Biodiversity and Conservation (2023) 32:3731–3764
https://doi.org/10.1007/s10531-023-02692-x

REVIEW PAPER

Are Himalayan ecosystems facing hidden collapse? Assessing the drivers and impacts of change to aid conservation, restoration and conflict resolution challenges

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Received: 16 June 2022 / Revised: 22 July 2023 / Accepted: 25 July 2023 /
Published online: 10 August 2023

Abstract
The Himalayas are a global hotspot for biodiversity and endemism, and yet the health of its natural ecosystems is deteriorating rapidly. Natural ecosystems across the Himalayas are threatened by diverse drivers, with each of them increasing the probability of extinction of endemic species and collapse of natural ecosystems. The key concern of this review is to endorse the urgent need to develop an agreed approach at national and regional level and support for the adoption of IUCN's Red List of Ecosystems (RLE) at national, regional as well as biome level. With increasing population and diverse interests of stakeholders for subsistence, commercial and strategic needs, the threats are growing for the natural ecosystems. Deforestation and forest degradation rates are alarmingly high, with an exponential surge in unsustainable harvesting, developmental projects, urbanization, commercial tourism, pollution and climate change exerting more damage to natural ecosystems than expected. Countries in the region (Bhutan, China, India, Myanmar, and Pakistan) with a recent exception of Nepal, are rapidly losing their natural forest cover, ecosystem structure and functions to monoculture agriculture and commercial plantations. Wild life trafficking and transboundary illegal trade as a mega-driver has degraded even the most sensitive and high value high altitude alpine grasslands and timberline ecosystems. This review takes stock of diverse drivers of loss and their significant impact on ecological and social concerns that are not localized and are experienced beyond Himalayas by transboundary areas and downstream communities across Asia. It highlights the potential of existing and emerging risks in the region that indicates towards the compromised health of many Himalayan ecosystems. For data driven evidence-based decision making the RLE approach have been included as the headline indicators of the Kunming-Montreal Global Biodiversity Framework (GBF) for Goal A as well as in the UN System of Environmental Economic Accounting (SEEA). Hence, using RLE becomes a necessary and effective tool to support climate adaptations, conservation, conflict resolution and restoration planning efforts in the region. It is needed to help countries identify what strategic measures should be the priority to help halt, and reverse the collapse of Himalayan ecosystems.

Communicated by Nigel Stork.

Extended author information available on the last page of the article

Keywords Ecosystem health · Himalayas · Deforestation · Direct driver · Indirect drivers · Climate change · Red list of ecosystems

Introduction

Globally, mountain ecosystems are home to high floral and faunal diversity along with rich ethnic diversity supporting the well-being of half of human populations despite being exceptionally fragile due to natural and anthropogenic drivers of change. Ninety percent of global mountain populations in developing and underdeveloped countries, mostly in Asia–Pacific, are considered more vulnerable than elsewhere (Körner et al. 2005). The Himalaya is the tallest global mountain chain (length of 2400 km and width of 300 km), and has remarkable topographical and climatic variation (Rana and Rawat 2017). It includes parts of eight countries: Afghanistan (11.4%), Bhutan (1.1%), the Tibetan Autonomous Region (TAR) and China (48.1%), India (14.1%), northern Myanmar (9.3%), Nepal (4.3%) and Pakistan (11.8%) (Pandit et al. 2014) (Fig. 1). The Himalayan region is a rich repository of threatened endemic flora and fauna, high conservation value ecosystems, and precious medicinal plant species (Reddy et al. 2017; Areendran et al. 2020). The Himalayan mountains are a crucial water source for Asia, supplying fresh water and fertile soil to grow food through the Mekong, Ganges, Brahmaputra, Yangtse, Indus, Salween, and Irrawaddy river basins (Bandyopadhyay and Gyawali 1994). Bhutan in the west is reported to have the highest plant species richness (5452 species) while the Northwest Himalayas in India has least recorded plant species richness (1649 species) (Rana et al. 2019). Natural ecosystems in the Himalayas region are ecologically fragile and declining at an unparalleled rate (Saikawa et al. 2019). Unexpected, continuous, and rampant change in the state and dynamics of the natural ecosystems already had significant undesirable and adverse impact on the Himalayan biodiversity and its vital ecosystem services. Hence, Himalayan forests, as one of the most diverse ecosystems on Earth, face continuous pressure and high risk of ecological collapse (Lindenmayer et al. 2016; Dhyani et al. 2018, 2020; Dhyani and Dhyani 2020). By 2025, the IUCN intends to have evaluated the risk of collapse of all global ecosystems under the Red Listing of Ecosystems (RLE) framework (Sato and Lindenmayer 2018) to ensure localization and realization of UN Decade of Restoration targets (2021–2030) and also recently accepted Kunming Montreal Global Biodiversity Framework, 2022 along with other pertinent biodiversity, restoration and climate targets (Vloon et al. 2021). It is important to mention that, with the exception of Myanmar (Murray et al. 2020), there has been no ecosystem health assessment for any other Himalayan country. Hence this review becomes a significant baseline to initiate and support ecosystem health assessments for stressed and threatened Himalayan ecosystems and provides a broader understanding to initiate and support the framework assessment for data-driven, evidence-based conservation, restoration and conflict resolution planning.

Concerns and issues

The natural forest ecosystems of the Himalayas are among the most exhausted and degraded ecosystems in Asia (Schickhoff 1995). Deforestation in the Himalayas has mostly been credited to increasing population pressure resulting in severe resource depletion (Myers 1986). However, Ives et al. (1989) suggested this as an “overly simplistic” analysis

