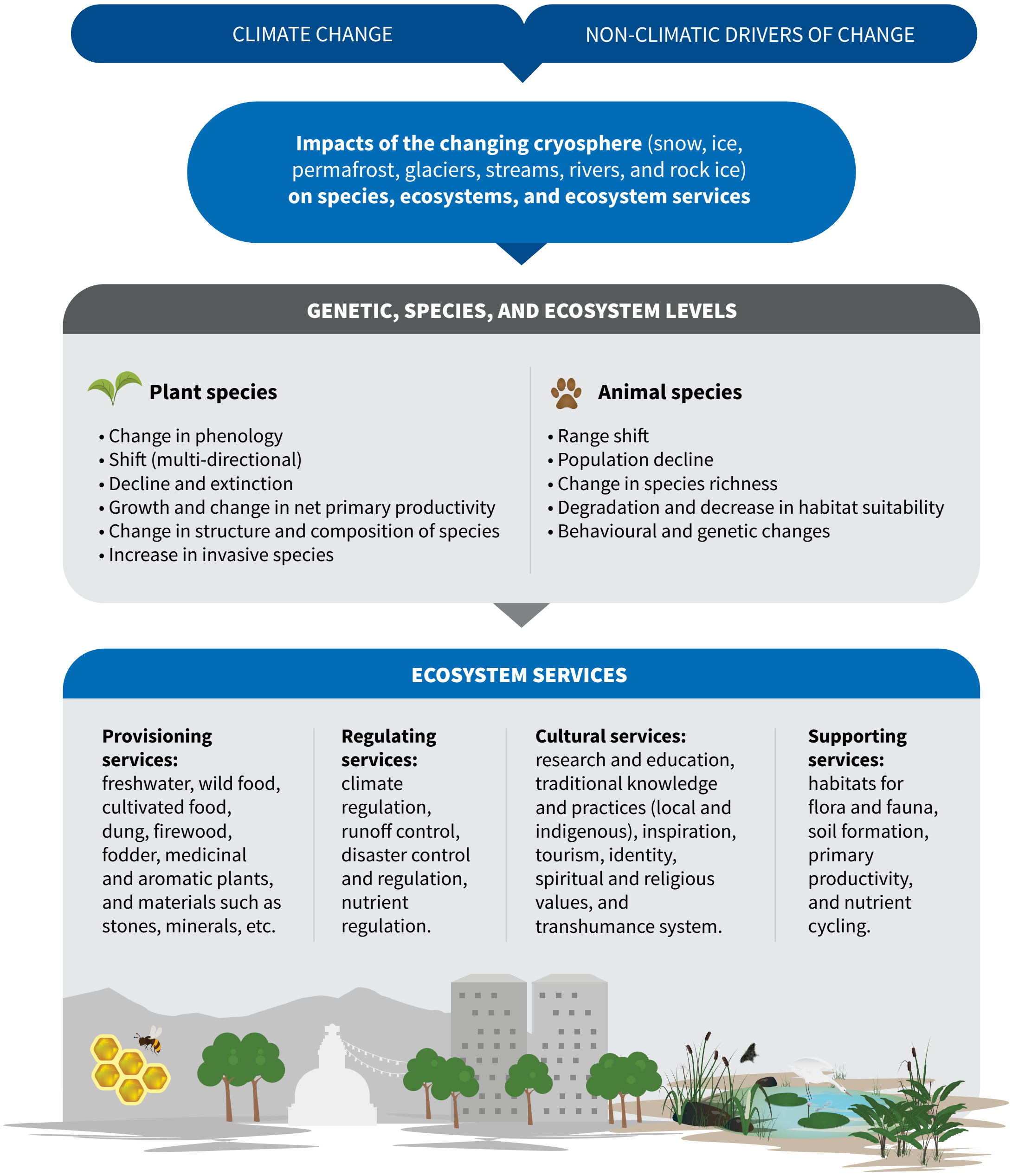
Source: Scopus-based literature review by the authors (2021); dataset available on request.

Although, provisioning services of the cryosphere are crucial and directly contribute to the 16 goals of the SDGs, they contribute more particularly to SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 6 (clean water and sanitation), and SDG 15 (life on land), as shown in Figure 4.3. For instance, income from the trade of caterpillar fungus contributed 53–64% of the total household income annually in Dolpo, Nepal (Shrestha et al., 2019), and 40% on average of the rural cash income in Bhutan (Laha et al., 2018). In fact, ecosystem services contribute to the direct attainment of 12 SDGs in Nepal (Adhikari et al., 2022). Similarly, numerous cryosphere services, mainly, provision of freshwater, climate regulation, habitat for biodiversity, and run-off regulation have been found to be critical in promoting multiple goals including agricultural development (SDG 2), eradication of extreme poverty (SDG 1), conservation of terrestrial biodiversity (SDG 15), economic growth (SDG 8), access to clean drinking water (SDG 6), and renewable energy (SDG 7) in Afghanistan, Bhutan, China, India, Nepal, and Pakistan (Zhang et al., 2022). Cultural services, including traditional ecological knowledge and practices, also indirectly contribute to multiple SDGs in the region. For example, spiritual and religious values, indigenous culture, and aesthetic and recreational values of the high mountains that are part of mountain tourism contribute to sustainable tourism and income generation (SDG 1), improving food security (SDG 2) and improving health and wellbeing (SDG 3) (Zhang et al., 2022) (see Chapter 5, section 5.3).

4.5. Impacts on biodiversity at genetic, species, and ecosystem levels

The cryosphere, a barometer of climate change, has been affected by different drivers of change. Some of the observed climate-related changes such as the ones in snow fall patterns, permafrost thaw, and glacier melt are well established (Bolch et al., 2019). These climate-induced changes in the cryosphere have profound impacts on biodiversity at ecosystem, species, and genetic levels (Xu et al., 2019). The following section highlights the major impacts observed at ecosystem, species (both individual and population), and genetic levels, where such information is available (Figure 4.4).

FIGURE 4.4 OBSERVED CHANGES AND IMPACTS AT THE GENETIC, SPECIES, AND ECOSYSTEM LEVELS



CLIMATE CHANGE

NON-CLIMATIC DRIVERS OF CHANGE

Impacts of the changing cryosphere (snow, ice, permafrost, glaciers, streams, rivers, and rock ice) **on species, ecosystems, and ecosystem services**

GENETIC, SPECIES, AND ECOSYSTEM LEVELS

Plant species

- Change in phenology
- Shift (multi-directional)
- Decline and extinction
- Growth and change in net primary productivity
- Change in structure and composition of species
- Increase in invasive species

Animal species

- Range shift
- Population decline
- Change in species richness
- Degradation and decrease in habitat suitability
- Behavioural and genetic changes

ECOSYSTEM SERVICES

Provisioning services: freshwater, wild food, cultivated food, dung, firewood, fodder, medicinal and aromatic plants, and materials such as stones, minerals, etc.

Regulating services: climate regulation, runoff control, disaster control and regulation, nutrient regulation.

Cultural services: research and education, traditional knowledge and practices (local and indigenous), inspiration, tourism, identity, spiritual and religious values, and transhumance system.

Supporting services: habitats for flora and fauna, soil formation, primary productivity, and nutrient cycling.

4.5.1. Observed impacts at genetic, species, and ecosystem levels

The impacts of and responses to climate and non-climatic changes are not uniform and are often shaped by the degree of vulnerability based on exposure, sensitivity, and adaptive capacity (Weiskopf et al., 2020). Increase in global temperatures, changes in precipitation patterns, glacial retreat, snowmelt, and permafrost thaw are instigating a series of changes in high-elevation species across the HKH region. While some species in certain regions are benefiting from warming temperatures and changes in precipitation levels, an overwhelming majority of animal and plant species are negatively affected by these changes. These changes, which often interact with other anthropogenic changes, have significant impacts on biodiversity and ecosystem services, and ultimately on the people who inhabit the region.