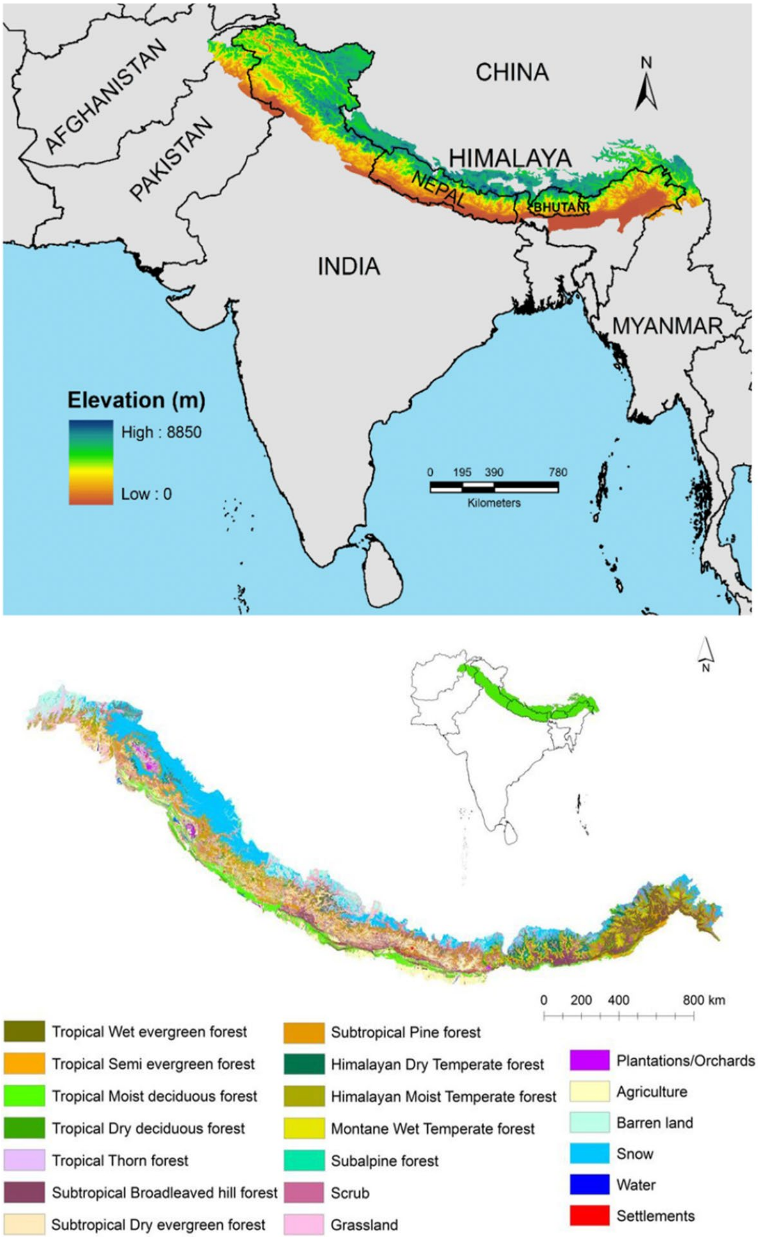

Fig. 1 Map showing the Himalayas and countries in South Asia and the distribution of the dominant forest types. *Source:* Manish and Pandit (2018) and Reddy et al. (2017)

of a very serious problem and labeled it "*Theory of Himalayan Environmental Degradation*" (Ali and Benjaminsen 2004). Transboundary cooperation in the region is required to manage or deter trafficking and illegal trade of wild species, human-wildlife conflicts, transboundary pastoral activities, commercial tourism, environmental pollution due to mining, waste disposal, and spread of persistent organic pollutants (Gurung et al. 2019). Increasing frequency and intensity of extreme climate events and disaster risks has also been rampant across Himalayas. Impacts of climate change as a mega-driver has amplified the risks in the region due to human induced pressures and interferences. This was clearly highlighted and also projected in previous as well as recent Intergovernmental Panel on Climate Change (IPCC) reports especially the special report on the ocean and cryosphere in a changing climate in 2019 as well as in cross chapters on mountains in the recently released IPPC report in 2022 on impacts, adaptation and vulnerability by working group II to the Sixth Assessment Report of the IPCC (Hock et al. 2019; Adler et al. 2022).

Deforestation and forest degradation

Overview of regional change

Despite concerns and efforts to protect and secure forests, deforestation and forest degradation have profoundly affected the natural forest ecosystems across the Himalayas (Brandt et al. 2012). The entire Himalayan region is reported to have rapid deforestation, and natural ecosystems in the region although appearing superficially intact, are facing continued decline with extended lag periods for retrieval. This clearly indicates Himalayan ecosystems are facing hidden collapse that might be evident soon (Lindenmayer and Sato 2018; Dhyani et al. 2022). The wider impacts of forest degradation on species populations and ecosystem functioning have been insufficiently documented (Pandit et al. 2007). A comparison of deforestation rates between 2000 and 2014 across the temperate forests of Bhutan, Nepal, China, India, and Myanmar indicate only 13% of forests being protected and deforestation rates varying by 1.4% between countries (Brandt et al. 2017; Ranjan 2018) (Fig. 2).

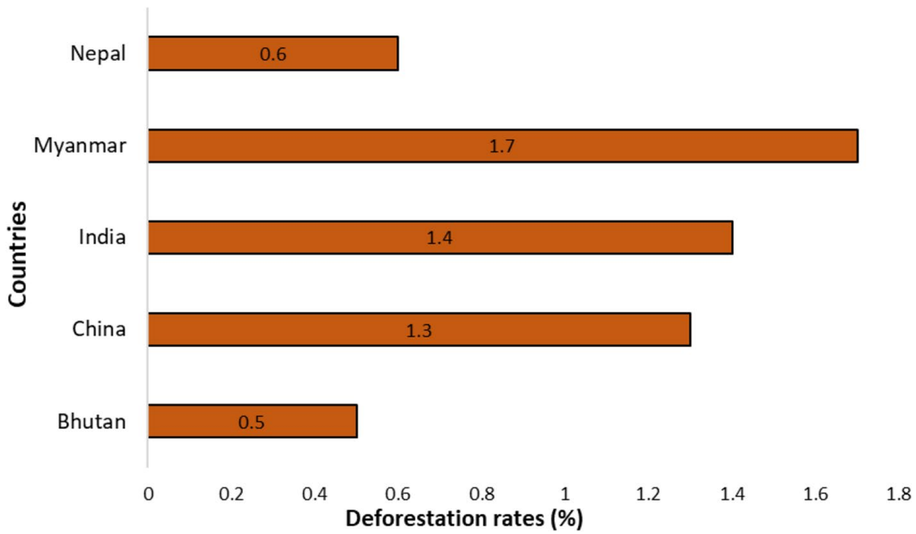

Fig. 2 Decadal deforestation rates (2000–2014) in forests outside protected areas of Himalayan temperate zone. *Source* Brandt et al. (2017)

Forest ecosystems in the Indian and Pakistan parts of the Himalayas have been degrading rapidly since the mid-1800. Northern Pakistan, in Himalayan-Hindu Kush-Karakoram region has < 3% forest cover compared to neighboring countries (Yusuf 2009; Khan 2016). Widespread deforestation in the last three decades (1990–2010) has resulted in the loss of more than 30% of the forest cover and three-quarters of these forests were lost during the last century with higher losses for the western region (23%) than eastern (7%) (Qamer et al. 2016). Bhutan is slowly emerging as a ‘crisis ecoregion’ because of increasing land and forest degradation (Dorjee et al. 2020). Bhutan has lost around 60.9% of forest cover between 1930 and 2014 with major loss in subtropical broad-leaved hill forest (64.5 km^2) and moist Sal Forest (9.9 km^2) (Reddy et al. 2016). There are reports of increasing forest cover in Bhutan but the quality of the structure of these forests has deteriorated significantly. Total annual deforestation in Bhutan as per statistical records for all the drivers is 5798 in comparison to 4274 ha as projected based on the spatial analysis (Watershed Management Division 2017). More than 50% of the forest cover of Nepal was lost between 1960 to 1990 mostly from Tarai and Churia regions followed by an accelerated pace of deforestation in the last three decades (1990–2020) (Ives et al. 1989; Chaudhary et al. 2015). However, between 1980 and 1990s, a reassessment of the national forest management practices by government of Nepal, facilitated the transfer of national forests from the forest department to community forest groups for community led management as a transformative approach under the pivot Forestry Act, 1993. A study by Van Den Hoek (2021) reported almost double (from 26 to 45%) increase in the forest cover between 1992 and 2016 in Nepal. Deforestation rates in the Himalayan part of China were much lower than 0.01% (1991–1999) which increased by 0.21% between 2001 and 2010 (Wang and Myint 2016). The Himalayan part of Myanmar contributes 28% of the entire deforestation in the Himalayas and is of grave concern. Forest degradation in the Himalayas corresponds to 61% of the forests having crown cover less than the ecologically sustainable threshold of 40% (Baland and Mookherjee 2014). Deforestation has reduced the forest cover from 84.9% in 1970 and is projected to reduce to 52.8% by 2100 (Pandit et al. 2014). Despite widespread deforestation across the Himalayas, countries in the region have been continuously projecting increasing forest cover while continuous loss of biodiversity is reported by researchers and this is really alarming (Brandt et al. 2012).

Drivers of large-scale deforestation

Deforestation and forest degradation rates may be different across the region, but the core reasons behind them are common and that includes weak governance, unsustainable and overexploitation of wild species, increasing urban sprawl, and loss of traditional culture and practices (Wang et al. 2019). Crucial deforestation drivers across the Himalayas are unsuitable land management, the rampant pace of development, forest fires, organized criminal activities, institutional insufficiency, administrative dispiritedness, and the uncertainty of tenure of forest land (Roy et al. 2015; Sheth et al. 2019). Demographic changes brought extensive land-use changes through agricultural intensification and, large-scale deforestation in all the Himalayan nations (Yusuf 2009; Ranjan 2018; Dhyani and Dhyani 2020; Dhyani et al. 2022) (Fig. 3).

Hauchhum and Singson (2020) reported *jhum*, shifting or slash and burn farming in Eastern Himalayas of India, as an important cultural driver of deforestation and forest degradation that facilitates clearance of primary forest at regular intervals followed by shorter *jhum* cycles that is significantly affecting natural forests. In addition, ’rat hole’ coal mining

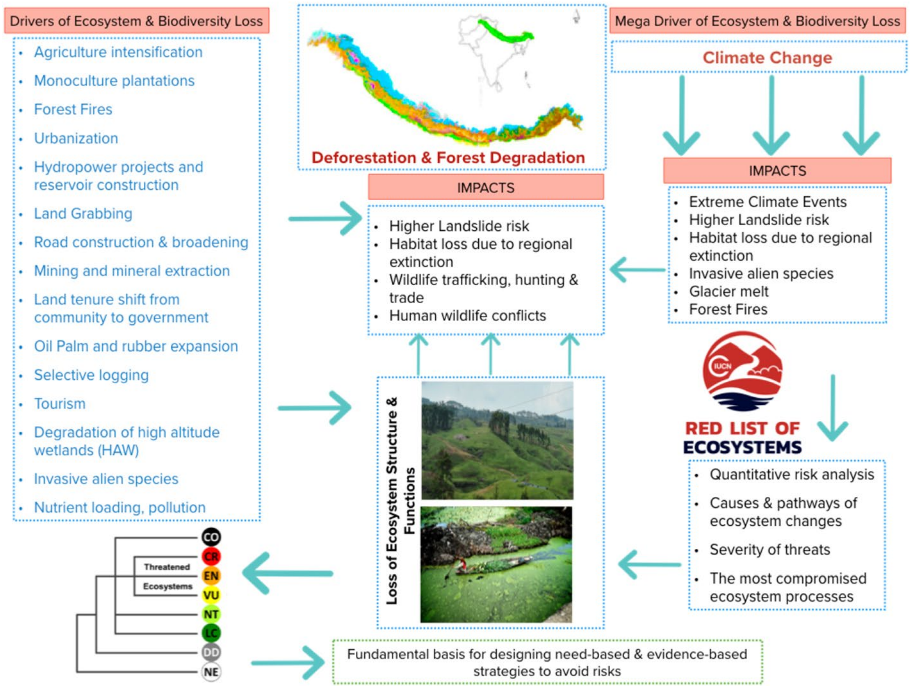

Fig. 3 Diverse drivers of ecosystem and biodiversity loss across Himalayan region, their impacts and necessity to use IUCN Red List of Ecosystem tool to address the growing threat of loss of ecosystem structure and functions

in Garo, Khasi and Jaintia Hills of northeast India has resulted in large-scale deforestation and highly degraded landscapes in the biodiversity hotspot of Meghalaya making the fragile ecosystems vulnerable to rapid environmental degradation (Yadav et al. 2013). The primary causes of recent deforestation in Bhutan since 2000 are infrastructure development (34%), fires (26%), timber harvesting (22%), and agricultural intensification (14%) (Sears et al. 2017). The primary drivers of deforestation in Bhutan has been allocation of State Reserve Forest Land (SRFL) for hydropower projects, road construction and widening, agriculture intensification, mining, and construction of power lines. Increases in population, influence of "land mafia", commercial and illegal harvesting, lack of proper monitoring, wide-spread poverty, and cultural outlooks of locals in Pakistan has left the forests in their part of the Himalayas on the verge of collapse (Ali and Benjaminsen 2004; Shehzad et al. 2014; Ahmad et al. 2018).

Landscape-scale agricultural intensification and monoculture

Expansion of commercial crops

Agriculture intensification in Bhutan has led to the loss of 60.9% of forest cover between 1930 and 2014 with a major decline between 1930 and 1977 (Reddy et al. 2016). In Pakistan, traditional cropping has shifted to commercial agricultural that is neither suitable for landless pastoralists or ecological sustainability (Khurshid et al. 2017). In the Swat district of Pakistan land use land cover change (LULC) analysis shows a decrease in forest cover by 30.5% with 11.4% due to expansion of agriculture. In the agro-scrub forest zone of Barikot, forest cover decreased by 32.7% in 1968 to 9.5% in the year 2007 while agriculture expansion of 129.9% was at the expense of forest areas (Qasim et al. 2011). Agriculture intensification has also resulted in deforestation in Nepal and a larger area of forest land in Nepal is projected to completely change to agriculture by 2030 at the rate of 24% per year. Nepal's Kailash Sacred transboundary landscape from 1990 to 2009 experienced a 9% reduction in forest cover due to a 12% expansion of agriculture (Uddin et al. 2015). Though, forest conservation and management model of Nepal has been recently appreciated where shift of forest management from forest rangers to community forest groups have helped increasing forest cover in Nepal. Ying-qiu et al. (2001) used area production model in a study in Nepal to project increased productivity of subsistence food crop at the rate of 1% annually with a projected reduction in deforestation rates of 17% per annum. They concluded that agriculture productivity is an important factor to deforestation, hence reducing agriculture intensification will be crucial for reducing deforestation and forest degradation across Himalayas. In the last five decades the Indian Himalayan Region (IHR) has witnessed a rapid shift from subsistence hill farming to commercial agriculture with increasing importance of horticulture or tree-based cash crops, such as apples, navel oranges, blood oranges, tea, and rubber. In Himachal Pradesh, India, the area under apple orchards increased from 400 ha in 1950–1951 to 3025 ha in 1960–61 and further 99,564 ha in 2009–2010 and continues to increase in area and reach higher altitudes (up to 3500 m amsl) due to climate change (Basannagari and Kala 2013; Sahu et al. 2020). In Darjeeling, India land under tea cultivation between 1874 and 2010 has increased by 30.7% resulting in forest decrease of 69.5% (Prokop 2018). Rapid deforestation at 16–30 km^2/year has largely been due to increase in large tea plantations, followed by an increase in tea production areas by 16 km^2/year leading to forest cover change of 2,105.9 km^2 across the Himalayas.