The major effects that cryospheric changes have on plants at species and ecosystem levels are changes in phenology, upslope habitat shifts, changes in structure of populations and communities, densification, growth enhancement, physiological changes, and changes in biochemical processes. Besides these, changes in soil stoichiometry characteristics (Zhang et al., 2019), increase in incidences of invasive alien species, species redundancy, and shift in dominance between species (Behera et al., 2019) are among the other impacts observed. In some cases, regions that were inhospitable due to colder climatic conditions at higher elevations have now become suitable for various monoculture plantations, which pose a threat to the habitats of endemic species through encroachment (Zomer et al., 2014).

CHANGES IN PHENOLOGY

Climate-induced changes in the cryosphere are causing profound changes in plant phenology across the HKH. The reported changes include the timing of leaf-fall and fruiting (Borogayary et al., 2018), changes in cambial activity, and flowering phenology (Hassan et al., 2021; Robbie et al., 2014). This is leading to a decrease in survival rates and increase in vulnerability of endemic and threatened species across the HKH.

Changes in flowering phenology have been reported for a range of species, including alpine ginger *Roscoea* species in the central Himalaya (Mohandass et al., 2015), early onset of flowering of yellow amaryllis (*Sternbergia vernalis*) in the Kashmir Himalaya (Hassan et al., 2021), and the Ghizer valley of Pakistan, and contrasting phenological responses of Himalayan rhododendron where annual warming leads to advanced flowering and fall warming leads to delayed flowering (Robbie et al., 2014). The literature has also reported a lengthening of the overall average growing season of vegetation in Nepal and the adjacent HKH region (Shrestha et al., 2012). In northeast China, the start date and the length of land surface phenology are reported to have advanced by one day per year (Zhang et al., 2017). In the Qinghai-Tibet Plateau, increase in temperature led to a prolongation of the length of the growing season by about one to two days per decade between 1982 and 2005 (Zhang et al., 2018). Vegetation phenology has also advanced in the Qinghai-Tibetan Plateau in terms of greening, withering, and the growing season with an average advancement of 15–18 days (Zhang et al., 2018). Furthermore, extreme drought led to significant changes in the start and end dates of the growing season in the in the Yungui Plateau (Ge et al., 2021). These changes in phenology also have consequences for the migratory patterns of species such as birds, butterflies, mammals and others dependent on nectar, fruits, and seeds (Adhikari et al., 2018; Joshi et al., 2018; Shi et al., 2021).

MULTI-DIRECTIONAL SHIFTS

Shifts due to a rise in temperature and changes in snowfall patterns at higher elevation areas have been observed across the HKH. Most plant species demonstrate multi-directional shifts across the region. Upward or elevational range shift of multiple species has been recorded in different parts of the HKH (Dolezal et al., 2021; Hamid et al., 2020; Telwala et al., 2013). Singh et al. (2021) have reported an upward shift of the treeline from a few metres to 30 metres per decade in the Indian Himalaya. For example, the Himalayan pine (*Pinus wallichiana*) treeline has been reported to shift towards the upper elevations at the rate of 11 to 54 metres per decade in the monsoon and monsoon-shadow zones in the western Himalaya of India (Yadava et al., 2017). According to Singh et al. (2018), the *Rhododendron* *campanulatum* krummholz has expanded by 1.4 metres per year in Tungnath, Garhwal Himalaya with recent stabilization in the treeline ecotone. In India, the shrub species *Juniperus polycarpos* has been observed above the treeline at 4,000 m (Singh & Samant, 2020). Ninety percent of endemic plant species in the Sikkim Himalaya have been observed to undergo a warming-driven geographical range shift of 23–998 m with a mean upward displacement rate of 27.53±22.04 m per decade (Telwala et al., 2013). Several species including *Potentilla pamirica* in eastern Ladakh of the northwest Himalaya have shifted upward about 150 metres above the limit of plant distribution (Dolezal et al., 2021).

Upward shifts have also been reported in Nepal. The average rate of the upward shift of the forest line in Nepal is 0.46 m per year at a rate of 0 to 2.6 m per year with site- and species-specific differences (Chhetri & Cairns, 2015; Gaire et al., 2014, 2017, 2022; Gaire et al., 2023; Sigdel et al., 2018; Tiwari et al., 2017). Researchers have attributed shifts in the east Himalayan fir (*Abies spectabilis*) and bell rhododendron (*Rhododendron campanulatum*) in the Nepal Himalaya to increasing temperature in the region (Gaire et al., 2017; Mainali et al., 2020). *Abies spectabilis,* found between 2,500 and 4,100 m, has reportedly shifted by approximately 239 m to a higher elevation over a 150-year time period (1851–2009) in the Manaslu Conservation Area of Central Nepal (Gaire et al., 2014). Species-specific shifts have also been reported in the Everest region (Figure 4.5). Similarly, an overall advancement of the treeline in the Tibetan Plateau and adjacent mountain regions in China has also been reported (Wang et al., 2022). Wang et al. (2022) have recorded rapid advancement (>10m) of the treeline across the Tibetan Plateau for 50.8% of the sites studied over the past century while they have recorded slow advancement (0–10m) for 16.9% of the sites, and a stable treeline for 32.2% of the sites. Researchers have also observed an advancement of tree species including *Pinus wallichiana* in glacier-retreated sites in the HKH (Sigdel et al., 2020).

FIGURE 4.5 **TREELINE DYNAMICS IN RESPONSE TO ENVIRONMENTAL CHANGE IN THE EVEREST REGION, NEPAL**

Source: Gaire et al. (2017)

Variations in the rate of advancement regarding site, species, and climatic patterns have also been noted. The average rate of the upward treeline shift in Nepal is 0.46 m per year with differences in the rate ranging from 0 to 2.6 m per year (Gaire et al., 2023) when site- and species-specific differences are factored in.

An increasing trend in greening has been observed across the HKH. While most of the alpine pasture is greening (a positive trend) (Zheng et al., 2022), browning has been simultaneously observed in some areas exposed to high frequency of drought events and anthropogenic pressure such as population increase, urbanisation, and shifting cultivation (Kumar et al., 2022). In the eastern Himalaya, browning (a negative trend), especially at higher elevations (likely due to pre-monsoonal drought), has been observed while the lower and middle elevations of vegetation in the eastern Himalaya are predominantly greening. In Nepal, Baniya et al. (2018) have observed an overall increasing trend of greening between 1982 and 2015 with precipitation and temperature both contributing to the greening process (Mainali et al., 2015). Greening is also driven by increased CO_2 fertilisation, Nitrogen deposition, and anthropogenic activities such as irrigation and agricultural fertilisation (Mishra & Mainali, 2017).

Shrub encroachment is also apparent in the alpine meadows of different parts of the HKH region. For instance, around 39% of the alpine meadows converted to woody shrubs between 1990 and 2009 in northwest Yunnan, China (Brandt et al., 2013). A region-wide analysis of the changes in the spatial extent of subnival vegetation in the HKH from 1993 to 2018 using remote sensing data indicated that there has been an increase in subnival vegetation from 1993 with a rapid increase between 5,000 and 5,500 m (Anderson et al., 2020). Densification of shrubs just above the treeline has also been reported (E. Liang et al., 2016; Schickhoff et al., 2015).

DECLINE AND EXTINCTION

Species decline and even extinction are among the negative consequences of the changes in the cryosphere. A decreasing trend in tree growth has been observed in the western HKH while it has been relatively stable in central-eastern HKH (Zheng et al., 2021). The negative consequences are mostly mediated by increasing moisture stress and temperature increases. For example, increasing degradation of the permafrost can lead to a decrease in soil surface moisture and soil nutrient supply capacity, which in turn can negatively affect the diversity of alpine plant species, as reported in the Qinghai-Tibetan Plateau (Yang et al., 2013). Endemic species, in particular, are at increased risk as even a slight change in the optimal combinations of temperature and precipitation can lead to a sharp decline in their survival rate and, ultimately, extinction. Species at relatively low-elevation areas in the HKH that are not flexible enough to make niche shifts in response to climate change risk possible extinction (Upadhyay et al., 2021).

GROWTH AND PRODUCTIVITY

Tree species respond to climate change in several ways. An increase in growth has been observed for several species across the HKH. While some species have shown significant growth enhancement, it has been slight for others (Camarero et al., 2021; Panthi et al., 2020; Thapa et al., 2017). The east Himalayan fir (*Abies spectabilis*) has shown growth enhancement in the high-elevation regions of Nepal (Thapa et al., 2017). A similar trend has been observed for *Androsace tapete*, an endemic cushion species found in the Tibetan Plateau. Rapid growth enhancement has also been observed since 1982 in three dominant genera (*Abies*, *Juniperus*, and *Picea*) in the southern and southeastern Tibetan Plateau (Zheng et al., 2021). A long-term growth study of dominant high-elevation species such as *Abies spectabilis*, *Juniperus indica*, and *Picea* species that are found above 3,000 m using regional datasets of tree-ring chronologies has shown little variation in growth of the species across the HKH in response to climate change since the 1950s (Zheng et al., 2021).

According to Mirzabaev et al. (2019), trees from the humid regions are more sensitive to temperature change while those from the dry and arid regions are more sensitive to moisture availability (precipitation and drought). Tree growth has been found to be more responsive to temperature than to precipitation at high-elevation areas indicating that the minimum temperature rather than the mean temperature is the main climate variable that influences tree growth in the HKH (Zheng et al., 2021). Tree growth has been positively correlated with winter and spring precipitation in the drier western part of the HKH, and with winter temperature and spring precipitation in the humid southeastern Tibetan Plateau (Cheng et al., 2019). Moisture availability, especially during the spring season, is crucial for the growth of diverse tree species as evident from the positive relationship between several tree species in the region with precipitation of the spring season (N. Gaire et al., 2019).

Increase in temperature has also been reported to lead to an increase in aboveground net primary productivity in some locations without a permafrost presence and to a decrease in the same in other locations (Yang et al., 2018). Similarly, net primary productivity in the Source Region of Yangtze River also increased by 0.18 TgC per year from 2000 to 2014 as a result of the increase in temperature and precipitation due to climate change (Yuan et al., 2021). There has also been an increase in plant productivity in the alpine wetlands due to increase in temperature and precipitation (Kang et al., 2020). According to Chatterjee et al. (2010), direct warming of the lakes in high-elevation areas have altered the circulation patterns with continuous impacts on the biogeochemistry and functioning of the wetland ecosystem.

STRUCTURE AND COMPOSITION OF SPECIES

Changes in the composition, distribution, and abundance of species are reported across the region (Schwab et al., 2022; Singh et al., 2021). Early snowmelt instigated by warming temperatures has been linked to the increased diversity and density of herb communities in the Uttarakhand Himalaya (Adhikari et al., 2018). Similarly, phenological changes have been reported to lead to changes in plant community interactions, thereby changing their structures. For example, the rhododendron species, which were reported to be flowering earlier as a response to warming temperatures in Mount Yulong of Tibetan Plateau, were found to dominate “non-flexible” species of rhododendron. This has changed the plant community compositions and structure, thus threating the existence of some species of rhododendron (Hart & Salick, 2018).

Changes in species composition are also happening in the mountain summits of the Kashmir Himalaya of India with increasing species richness on the lower summits, which decrease towards the summits in the nival zone (Hamid et al., 2020). There has also been an increase in the cover of dominant shrubs, graminoids, and forbs as well as thermophilization (Hamid et al., 2020). In the Sikkim Himalaya and Tibetan Plateau, Hamid et al. (2020) and Telwala et al. (2013) observed an increase in species richness in the upper alpine zone with changes in snowfall and decrease in permafrost.

Peatlands are also impacted by changing weather patterns in the HKH. Peatlands in the HKH region have shrunk significantly, which has weakened its capacity to sink carbon (Wang et al., 2016). The change in carbon emissions from peatlands caused by frozen ground degradation will increase the uncertainty of the regional soil carbon pools and the GHG budget (IPCC, 2019), posing thereby a threat to the overall ecological security of the entire HKH region. Peatlands overlie permafrost and seasonal frozen ground across the HKH (Wang et al., 2016; Zou et al., 2017). Thus, there is strong interaction between peatland and permafrost as the latter forms an isolation layer that reduces hydrological conductivity in the vertical profile of soil while maintaining the water-table that favours the formation and development of peatland. When peat has accumulated in the surface soil, the thermal exchange between the atmosphere and deep soil is attenuated, as a result of which the permafrost is preserved (Zhang, 1993). Most of the peatlands are distributed in high-elevation areas where the seasonal freeze-thaw is a typical surface process (Zhang & Armstrong, 2001). The intensive diurnal freeze-thaw cycles (FTCs) during the seasonal freeze-thaw periods of autumn freeze and spring thaw are called the “shoulder season” (Arndt et al., 2019; Pirk et al., 2015).

Researchers have reported considerable methane emissions during the spring thaw (Song et al., 2012; Tokida et al., 2007) and autumn freeze (Bao et al., 2021; Mastepanov et al., 2008; Pirk et al., 2015). Methane emissions during the FTCs account for 11–27 % of emissions annually, while methane emissions during the autumn freeze are higher than that of the spring thaw in the peatland of the Qinghai-Tibet Plateau (Chen et al., 2021). Thick peat accumulation has also been reported in the Tibetan Plateau due to the warm and humid climate (H. Chen et al., 2014). In high-elevation regions, due to the stronger diurnal temperature variations in the cold season (Dong & Huang, 2015), the seasonal freeze-thaw processes are influenced by a brief period of freeze up and long shoulder season of ground freezing and thawing (Yang et al., 2006). A recent study found increased methane emissions after simulated FTCs from peat soils of a high-elevation peatland on the QTP. The methane emission peak occurs after the first FTC. The longer duration of the FTCs appears to have a profound effect on elevating methane emission levels compared to the shorter duration FTCs of the low-elevation peatlands. The incubated soils with mild freeze-thaw intensity and higher water content thus had higher cumulative methane emissions. Under future climate scenarios, higher methane emissions were observed during the seasonal freeze-thaw process from high-elevation peatlands, as both longer and warmer shoulder seasons could be expected (Yang et al., 2022). Frequent flooding and irregular waterflow in the wetlands may also degrade the wetlands and their ecological parametres and species (Singh et al., 2021).

INVASIVE SPECIES

The introduction, establishment, and spread of invasive species in terrestrial ecosystems is widely recognised as one of the most serious threats to the health, sustainability, and productivity of native ecosystems. It has been identified as one of the five major drivers of change and biodiversity loss (IPBES, 2019). In the region, there are reports of new and invasive species that were not observable 10–15 years ago (Khan & Dhani, 2017). There is evidence of increase in the number of invasive species and faster colonisation and infestation of protected areas, agricultural lands, freshwater ecosystems, and high-elevation rangelands (Everard et al., 2018; Khan et al., 2014; Pathak et al., 2019; Thiney et al., 2019).