Monoculture plantations

There has been an increase in large and small-scale plantations of Pine, Bamboo, Rubber, Eucalyptus, Casuarina, and Oil palm, resulting in massive forest conversions. Opium farming by locals along river banks in the Hukaung Valley of Myanmar has resulted in large losses of forests (Papworth et al. 2017). Demand for rubber is such that plantations are projected to increase by 4.3–8.5 million hectares by 2024 threatening Asian forests, including many biodiversity hotspots and protected areas (Thomas et al. 2015). From 1997 to 2013 the area under rubber e increased from 4.47 km^2 to 28.42 km^2, with most of these plantations located in forests (Chakraborty et al. 2018). Indigenous *jhum* in many parts of Tripura in India has also been substituted by rubber plantations (Pandey et al. 2020). The area occupied by bamboo plantations in China has increased in the last two decades (6.01 million ha) and these un-managed bamboo stands are encroaching nearby natural forests as invasives. In the Eastern Himalayas, the Indian native bamboo species, *Yushania maling*, has already reached alarming levels of invasion with a huge concern for forest managers (Xu et al. 2020). *Banj* oak (*Quercus leucotrichophora*) forests are declining being replaced by Chir pine across Central Himalayas and this is expected to also compromise the water supply from natural springs which are supported by Oak forests. Large-scale alteration of the landscapes occurred during colonial times with extensive planting of Chir pine (*Pinus roxburghii*) plantation for timber and especially railway sleepers (Nautiyal 2015; Shah and Sharma 2015). Extensive plantation of Chir pine (*Pinus roxburghii*) and *Eucalyptus* to restore 350,000 hectares degraded land under Pakistan's Billion Tree Tsunami launched in 2014 has brought severe criticism (Khan 2016). Fast growth and biomass production (57 t/ha in 5 years) of *Eucalyptus* hybrid is preferred by locals than native Sal (*Shorea robusta*) and large plantations of monocultures are growing in the Himalayan foothills reducing and compromising present and groundwater availability (Dogra et al. 2009).

Land grabbing

Hundreds of hydropower projects on the rivers of the Himalayas are destroying thousands of hectares of natural forests and pristine ecosystems (Dharmadhikary 2008). Threats of logging and land grabbing have endangered Nepal's Tinjure-Milkhe-Jaljale (TMJ) forest complex also known as the "*Rhododendron Capital of the Himalayas*," home to 28 out of 32 rhododendron species of Nepal (Lemelin 2020). Land grabbing for agribusiness purposes is widespread in the Himalayan highlands of Myanmar, as well as for tourism in many parts of the Indian and Nepal Himalayas. Land grabbing for monoculture plantations of rubber, palm, and bamboo for commercial purposes has intensified due to their increasing market demand. Land grabbing for strategic purposes especially security is common across transboundary areas of India, Pakistan, and China. China has emerged as the biggest land grabbing nation with historical incidences of land grabbing reported from transboundary areas of India, Pakistan, China occupied Tibet, Bhutan, and Nepal (Chellaney 2017; Wu and Myers 2020). It is anticipated that by 2030 urban areas in China will encroach further inside Indo-Burma hotspots by more than 200% (Güneralp et al. 2015).

Land tenure shift from community to government

Although tenure and supervision of forest management is still mostly with state forest departments in many Himalayan states of India, Nepal, and Bhutan, some areas, known as community forests, were historically owned and successfully managed by local communities. Over the centuries it has helped to moderate harvesting and also facilitated forest regeneration through rotational harvesting and in last few years have helped the natural forests grow back. In Nepal, it is known as forest-user-groups (FUGs) and Van Panchayats (VPs) in the Uttarakhand state of IHR where locals have enforced rules for biomass extraction followed by rotational harvesting for regeneration support (Misra et al. 2009; Baland and Mookherjee 2014). The Forest Rights Act 2006 in India intended to address the historical injustice to forest-dependent communities. However, the Act has still not been acknowledged by the governments of many Himalayan states. In Meghalaya state in IHR customary land rights have led to rampant rat hole mining (customary coal mining practice is considered risky as it is carried out by digging narrow tunnels underground that can hold one person at a time inside to collect coal), *jhumming* (traditional shifting agriculture) (Dasgupta et al. 2021). Repurposing of local lands for hydropower projects especially in China, India, and Nepal, is a serious concern and land rights are lost. Road broadening and construction for strategic and defense purposes in transboundary areas is an unavoidable activity that results in shifting of community land to government.

Oil plam and rubber expansion

The Special Programme on Oil Palm Area Expansion (OPAE) with support from states in the Eastern Himalayas by the institution of a New Land Use Policy (NLUP) has been a launchpad for the promotion of oil palm (Srinivasan 2015). Clearing for oil palm has resulted in lost rainforest biodiversity: more than 1,01,000 hectares were recognized for oil palm cultivation and with the entry of three commercial oil palm houses, more than 17,500 hectares have already been logged in less than a decade (Raman 2014). Four tyre corporations represented by Automotive Tyre Manufacturers Association (ATMA) have organized to fund Rs. 1000 crores for rubber plantation expansion over a period of five years across 200,000 hectares of land in seven states in North East India (PIB 2021).

Impacts of deforestation and forest degradation

Higher landslide risk

Increasing anthropogenic interventions including railway and road construction, mining, deforestation, and agriculture intensification have accelerated landslide risk across the region (Pande et al. 2002; Rimal et al. 2015). The annual financial loss due to landslides in the Himalayas was assessed to be more than USD 1 billion, which is around 30% of the global financial losses due to landslides. More than USD 9 million of loss and 300 deaths every year are reported from Nepal alone (Wang et al. 2019). Landslides are more frequent on lands without trees than undisturbed forests, or wisely planned agriculture areas in Bhutan (Sears et al. 2017). More than 12% of Indian Himalayan terrain is highly susceptible to landslides and more than 11,000 deaths due to the landslides were reported between 2004 and 2016, making India the most landslide affected region. The situation has further deteriorated because of unrestricted and unregulated expansion of large-scale developmental projects (Pande et al. 2002; Chawla et al. 2018; Ray et al. 2020). In Pakistan multiple geohazards have increased due to slope destabilization from increasing deforestation due to rampant un-planned urban sprawl (Atta-ur-Rahman et al. 2011). Deforestation and road widening including all-weather roads in Western and Central Himalayas in India, roads in Nepal and Bhutan followed by belt and road extension in Tibet and other neighboring areas, are major threats to regional biodiversity (Kamp et al. 2008).