In the HKH, an increasing number of invasive species with faster expansion and range shifts at higher elevation areas has been observed (Table 4.1). The global rise in temperature and elevation-dependent warming coupled with prevailing anthropogenic activities, it is predicted, will provide more favourable conditions for invasive species in the high-elevation areas.

TABLE 4.1 **SCENARIOS OF INVASIVE SPECIES AND THEIR PREDICTED EXPANSION**

Species	Scenarios	Predicted spread area (%)	Predicted new elevation	Citations
Ageratina adenophora	RCP8.5	45.3%	3,029 m	Chaudhary et al., 2021
Lantana camara	RCP8.5	29.8%	3,018 m	Chaudhary et al., 2021
Tithonia diversifolia	RCP2.6, 8.5	23%–53%	13 new PAs	Dai et al., 2021
Parthenium hysterophorus	RCP2.6, 8.5	NA	Higher elevation protected areas	Maharjan et al., 2019

For example, under a Representative Concentration Pathway (RCP) 8.5 scenario, *Ageratina adenophora* and *Lantana camara* are predicted to increase their coverage by 45.3% and 29.8%, respectively, than at present and reach up to elevations above 3,000 metres in the Kailash Sacred Landscape, India (Chaudhary et al., 2021). Similarly, according to the projections on the distribution of 26 invasive plants under the RCP6.0 scenario, 75% of the species range will expand and 25% of the species range will contract due to climate change (Shrestha & Shrestha, 2019). Similarly, it is projected that *Parthenium hysterophorus* will reach higher elevation protected areas such as Langtang, Annapurna, and Manaslu of Nepal in the future (Maharjan et al. 2019).

The aggressive and rapid expansion of invasive species at higher elevations is posing challenges to biodiversity and food security with significant economic costs (Sheergojri et al., 2022). For example, Nepal is among the topmost countries in the world facing invasive threats to the agricultural sector, the estimated annual cost of which is USD 1.4 billion (Paini et al., 2016).

4.5.2. Mountain fauna

Impacts of the changing cryosphere on mountain fauna in the HKH are significant. Elevational shifts, sharp population decline, decrease in species richness and habitat suitability, behavioural and genetic change, and emergence of new species are the identified impacts on the six categories of mountain fauna, namely, mammals, insects, microbes, birds, amphibians, and fishes (Table 4.2).

TABLE 4.2 **OBSERVED IMPACTS OF THE CHANGING CRYOSPHERE ON ANIMAL SPECIES IN THE HINDU KUSH HIMALAYA**

Vertebrates	Observed impacts
Mammals	Decreased habitat suitability, genetic change, population decline, range shift
Birds	Range shift, extinction probability, habitat decline
Fish	Range shift, richness of benthic invertebrates (population increase)
Reptile	Range shift, likely extinction
Amphibian	Genetic diversity affected, likely extinction
Invertebrates	**Observed impacts**
Insects	Range shift upward, species decline, extinction, abundance, new species
Microbes	Increase in microbial activity increase, upward range shift

Source: Scopus-based literature review (2021)

MAMMALS

Mammals in the HKH have been reported to experience distribution range changes, new species assemblages, genetic change, local population changes, and extinction. The changes in the snowline and shift in vegetation have led to movement of species. The upward shift of the snowline has negatively impacted the snow leopard habitats (Li et al., 2016) and, according to Farrington & Li (2016), their suitable habitats are likely to be reduced in Bhutan, Nepal, India, and Myanmar by 2080. Snow leopard (*Panthera uncia*), golden snub-nosed monkey (*Rhinopithecus roxellana*), Himalayan musk deer (*Moschus chrysogaster*), and Himalayan grey langur (*Semnopithecus entellus*) are already experiencing range shifts across the HKH. For instance, the range shift of the golden snub-nosed monkey in the Tibetan Plateau has resulted in a dramatic decline in its population size (Luo et al., 2012).

The major driver of the range shift and population decline for most mammal species is decreased food availability and habitat change along with high fragmentation. Loss of suitable habitats due to upslope range shifts have also been reported for other species such as the giant panda (*Ailuropoda melanoleuca*), blue sheep (*Pseudois nayaur*), and Asiatic brown bear (*Ursus thibetanus*). The range of habitats of Tibetan antelope (*Pantholops hodgsonii*), Tibetan wild ass (*Equus kiang*), and wild yak (*Bos mutus*), which are endemic to the HKH, has also decreased by 44%, 7%, and 20%, respectively. Even genetic changes have been reported in the Arunachal macaque (*Macaca munzala*) because of climate and anthropogenic changes (D. Chakraborty et al., 2015).

BIRDS

Changes in the patterns of the snow forming period and snow melting period of the cryosphere impact the distribution of species. Upslope range shifts, decline in suitable habitats, and increased possibility of extinction are the reported impacts on birds with the changing cryosphere. For instance, with climate warming, pheasants such as satyr tragopan (*Tragopan satyra*) have shifted their habitats to higher elevations and are predicted to further shift to even higher elevation areas therfore shrinking their range (Chhetri et al., 2021). Under extreme future climatic scenarios, the species could become restricted to sky islands in the Himalayan region (Chhetri et al., 2018, 2021). There has also been a significant decline in habitat suitability as well as range shift for the Chinese grouse (*Tetrastes sewerzowi*) (Lyu & Sun, 2014). The black-necked crane (*Grus nigricollis*) in the alpine environment has also been found to adjust its behaviour in relation to incubation based on weather conditions and the thermal requirements of its eggs (Zhang et al., 2017).

AMPHIBIANS, REPTILES, AND FISHES

The amphibians are among the species most impacted by the changing climate. The Kashmir paa frog (*Allopaa hazarensis*) and Himalaya paa frog (*Nanorana vicina*), which are endemic to Pakistan, face likely extinction due to metamorphosis, reduction in body size, more frequent developmental complications, deformities such as edema and tail kinks, lower fitness, and higher mortality at elevated temperatures (>26°C) (Saeed et al., 2021). The genetic diversity of the high Himalaya frog (*Nanorana parkeri*) has been affected by both climatic and non-climatic changes (Hu et al., 2019). Higher elevation shifts from 1,000 m to 1,700 m have been reported among the monocled cobra (*Naja kaouthia*) and king cobra (*Ophiophagus hannah*) in the Sikkim Himalaya (Bashir et al., 2010). Advanced breeding among the frogs in the region has also been reported. For instance, the Sikkim paa frog (*Nanorana liebigii*), has been reported to have advanced breeding by three months in in Sikkim, India (Acharya & Chettri, 2012). Similarly, the richness of benthic invertebrates has been depleted and a range shift has been observed among warm dweller fishes to higher elevations along with losses in cold dweller fishes (Li et al., 2016). Range extension of four agama lizards to higher elevations in Pakistan is partly attributed to the changing snow cover of high-elevation areas in the western Himalaya of the HKH (Khan et al., 2012).

INSECTS

Population decline and change, upward shifts, and emergence of new species are some of the changes reported for insects at higher elevation areas in the region. The Apollo butterfly (*Parnassius apollo*), endemic to China, has experienced a sharp decline in its population (Yu et al., 2012) while a constant monotonic decline of ants (*Hymenoptera: Formicidae*) has been reported in the eastern Himalaya (Wu et al., 2017). The decline is widely attributed to changes in weather and habitat conditions. In recent years, a sharp decline in caterpillar fungus (*Ophiocordyceps sinensis*) has also been reported across the region. The caterpillar fungus is threatened by the combined pressures of climate change and over-exploitation (Wei et al., 2021).

Similarly, a decrease in species richness and local extinctions are also apparent. For instance, a total of 14 species of butterflies have disappeared from the coniferous forests of Murree Hills and its adjacent areas in Pakistan (Saadat et al., 2016). Changes in weather patterns over decades (precipitation decrease and temperature increase), extreme weather events, and emergence of new species were found to be the contributory factors to the disappearance of some butterfly species in the area. Similarly, a decreasing species richness pattern along the elevational gradient has been observed in the Langtang National Park of Nepal where butterfly families were reportedly present in the past in the high, medium, and low elevational zones (Pandey et al., 2017).

An upward shift of the Chinese three-tailed swallowtail (*Bhutanitis thaidina*) and the Himalayan relict dragonfly (*Epiophlebia laidlawi*), which are endemic to the HKH, to a suitable altitudinal range due to changes in temperature and precipitation has been reported. There are also reports of an upward shift of forest pests, such as the tea shot-hole borer *Euwallacea fornicatus* (Eichhoff). Similarly, insects, pests, and mosquitoes have emerged in Everest region (Sherpa, 2014).

MICROBES

The changing cryosphere has impacts on microbial activity and related biogeochemistry (Bourquin et al., 2022). The impacts take the form of high microbial activity in some areas and low to no change in other areas. The high soil microbial activity influences the soil carbon dynamics resulting in a reduction in soil carbon loss (Li et al., 2019). There has also been a shift in micro-invertebrates and lichen such as the epiphytic foliose lichen (*Lobaria pindarensis*) to higher elevations with the vegetation shift (Sahu et al., 2019). For instance, significant changes in the lichen community structure have been observed in response to anthropogenic factors and climate change in Darjeeling, India (Bajpai et al., 2016).

4.5.3. Predicted future changes

Changes in the cryosphere have already affected ecosystems and biodiversity and will continue to affect them in the coming decades in the high mountains of the HKH.

RANGE SHIFTS

Range shifts of plants and animals are one of the major concerns. Glacier retreat and decreasing snow cover allow species to increase their abundance and extend their range (He et al., 2019; Liang et al., 2018; Yang et al., 2018). For example, Liang et al. (2018) used ecological niche modelling to predict the distribution of 151 species in the Hengduan Mountains since the Last Glacial Maximum. They found that all the species will expand their range size and shift upslope. Wang et al. (2011) employed forest gap models to predict the potential changes in subalpine forest over the eastern Tibetan Plateau and found a distribution shift to higher and colder regions (Xiaodan et al., 2011).

Predictions by Naudiyal et al. (2021) regarding the potential distribution of *Abies, Picea,* and *Juniperus* species in the subalpine forest of the Minjiang headwater region under current and future climate scenarios indicated changes in their future distribution range with possible implications for the supply of ecosystem services such as fuelwood and timber.

The Maxent model, which is one of the ecological niche-based models, indicates a regional increase in suitable habitats for three treeline species (*Abies spectabilis*, *Betula utilis*, and *Pinus wallichiana*), predicting a possible northward and upslope advance (Chhetri et al., 2018). Another model study on the distribution of *B. utilis* across the HKH region for the present and future (RCP's 2.6–8.5 covering 2050 and 2070) indicated that the highly suitable area for *B. utilis* is predicted to shift towards the eastern parts of the Himalaya in the future, with suitability declining towards the western part of HKH (Hamid et al., 2020).

As forests play a vital role in the provision of goods and services and the function of mountain ecosystems, the potential distribution range shift of forests has critical implications for the supply of these ecosystem services. Material services such as timber, non-wood forest products, and freshwater as well as non-material services such as recreation, carbon sequestration, hydrological cycle maintenance, and erosion control obtained from forest ecosystems are fundamental to sustaining and supporting the wellbeing of the people. The range shift pressures therefore raise serious concerns regarding the continued supply of essential ecosystem services necessitating immediate attention from forest managers and conservation planning agencies. Further research and investigation into the overall supply of ecosystem services are also urgently needed.

Similar trends in range shifts towards the northern latitudes and higher elevations are observed in the case of animal habitats. For example, Thapa et al. (2021) applied Maxent to predict the occurrence of five species of bats under different climate scenarios (present and RCPs 4.5 and 8.5 for 2050 and 2070, respectively) and found similar trends in range shifts towards the northern latitudes and higher elevations for all five species. Using a multi-scale Random Forest model under all four RCPs, Dar et al. (2021) found that the habitat of the Himalayan brown bear (*Ursus arctos isabellinus*) would decrease by more than 90% under the high emission scenario with a significant percentage of the species shifting range to higher elevations. Another Maxent study under RCP4.5 and 8.5 for 2050 and 2070 found range shifts for the Himalayan ibex (*Capra sibirica hemalayanus*) and blue sheep (*Pseudois nayaur*) due to a significant loss in habitat for both species (Ali et al., 2022).

MOVEMENT, DECLINE, AND LOSS

Range shifts do not always mean expansion. Liao et al. (2020) applied ecological niche modelling to project the climatically suitable areas for six fir species in southwest China. Their results showed a northward and westward migration of the species to the interior Qinghai-Tibet Plateau. But as this migration cannot compensate for the range loss, it would result in a declined distribution of most fir species. Also using ecological niche modelling, Naudiyal et al. (2021) drew maps of the potential distribution of *Abies, Picea,* and *Juniperus* species in the subalpine forest of the Minjiang headwater region under current and future climate scenarios. They found that precipitation in the wettest month is the key environmental variable for determining habitat suitability for the three species. Climate change and associated precipitation changes will, therefore, likely lead to a clear decline in potentially suitable habitats for all three species according to all the RCP scenarios, with a shift downward of the mean elevation and a decrease in the elevation range of suitable habitats (Naudiyal et al., 2021).

In addition to a shift in the vegetation range, Wei et al. (2021) found significant shrinking in suitable habitats for the Chinese caterpillar fungus, an important fungus grown in the southwestern Tibet Plateau, under RCP4.5 and RCP8.5 climate scenarios. Similarly, projections of habitat suitability under future climate change scenarios for all concentration pathways using RCPs for two time periods (2050s and 2070s) showed a clear decline in potentially suitable habitats for all four ecologically and economically dominant forest tree species (*Quercus leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *Pinus roxburghii*) in the central region of Nepal (A. Chakraborty et al., 2016). These results show both increase and decrease in suitable habitat range across all future climate change scenarios.

Future projections also showed that animal habitats in the Himalaya are under threat due to cryospheric change (Farrington & Li, 2016). For example, the suitable habitat for the Himalayan grey langur (*Semnopithecus entellus*) was predicted to decline by more than 60% in 2050 under both RCP4.5 and RCP8.5 scenarios (Bagaria et al., 2020). In addition, the current suitable habitats are likely to get further fragmented in future scenarios, which would reduce the quality of the habitat.

Similarly, the suitable habitats of the snow leopard, too, are likely to be reduced in Bhutan, Nepal, India, and Myanmar by 2080 (Farrington & Li, 2016). Using the multi-scale Random Forests machine-learning algorithm, Dar et al. (2021) also predicted a habitat range shift for the Asiatic black bear towards higher latitudes in Asia under climate change. Similarly, the Himalayan and Tibetan brown bears' dispersal paths would also shift to higher latitudes. The study predicted that the habitats of the Himalayan and Tibetan brown bears would lose over 34% and 32%, respectively, of the current habitats under the most severe climate change scenario (Y. Dai et al., 2021).