Habitat loss due to regional extinction

Selective logging

Selective logging in Nepal has reduced the supply of non-forest products and has enhanced degradation, and carbon emissions (Poudyal et al. 2019). In China, while implementation of a logging ban has resulted in some positive forest conservation outcomes, it has accelerated selective logging inside old-growth forests and sacred areas in Tibet autonomous region. This reflects local institutions in the region being destabilized by official policies (Brandt et al. 2015). Organized crime, institutional shortfalls due to inadequate resources, bureaucratic apathy, and uncertainty in use and tenure of forest lands other than community forests, which seem to have strong systems to manage them, have resulted in increased incidences of illegal selective felling across IHR despite a clear ban (Sheth et al. 2019). In the Eastern Himalayan states of India, selective logging has reduced the species richness and abundance of epiphytes due to changes in microclimate and habitat characteristics (Padmawathe et al. 2004). *Tectona grandis* (Teak) and *Xylia xylocarpa*, are illegally selectively logged for timber in production forests of Myanmar (Khai et al. 2016). Selective logging, especially illegal logging, has degraded the accessible previously non-logged forests in Myanmar followed by intensive clearing (Win et al. 2009).

Urbanization

Almost half a percent (132 km^2) of the geographical area under urban expansion in the IHR is home to 4 million inhabitants. The western and middle Himalayas have seen rampant urban sprawl coupled with demographic changes in the last few decades that is less in Eastern Himalayas (Diksha 2017; Rimal et al. 2018). Rapid population growth (830.92%) followed by demographic changes (333.45%) over almost four decades (1972–2015) has been reported from all the state capitals of IHR. During that period a significant upsurge in the mountain population has been observed of 0.5–1 million (Diksha 2017) (Fig. 4).

Along the India-Pakistan border in the Kashmir state of India the increase in urban populations has risen from 1 in 1901 to 46 in 2011 and other small towns are rapidly transforming into urban sprawl at a rate that was 18.41% in 1951, was almost double (31.6%) by 2011 and is still increasing (Reshi et al. 2020). According to the Ministry of Works and Human Settlement Royal Government of Bhutan (2016), rapid urbanization in the last few decades has resulted in 30% of the population of Bhutan living in urban areas compared to 15% in 1999. In the Barikot region of Pakistan forest cover has reduced from 32.7 to 9.5% over four decades (1968–2007) whereas, infrastructure built up has increased by 161.4% with a loss of 12.7% of forest cover between 1968–1990 and 18.96% between 1990–2007 (Qasim et al. 2011). Urban expansion increased by 13% in China inside the Himalayan

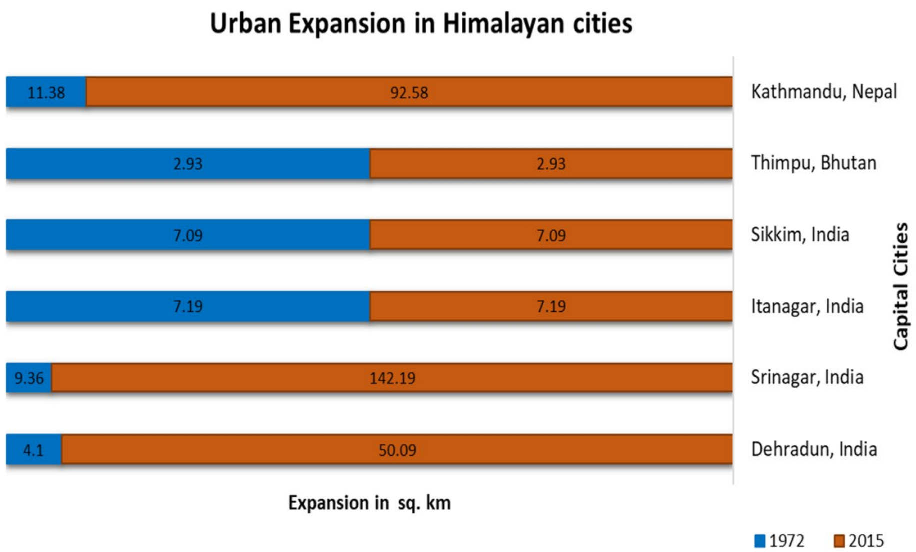

Fig. 4 Urban expansion in fast growing cities across Himalayas. *Source* Diksha (2017)

biodiversity hotspot by 2000 and is projected to increase by 200% by 2030 which will have a significant impact on the protected areas and biodiversity hotspots (Güneralp et al. 2015).

Prognosis

Wildlife hunting, trafficking, and trade

The illegal wildlife trade has led to the decline of some threatened species populations across Himalayan states for many years (Yi-Ming et al. 2000; Uprety et al. 2021). Alhough, hunting and illegal trade are prohibited by national and international laws, the global black market, wildlife smugglers, and poachers involved in illegal trade have worsened the situation in the region. The survival of many threatened species especially Giant pandas, Tibetan antelope, Saker falcon, Musk deer, and Snow Leopard is compromised (Yi-Ming et al. 2000). Pangolins and red pandas, endemic to the eastern Himalayas, are threatened because of the growing illegal trade due to geographic as well as diverse socio-economic complexities (Tamang 2020). Although the area under the protected area network (PAN) of the region is large, and China accounts for more than 70% of these protected natural reserves, the illegal wildlife trade and trafficking across transboundary areas along China border for local consumption is widespread. Myanmar, because of its geographic location, area and weak administration, has become an important route for illegal trade and trafficking of pangolins to China (Nijman et al. 2016). Mong La in Northern Myanmar Myanmar is the illegal pangolin trade hub (Nijman et al. 2016). Every year 140–168 pangolins are illegally shipped to China (Zhang et al. 2017). Widespread trade of the sun bear and the Asiatic black bear parts from Myanmar occurs due to the lack of enforcement of international wildlife trade regulations (Shepherd and Nijman 2008). Nepal's maoist insurgence has resulted in substantial control of many of its protected areas and enhanced nationwide poaching and illicit wildlife trade (Baral and Heinen 2005). Himalayan musk deer populations are declining due to historical customary hunting for meat and use of their canines for traditional ornaments that has now been banned and in recent times increasing demand of musk pods (The musk pod is source of musk that is a preputial gland in a sac under the skin of the male musk deer's abdomen) in pharmaceutical industries (Khan et al. 2006).