Another study reported a 56–58% range reduction in the currently available suitable habitat for the blue sheep (*Pseudois nayaur*) and a 33.7–64.8% range reduction for the Himalayan ibex (*Capra sibirica hemalayanus*) in the extreme climate scenario (RCP8.5 of 2070) of Gilgit-Baltistan in the Pamir-Karakoram of Pakistan (Ali et al., 2022). This is consistent with Aryal et al. (2016) who predicted a decrease in suitable habitat for blue sheep in the future due to climate change in Nepal.

Inhabitants residing in the glacier-fed river basins which originate in the HKH, including the Indus, Ganges, Brahmaputra, Salween, Yangtze, and Yellow, have observed the impacts of climate change on native wildlife habitats. The snow-shrinking has led to catastrophic snow avalanches, flash floods, landslides, and erosions (Arora et al., 2016) resulting in short- to long-term damages to habitats. The acceleration in snow melting and changes in precipitation patterns can potentially change stream channel width, water velocity, bed roughness, nitrogen and phosphorus processing, dissolved organic matter processing, and net stream metabolism, ultimately changing the functioning of ecosystem and habitat support services (Sweeney et al., 2004) in the region.

CHANGES IN SPECIES POPULATION

Another observation regarding the impact of cryospheric change on the ecosystem is change in species numbers (Fell et al., 2017). Li et al. (2016) have predicted significant increases in benthic invertebrate taxonomic richness in the Himalayan rivers in future decades under climate change. But the increasing rates were different in the three elevational bands. In the eastern region of the HKH, the rate of change was stable overall at lower elevations while slowing down considerably at higher elevations. This indicates higher climate-induced stress compared to the other regions of HKH as well as the general vulnerability of mountain inhabitants, albeit with regional variations, to future climate warming. On the contrary, Klein et al. (2004) predicted that warming caused a 26–36% decrease in species richness in the north-eastern Tibetan Plateau and higher species loss towards the more northward locations due to lack of nitrogen nutrients. Some cold-tolerant diatom species will be lost due to the loss of critical habitat for wildlife that depend on snow and ice cover.

IMPACTS OF INCREASED EXTREME EVENTS

Increase in wildfire as well as other climate extremes such as drought, storms, and cyclones can fundamentally alter species distribution, composition, phenology, and forest structure (Mirzabaev et al., 2019). Habibullah et al. (2022) observed an increase in the magnitude and frequency of extreme weather events under climate change with negative impacts on biodiversity at global scale including HKH. Vilà-Vilardell et al. (2020) applied a spatially explicit wildfire simulation model to predict forest fire hazards in blue pine (*Pinus wallichiana*) ecosystems. The results show a two-fold increase in the fire hazard occurrence by the end of this century for both the study areas of the wildland-urban interface in Bhutan under the RCP8.5 climate scenarios. Studies reveal that climate change and increased human activities have caused massive forest fires in Pakistan (Krebs et al., 2010). Prediction maps also indicate that 22% of Pakistan's natural forests are highly vulnerable (>0.65) to forest fires (Tariq et al., 2021). Chitale & Behera (2019) predicted and quantified wildfire impacts on forest distribution. They used four endemic tree species in the western part of the HKH under the A1B balanced future emissions scenario for this purpose. The model results showed a significant reduction in the geographic distribution of the indicator species under the "with wildfire" scenario in comparison with the "no wildfire occurrence" scenario. The future distribution range is also projected to shift towards the northern and north-eastern regions of the study area oriented by higher moisture availability.

SPECIES RICHNESS

Cryospheric change is predicted to affect regional biodiversity too (Fell et al., 2017). Results from Peter & Sommaruga (2016) indicate increased diversity. They predicted that the reduced glacier run-off in the summer season would improve water clarity in many mountain lakes, thereby increasing biotic diversity and the abundance of bacterial and algal communities and, in turn, primary production. There is strong agreement that summer run-off will decline in the 21st century in many basins for all emission scenarios in the HKH (Engelhardt et al., 2017; Prasch et al., 2012) due to less snowfall and decrease in glacier melt after peak water discharge, thus indicating potentially long-lasting enhanced water clarity and increased aquatic biotic diversity. However, another study in the Yarlung Zangbo-Brahmaputra River found an overall increase in sediment deposition that could indirectly lead to regional wetland degradation and declined riparian biotic diversity (Wang et al., 2020).

Species-specific responses to the warming climate might eventually transform the subalpine Abies fabric forest in the mountainous areas of the eastern Tibetan Plateau into *Betula utilis* forest while subalpine forests could move to higher and colder areas, which are currently tundra (Xiaodan et al., 2011).

Modelling simulations of forest vegetation along the elevation gradient in the Gonga mountain in response to IPCC's different emission scenarios indicated that the vertical belts of mountainous vegetation will shift upward by approximately 300 m, 500 m and 600 m in the B1, A1B and A2 scenarios, respectively (Chen et al., 2020). The high-elevation ecoregions (3,000–8,585 m) will either shrink or shift to higher elevations while the mid-elevation ecoregions situated between 500–3,000 m will expand and the low-elevation ecoregions (0–500 m) will shrink substantially.

4.6. Impacts on ecosystem services

People living in the mountains and lowlands are highly dependent on ecosystem services. Ecosystem services from the HKH support around 240 million people residing in the region as well as 1.6 billion people residing in the downstream river basins (Xu et al., 2019). However, both climate and non-climatic changes are impacting the ecosystems and their services. Whether the ecosystems are managed or remain in their pristine natural state, they have been observed to be already impacted and will likely be impacted significantly in the future, too, by climate change (Malhi et al., 2020) and other anthropogenic changes. The changes reported are often negative as well as heterogeneous depending on the context, management system, and ecosystem conditions as also noted by Mina et al. (2017). Although some positive changes have also been reported, negative impacts far outweigh the positive impacts across the HKH.

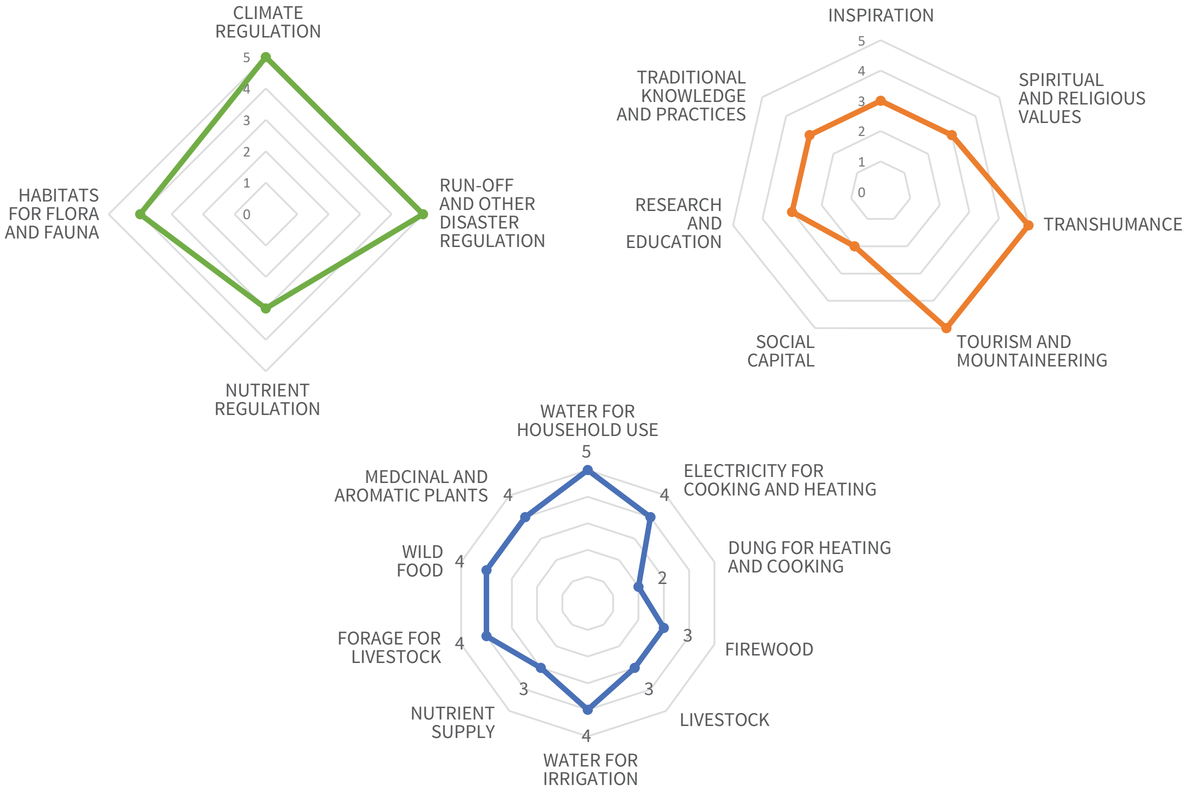
The major impacts reported relate to provisioning services, followed by cultural services, and supporting and regulating services (Figure 4.6). Food, fibre, and ecosystem products, both wild and domesticated, are the provisioning services from forests, lakes/rivers, agriculture lands, and rangelands that are impacted. The medicinal and aromatic plants are likely to lose their existing habitats by 2050 and 2070 due to phenological changes and shifts in habitats in a northerly and upward direction (Gaire et al., 2014; Manish, 2022). Species that have a limited habitat range are highly vulnerable and likely to face extinction (Manish, 2022). According to Manish (2022), 13–16% of the medicinal plant species in the Sikkim Himalaya will be lost. The collection of and trade in NTFPs and MAPs have not only supported the subsistence living of people but has dramatically changed livelihoods due to the diversified economies in the mountain regions of the HKH (Gurung et al., 2021; Kandari et al., 2012). The collection and sale of *Ophiocordyceps* in Nepal is a case in point. It has not only helped to support livelihoods but also created opportunities for business investments while bringing about improvements in the overall quality of education (Childs & Choedup, 2014). Pest attacks and diseases relating to apple production in Nepal and Himachal Pradesh of India have also been reported with production declining by 9.4 ton per hectare over the last two decades in Himachal (Das, 2022). Similarly, the size of the fruits of box myrtle (*Myrica esculenta*) is reportedly decreasing in the HKH (Shah & Tewari, 2016).

High-elevation wetlands, which provide a variety of services, face severe degradation from changing weather patterns, cryospheric changes (glacier melting/disappearance, permafrost thawing), and soil erosion (Chatterjee et al., 2010). As such, the quality and quantity of water, habitat functions of biodiversity, cultural and spiritual values, and local livelihoods linked to the wetlands are impacted. Mountain communities depend on glacier melt for drinking, cooking, and other household uses (Rasul & Molden, 2019) and these communities are facing a shortage of water because of reduced glacier melt (Rasul et al., 2020). Areas that were once covered by glaciers and snow are now dried up and exposed allowing vegetation growth (Molden et al., 2022). The increased occurrence of floods, debris flow, and droughts also degrade wetlands with high sedimentation, losses, and damages.

Climate change may also affect tourism and mountaineering significantly. The intensity and frequency of disasters and hazards like avalanches, landslides, debris flow, flooding, and GLOFs may negatively impact both access and destinations (K. C. & Parajuli, 2015). Climate change may also impact spirituality, cultural identity, and aesthetic values (Palomo, 2017). In the HKH, snow-capped mountains and glaciers are considered both symbolic and sacred (Allison, 2015). The identities of monks and highlanders, for instance, are linked with glaciers and mountains.

Among the livelihood options impacted are small-scale mountain agriculture and pastoral systems which are the major livelihoods of mountain communities (Molden et al., 2022). The melting of snow and ice, and permafrost thawing as well as extreme events such as floods, disasters, and debris flow significantly impact the pastoral and agriculture systems. Snow and glacial melt water are the only options for irrigation and, therefore, agricultural activity will be significantly impacted by changes in the melting patterns (Rasul & Molden, 2019). Mountain agriculture is also impacted by pest

FIGURE 4.6 **AN INDICATIVE FIGURE SHOWING IMPACTS ON ECOSYSTEM SERVICES ACROSS THE HKH**



Source: Scopus-based literature review by the authors (2021); dataset available on request

infestations and diseases, which have a direct impact on people's livelihoods. According to Basnet et al., (2021), pests and diseases have caused a rapid decline in large cardamom production in the eastern part of the HKH.

At highest risk is biodiversity of the HKH, especially the endemic and threatened species that have a limited and specific habitat range and are already impacted by land use change and other pressures (Zomer et al., 2014). It has been found that the temperate and alpine areas are especially at risk. Zomer et al. (2015) has predicted an upward shift of bioclimatic zones by 2050 with significant impacts on biodiversity of high value in the Yunnan province of China. Changes in the vegetation composition, community structure, and conditions will affect wildlife habitats as well as cultural and religious values associated with high-elevation lands including rangelands (McCollum et al., 2017). Johnson et al. (2022) has drawn attention to the implications of the ecoregion shift of umbrella species like the snow leopard, red panda, and Asian elephant in the transboundary Kangchenjunga landscape across Bhutan, India and Nepal.

Forests are the storehouse of goods and services, providing fuelwood, timber, fodder, MAPs, NTFPs, carbon sequestration, air, water, nutrients cycling, and species and genetic diversity which are fundamental to life (Joshi & Joshi, 2019; Joshi & Negi, 2011). The increased wildfires in the forests and grasslands across the HKH may impact the diversity and density of both plant and animal species. For instance, forest fire frequency has reduced the richness and density of floristic diversity due to poor regeneration processes in the forests of Uttarakhand, India (Bargali et al., 2022). Fires may also reduce the ability of forests and grassland to provide provisioning, regulating, cultural, and supporting services, thereby impacting people's livelihoods significantly. This may ultimately affect the faunal diversity.

Rangelands in the HKH provide services to enhance food security, household survival, and community-wellbeing. Climate change leading to increased disasters and risks in the higher elevation areas, however, have posed risks to rangelands and their resources and practices including pastoralism (Caplins et al., 2018). Drought-induced degradation has accelerated erosion and natural hazards while disaster-induced degradation and upward shifts can have a negative impact on livestock rearing, productivity, and food security of pastoral communities (Rasul et al., 2014; Tiwari et al., 2020).

The increased number and frequency of disasters in the high mountains have been affecting people, their cultural practices, and overall wellbeing (Stäubli et al., 2018). For instance, the avalanche following the earthquake of 2015 in the Langtang valley of Nepal not only destroyed most of the Langtang village, forests, and grassland but also claimed the lives of more than 380 local inhabitants, tourists, and over a hundred heads of livestock (Government of Nepal, 2015).

In terms of positive impacts, Hussain et al. (2016) reported higher productivity and favourable growing conditions for fruits and vegetables in Gilgit-Baltistan of Pakistan while S. Thapa & Hussain (2021) reported higher productivity for traditional crops in the Karnali region of Nepal. Higher grass productivity has also been reported in some areas of HKH (McCollum et al., 2017).