The Himalayas is a rich repository of many valuable and threatened plants and all countries in the region benefit through the export of raw herbal drugs (Peerzada et al. 2021). The growing local and global demand for natural medicines and nutritious food has resulted in rampant and unsustainable harvesting which, in turn, has increased the risk of extinction for these species (Badola and Aitken 2003). Medicinal plant harvesting is an important part of the rural livelihood in Nepal and also in India, Myanmar, China, and Bhutan that contributes up to 44% of the rural household income per annum (Cannon et al. 2009; He et al. 2011). Thousands of tonnes of roots, tubers, rhizomes, foliage, and fruits worth many millions of US dollars are annually traded (Olsen and Larsen 2003). A total of 1,748 medicinal plant species are present in IHR. Though, the first comprehensive assessment discovered that 112 plant species are currently threatened due to increasing commercial collection, unregulated commerce, habitat destruction, and unsustainable harvesting still, conservation strategies are in place for only five of these species (Banerjee 2021; Mehta et al. 2021). More than five decades of harvesting for 100 high-value medicinal plants from the Lingzhi region of Bhutan for traditional *gso-ba-rig-pa* hospitals in Bhutan has increased ecological pressure on these plants as well as their habitats (Wangchuk et al. 2016). High-value medicinal and aromatic plants from Nepal, with many of them being rare and threatened, are traded to 50 global destinations (Ghimire et al. 2016). Trade of caterpillar fungus (*Ophiocordyceps sinensis*) is the world's most exclusive high altitude bioresource that has affected the natural populations as well as fragile and sensitive alpine and timberline vegetation in higher reaches of India, Nepal, China (Tibet) and Bhutan (Shrestha and Bawa 2013, 2014; Hopping et al. 2018) (Fig. 5).

China's Belt and Road Initiative (BRI) is expected to promote its Traditional Chinese Medicine (TCM) by enhancing both demand and supply of wildlife-based traditional Chinese medicine (TCM) sourced from unexplored pristine mountain ecosystems (Hinsley et al. 2020). Illegal harvesting of wild orchids in Nepal and India in traditional medicine and trade to China, India, and Hong Kong is another concern for conservationists (Subedi et al. 2013).

Regulation of hunting and trade

A large number of species are listed in national, state and local protection lists due to increasing international commitment and influence of CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora), TRAFFIC (Trade Records Analysis of Flora and Fauna) and IUCN's Red List of plants and animals by the IUCN SSC (Species Survival Commission). All the countries in the region are Party to CITES and their national laws like China Wildlife Protection Law (CWPL); Burma Wildlife Protection Act, 1936; Forest and Nature Conservation Act of Bhutan, 1995; West Pakistan Wild Life Protection Ordinance, 1959; Wildlife Protection Act, 1972 by India and Nepal National Parks and Wildlife Conservation Act, 2029 (1973). Despite significant efforts on ground, all the countries consider curbing the wildlife trade in the region a challenging task. Most

Fig. 5 Cordyceps harvesting in India follow a shadowy trade to reach Chinese markets from India as well as other Himalayan countries in the region

of these wildlife legislations are difficult to be fully enforced in areas dominated by indigenous communities (Yi-Ming et al. 2000). There are some recent positive reports where the Myanmar government has started conserving the declining wild ibex populations along with IUCN by formalizing a trophy hunting scheme that ensured that local communities refrain from illegal hunting and trade by limiting hunting permits being sold to international hunters (Duffy et al. 2016). The Myanmar government has also initiated efforts to protect bears by enforcing wildlife trade regulations (Shepherd and Nijman 2008). Unfortunately, most of the wildlife trade regulations are for flagship animal species and trade of lesser-known plants or animals still needs more monitoring (Shrestha and Bawa 2013). During the COVID-19 pandemic, China's resolution in 2020 to impose a ban on the trade and consumption of wild species was considered a strong response to protect many threatened species (Koh et al. 2021).

Human-wildlife conflict

Livestock depredation across the trans-Himalayas results in substantial financial losses to local pastoral communities and hence human-wildlife conflicts have exponentially increased (Gupta et al. 2017; Tiwari et al. 2020). These conflicts have been a serious setback for ongoing conservation efforts sin the region (Naha et al. 2018). Human-wildlife conflicts surpass socio-economic factors, with ecological borders extending across neighboring Bhutan, India, Nepal, and China making it a crucial transboundary challenge (Sharma et al. 2020). Involvement of Rhesus macaque, wild pig, porcupine, common leopard, snow leopard, Asiatic black bear, Himalayan brown bear, and wolf has been frequently reported from human-wildlife conflicts (Sambandam et al. 2016). The intensity and frequency of human-wildlife conflicts in the last few decades in the lower Shivaliks and Tarai areas to trans-Himalayan sensitive landscapes has increased and Tiger, Common leopard and Asian elephant were considered most problem creating wildlife causing massive loss and damage to crops property, livestock and human lives. Subtropical Chir pine forests and Terai-Duars savannah grasslands in low and mid-elevation zones are high conflict zones having ~ 63% and ~ 43% frequency of cases, respectively. Eastern, central and western zone of eastern Himalayas followed by the central, and northern zone of western Himalayas are the hotspots for human-leopard conflicts. Between 2015 and 2018, 857 assaults by leopards on livestock in eastern Himalayas and 375 in western Himalayas were reported. Central and northern regions of Pauri Garhwal in Western Himalayas, India are high human-leopard conflict risk zones (Naha et al. 2018). Due to human-wildlife conflicts in Nepal, around 1150 humans and 370 elephants are reported to have died between 1980 and 2003 (Choudhary 2004). Man-animal conflict in Nepal has become unusually controversial when locals are attacked by threatened or legally protected large mammals and in most cases, locals strike back and kill the animal (Acharya et al. 2016). Reports from the Pakistan part of Western Himalaya also support the increased risk to wildlife especially common leopard (*Panthera pardus*) due to escalating human-wildlife conflict (Awan et al. 2020). Several northern districts of Bhutan are also 'human-wildlife hotspots' because of frequent attacks and livestock killing by tigers, common leopards, snow leopards, and Himalayan black bears (Sangay and Vernes 2008). Although Myanmar provides an excellent habitat for the conservation of Asian elephant populations, increasing wildlife conflicts have disrupted ongoing conservation efforts (Sampson et al. 2019). To limit crop depredation, Rhesus macaques, blue bulls, and wild boars are recognized as problematic wildlife and are declared vermin under Indian Wildlife Protection Act, 1972 which allows affected locals to kill them if required (Anand and Radhakrishna 2017).

Hydropower projects and reservoir construction

Collectively, Himalayan rivers as an important source of hydropower generation are projected to have potential of more than 500 GW (Xu et al. 2019), with more than 550 projects running or under construction across the Himalayas (Pandit et al. 2014; Ahlers et al. 2015) (Fig. 6). The rivers in India, Pakistan, and Nepal have commercial hydropower potential worth 190 GW, while Nepal and Pakistan have utilized only 2% and 12% of their hydropower potential, respectively (Hussain et al. 2019). Bhutan with a hydropower potential of 30,000 MW is harnessing only 1480 MW but intends to expand it to 10,000 MW capacity from 10 new projects (Tariq et al. 2021). All the major Himalayan basins are already marked for hydropower projects and 90% of the valleys will be affected. Twenty-seven percent of these projects will degrade dense forests by submerging 54,117 ha of forests and damaging 114,361 ha due to associated activities (Hussain et al. 2019). Two hundred and ninety-two under construction or proposed hydropower projects in the Himalayas will have a damaging impact on natural terrestrial ecosystems due to the submergence of 1700 km^2 of forests (Pandit and Grumbine 2012). Hussain et al. 2019 projected that by 2025, hydropower-led deforestation will lead to the extinction of 22 angiosperms and 7 vertebrate taxa with a reduction of tree species richness by 35%, tree density by 42%, and tree basal cover by 30%. Degradation of habitat and alterations in the physico-chemical properties of river water due to hydropower projects has already affected the fish population structure (Singh and Agarwal 2017). Habitats of native Golden Mahseer, *Tor putitora* (GM), and Snow trout (*Schizothorax richardsonii*) naturally distributed across the region in fresh and cold-water

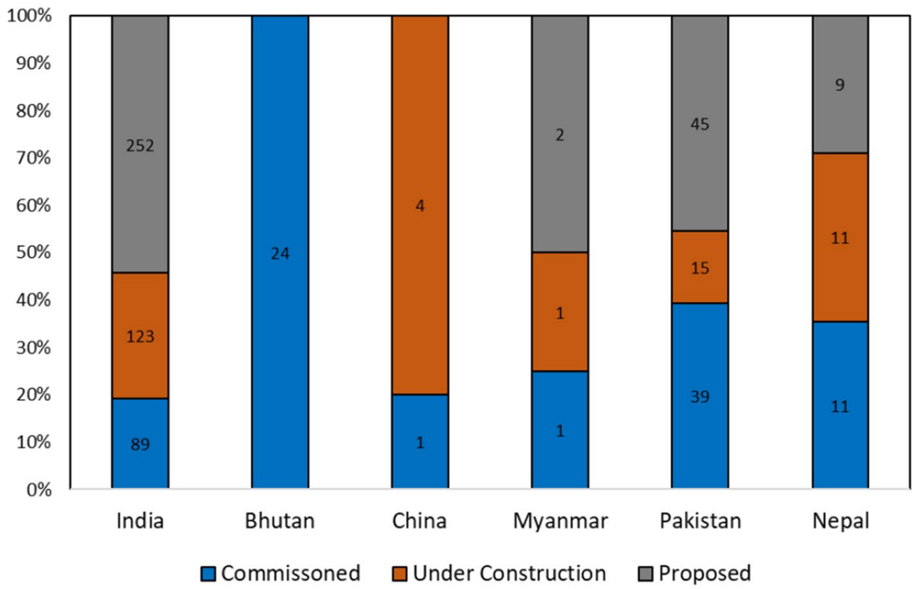

Fig. 6 Commissioned, under construction and proposed hydropower projects across Himalayan Nations. *Source* Various Sources

habitats of the Himalayan rivers of India (the Indus, Ganges-Yamuna, and the Brahmaputra), with confirmed records from Pakistan and unconfirmed accounts from Afghanistan in the west to Myanmar in the east, are largely affected. The populations of Golden Mahseer have been severely affected by hydropower projects as the hydropower reservoirs disturb their longitudinal connectivity and free movement (Bhatt and Pandit 2016; Yadav et al. 2020; Sharma et al. 2021). Seabuckthorn (*Hippophae salicifolia*) habitats in riparian buffers of higher reaches of the western Himalayas are significantly degraded and will be further lost due to encroachment of these habitats by large hydropower projects (Dhyani et al. 2018).

Forest fires

Human-induced forest fires in the populated zones between 800 and 2000 m amsl are fairly common across the Himalayas (Singh et al. 2016) (Fig. 7). MODIS data-based reports highlight India, Pakistan, and Myanmar as potential hotspots of forest fires (Vadrevu et al. 2019). In Nepal, approximately 200,000 hectares of forests are lost to forest fires annually (Third 2021). More than 50 districts are affected by forest fires and more than 12,000 community forests were destroyed by forest fires in 2016 (Gurung 2017). Fifty eight percent of the total forest fires in Nepal are intentional by grazers, poachers, and NTFP harvesters and 18 out of 75 districts of Nepal are hotspots of forest fire risks (Kunwar 2006). In 2017–2018, 6561 ha of natural forests were lost to 37 forest fires across 12 districts of Bhutan (Tariq et al. 2021). Disastrous man-made forest fires from Western Himalayas in India were reported in 17 years between 1910 and 1980 and more recently in 1995, 1999, 2010, 2012, 2016 2018, and 2020 (Dobriyal and Bijalwan 2017). From December 2020 to

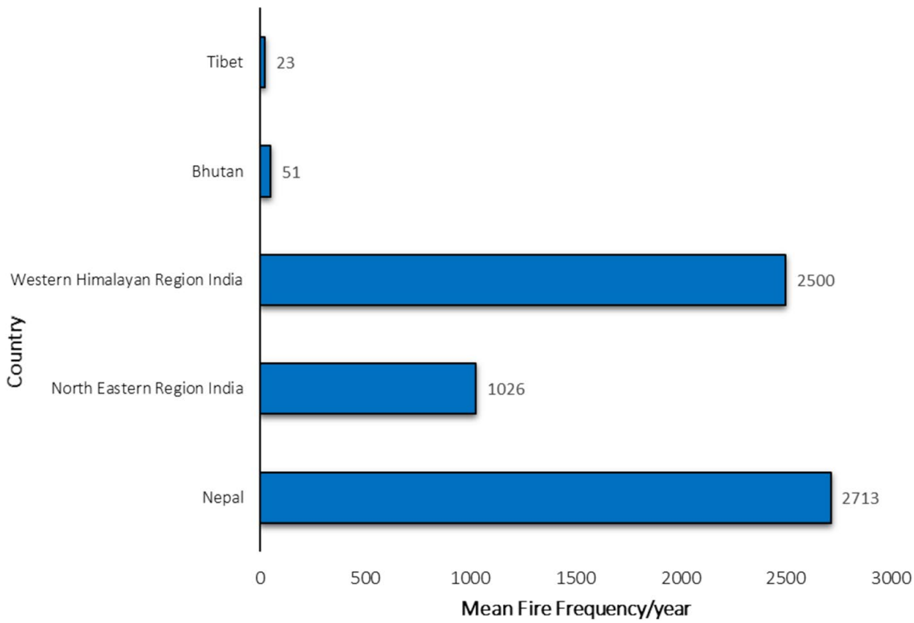

Fig. 7 Annual Forest fire frequency across Himalayan nations. *Source* Various Sources

June 2020 more than 1,000 fires were reported from Uttarakhand state whereas, and again March 2021 in Himachal Pradesh, India, 476 fires in less than two weeks led to the loss of 4555 ha of forests (Third 2021). Forest fires in Khyber-Pakhtunkhwa resulted in the loss of millions of trees, death of diverse partridge species, leopards, foxes, jackals, as well as impacting the migration of deer causing human-animal conflicts (Abbasi 2021).