4.7. Adaptation options

Adaptation to climate change is challenging in the mountains due to its geography coupled with existing socio-economic and political conditions (Gioli et al., 2014). Despite the challenges, people and nature have been adapting to changes induced by climate and non-climatic drivers of change. Adaptation, like impacts, is heterogenous and context-specific depending on the issue(s), condition, and context.

In the HKH, ecosystem-based adaptation (EbA) has been reported to be effective. They have been reported to be effective not only for human adaptation but also to reduce risks from landslides and floods and to restore ecosystems (Klein et al., 2019; Lavorel et al., 2019). In China, the EbAs focus on restoration of degraded lands, urban forestry, and agrobiodiversity while, in India and Nepal, ecosystem-based disaster risks reduction (Eco-DRR), traditional knowledge for ecosystem management, EbA, and resilience building as well as ground water recharge are practiced (Chaudhary et al., 2021). These strategies have been reported to be successful in restoring landscape functions, sustain ecosystem services, and conserve biodiversity (Chong, 2014).

Among other EbA practices are sustainable water management practices such as recharging groundwater and adopting rainwater harvesting to improve soil moisture. In India, wetland protection and rehabilitation has been reported to increase water retention capacity, conserve wetland biodiversity, and improve ecosystem services (Dhyani et al., 2018). Diversification of crop species, agroforestry practices, and agrobiodiversity are also in practice across the HKH to adapt to the changing climate, enhance sustainability against pests and diseases, and retain soil biodiversity (Chaudhary et al., 2021).

Looking at transboundary landscapes beyond country borders to increase connectivity for biodiversity conservation is an ideal way to adapt to climate change (Johnson et al., 2022; Zomer et al., 2014). Elsen et al. (2018) have also highlighted the importance of protecting areas along the elevational gradients. Corridors and connectivity are important, particularly for species with limited habitat range and range shifts, to move to higher elevations. These strategies may help to halt population decline or even extinction (Thomas et al., 2014). Similarly, regenerating fire-adapted species and rehabilitating fire-damaged forest ecosystems have been recommended to protect the diversity and density of flora for a healthy ecosystem (Bargali et al., 2022). Moreover, improvements in ecosystem health and quality can significantly reduce the impacts of climate change (Choi et al., 2021). What is more, land management systems play an important role in enhancing the capacity of ecosystems through promoting sustainable practices like integrated watershed management (Thapa et al., 2021) and reducing anthropogenic impacts (Tchebakova et al., 2016). For instance, agriculture and infrastructure development are among the major reasons for peatland degradation in Pakistan (A. Khan et al., 2020). Halting such activities and restoring such lands can help protect and conserve peatlands. Finding ways to combat increased pest infestation and invasive species on agriculture and agroforestry practices is another feasible option (Gurung et al., 2021).

4.8. Key knowledge gaps

Major knowledge gaps exist regarding the impacts of the changing cryosphere on biodiversity and ecosystem services as well as response options. These knowledge gaps can be categorised into linkages gaps, impact gaps, and response gaps as in Chapter 3.

4.8.1. Gaps in linkages

The cryosphere and biodiversity at species, genetic, and ecosystem levels are highly interconnected (Qin et al., 2017). However, understanding of the links between the cryosphere and biodiversity across the HKH with regard to the processes involved, connections, and feedback is limited. Some of the knowledge gaps with regard to the linkages are given below:

1. Knowledge of the treeline shift in the HKH region has advanced since the last decade. However, these studies have been confined to the high mountain regions of Nepal, China and India, while few studies are available on treeline dynamics in Afghanistan, Bhutan, Myanmar and Pakistan (Gaire et al., 2014).
2. Permafrost, an important component of, and contributor to, the alpine ecosystems has been less studied. The interactions and links between permafrost and alpine ecosystems remain under explored in the region (Wang et al., 2022).
3. Similarly, linkages between cryospheric changes and different ecosystems such as rangelands, peatlands, and high-elevation wetlands remain relatively less explored. For example, evapotranspiration is a key hydrologic process linked to ecosystems but thus far there is limited understanding on the relationship between evapotranspiration and high-elevation vegetation (Wang et al., 2020), as also mentioned in Chapter 3.
4. There is limited understanding of the role that steep environmental heterogeneity can play in maintaining high diversity and endemism to fight against climate change;
5. There is also limited understanding of the two-way interaction between the cryosphere and biodiversity at species, genetic, and ecosystem levels;
6. Knowledge is limited on the response of fauna to changes in floral communities and vice-versa.

4.8.2. Gaps in impacts

This chapter has reported on the observed impacts of the changing cryosphere on biodiversity. We summarise the major gaps in knowledge below:

1. Although climate-driven extinctions and range retractions are already widespread, they are poorly reported due to failure to survey the distribution of species at sufficiently fine resolutions in order to detect declines and to attribute such declines to climate change (Thomas et al., 2006).
2. The impacts of cryospheric changes on high-elevation wetlands and peatlands need urgent attention (Bhatta et al., 2018; Zhu et al., 2021).
3. The impacts of hazards and disasters on biodiversity and their cascading impacts on society and their wellbeing need more careful study.
4. The impacts of a changing cryosphere on biodiversity at all levels and its cascading impacts on society and their wellbeing need further study.

4.8.3. Response gaps

How ecosystems or species respond to the changing cryosphere remains little explored. However, to better adapt, it is necessary to understand the process, degree, and type of responses. The identified knowledge gaps are as follows:

1. Knowledge of the ecosystem's sensitivity to extreme climate events is still limited. Hence, studies need to be conducted to understand the resistance, recovery, and resilience of ecosystems at higher elevations to such weather events as well as the extent and magnitude of ecosystem responses across the HKH (A. Chakraborty et al., 2018).
2. More studies to understand how biodiversity at ecosystem and species level adapt to changes including climate change are needed.
3. Long-term monitoring of the interrelationships between the cryosphere and biodiversity and studies of their climatic responses are still insufficient. Experimental studies are either insufficient or have narrow spatial/temporal coverage.
4. There is a need to standardise the methodology for purposes of reproducibility, comparability, and generalisation of the findings, something largely still lacking in the available studies.
5. A powerful model on the past and future simulations of cryo-biosphere linkages is lacking.

4.9. Recommendations

Several recommendations for better understanding the impacts of the changing cryosphere on biodiversity and ecosystems are given below:

Science

1. Long-term research and monitoring are required to better understand the linkages, interactions, changes, and responses across different ecosystems and ecotones at higher elevations in relation to a changing cryosphere. To do so, multi- and inter-disciplinary studies should be conducted to arrive at a holistic understanding of the complex issues around the cryosphere, biosphere, and society. Forest-water interactions and permafrost-grassland links are among subjects that need to be studied in detail.
2. An assessment of the nexus between the cryosphere, biosphere, and society needs to be undertaken to arrive at a holistic understanding of the central issues and their synergies.
3. Modern geospatial and information technologies and artificial intelligence such as geotagging, sensors, and bioacoustics should be used in studies to arrive at accurate assessments.
4. Research on contemporary issues need to be prioritised and strengthened in the region through collaboration and partnership at all levels which include local people and organisations. Participatory approaches like citizen science and participatory Geographic Information System are among possible methodologies.

Policy and practice

1. EbA, nature-based solutions, and nature-climate solutions should be mainstreamed into policy, plans, and practices at the local, national, and regional scales.
2. Regional cooperation for science, policy, and practice across the HKH is important to understand and address the impacts, and it should be given priority.
3. Prediction and projection studies should be prioritised to understand issues and to plan for evidence-based solutions.
4. South-South cooperation and collaboration among HKH countries for research and practice should be prioritised.
5. Corridors as well as connectivity between protected areas should receive serious consideration to enable species movement upwards and northwards.

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