Road construction and broadening

Major landslide zones in the region are frequently close to rivers or roads because of weakened slopes due to blasting or dumping of waste and debris on the slopes (Kamp et al. 2008; Khattak et al. 2010; Atta-ur-Rahman et al. 2011). The 889 km long Chardham all-weather road project, 2016 in Uttarakhand state of India caused uprooting and felling of more than 33,000–43,000 trees with diversion of 508 ha for widening the highway to 10 m for defense purposes. Road network development in Sikkim, India created conditions of serious flooding and massive landslides, resulting in immense loss of keystone species (Banerjee et al. 2019). According to Ito (2011) road widening has brought an unavoidable loss of traditional ecological knowledge systems, such as mules as a pack reducing physical and mental well-being of Bhutanese. China's Belt and Road Initiative (BRI) will bring multiple environmental impacts, especially on the fragile Himalayan ecosystems (Liu et al. 2019). The Belt and Road initiative, along with major expansion projects in Myanmar, will affect the clouded leopard (*Neofelis nebulosi*) due to a 36% reduction in its landscape connectivity and 29% decline in population size resulting in a considerable drop in genetic diversity. The Indian Highway and Silk Road network along with the pipeline railroad will further fragment the prime core habitats and reduce connectivity between (Kaszta et al. 2020). The construction of highways and roads across the region has accelerated the invasion of alien species by acting as habitat and prospective dispersal corridors (Wang et al. 2019). Road expansion is reported to have enabled and enhanced access for hunting and illegal poaching, trampling and destruction of natural forests for gathering NTFPs in Namdapha National Park in Arunachal Pradesh and other Pas in the region. It has also caused significant loss of gibbon populations due to fragmented landscapes as well as reduced populations of sambar deer and barking deer (Krishna et al. 2013).

Mining and mineral extraction

Pakistan's Gilgit-Baltistan region has huge mineral deposits, including valuable metals but crude methods of mining have destroyed the ecosystems. (Lahiri-Dutt and Brown 2017). The Central Indus basin of Pakistan has more than 160 active coal mines and acid mine drainage from them has caused enormous deforestation and land degradation in the basin (Jabbar Khan et al. 2020). Gold mining in Myanmar's Hukaung Valley in Myanmar resulted in a significant loss of tree cover (Papworth et al. 2017). Open cast mining of limestone and dolomite in 44 large and 22 small limestone mines for almost 30 years in Doon valley, India until 1985 led to clear-felling of *Shorea robusta* dominant sub-tropical forests. with 1,086 ha forests degraded and 280 ha cleared (Raizada and Juyal 2012). Forest cover in Meghalaya, India, was reduced by 12.5% due to a three-fold increase in customary coal mining in the area from 1975 to 2007 that is still illegally practiced. Mining in Nokrek Biosphere Reserve (NBR) fragmented the landscape and mine spoil has degraded wildlife habitat (Sarma and Barik 2011; Sarma and Yadav 2013). Assam's globally-endangered lowland evergreen rain forests in and around the Dehing Patkai Elephant Reserve with two narrow elephant corridors used by 300 elephants and Wildlife Sanctuary, has borne the brunt of coal mining resulting in increased human-wildlife conflict and repeated displacement of indigenous tribal communities (Chakravartty 2020). The Qin-Ba Ecological Functional Zone, as a part of China's ecological security pattern, was planned to safeguard regional biodiversity and ecosystems due to rampant mining. Massive clearing of forests in Fengxian, Shaanxi, and Baokang County, Hubei Province for mining has also degraded natural ecosystems and biodiversity (Xu et al. 2016). Exploration of rich mineral deposits in the Tibetan autonomous region of China especially a large lithium mine in the sacred holy mountains in Sichuan province will destroy the entire sacred grasslands (Denyer 2016). China's large-scale mining proposals to excavate minerals worth US$60 billion in the Himalayas in the disputed transboundary areas with India will jeopardize the functioning of landscapes and will impact high conservation value ecosystems and species (Chen 2018).

Degradation of high-altitude wetlands

A study by Nie et al. (2017) mapped high altitude wetlands (HAWs) across the entire Himalayan region and recorded 4,950 glacial lakes across an area of 455.3 ± 72.7 km^2 between 4000 and 5700 m amsl. There are 79 HAWs in Nepal, 168 in China, 120 in Bhutan, and 12 in Pakistan, mostly in Gilgit-Baltistan and upper Khyber-Pakhtunkhwa (Gujja 2007; Khan and Baig 2017). These large water reservoirs are critical for the regional countries to the moderate water cycle and are freshwater reservoirs for the major river basins of Ganges, Indus, Yangtze, Mekong, Amu Darya, and Hilmand (Kumar and Lamsal 2017; Iqbal and Shang 2020). More than a third of recognized HAWs are within the protected area network but some HAWs with utmost conservation urgency, such as Mansarovar lake (in the transboundary area of India, China, and Nepal), are outside these zones (O'Neill 2019). In 2009–2011 'The Himalayan Wetlands Initiative (HimWet)' was initiated to endorse the vision of the Ramsar Convention to support Ramsar Strategic Plan by developing partnerships among the regional countries in the Hindu Kush Himalaya and Pamir-Alay region for conservation and judicious use of the HAWs. Commercial tourism, trekking, mountaineering, camping are key risks to these HAWs while degradation of the catchment areas due to infrastructure build up followed by human-animal conflict, urban expansion, concretization of catchment areas, increased grazing pressure have damaged them immensely (Gujja 2007).

Invasive alien species

More than 297 established non-native plants from 65 families are reported from IHR with a maximum of 78.1% of these in Himachal Pradesh, 64.6% in Jammu & Kashmir, and 60.90% in Uttarakhand state (Pathak et al. 2019). Eighteen of these species were introduced purposefully, while the rest of them invaded accidentally (Chandra 2012). Alien flora of Kashmir state in IHR constitutes > 35% of total flora with a comparatively higher percentage (80%) of herbaceous growth growing in the wild rather than that in cultivation (43%) (Mehraj et al. 2018). *A. adenophora* has been reported up to 2900 m amsl which is even higher than its reported altitudinal range (i.e., 300–2800 m amsl in the region) (Pathak et al. 2019). *Polygonum polystachyum*, a mixed forb community type, proliferates in the Valley of Flowers, a high-altitude protected area, Biosphere Reserve and also a world heritage site in Western Himalayas. Physical removal of *P. polystachyum* has resulted in the advancement of *Impatiens sulcate,* another mixed forb community (Kala 2005). *A. adenophora*, *Ageratum conyzoides*, *Chromolaena odorata*, *Lantana camara*, *Mikania micrantha*, and *Parthenium hysterophorus* are common invasive plants in Bhutan too (Thiney et al. 2019). Eighty six percent of alien plants in Bhutan have been introduced as ornamental, pasture or other unintentional purposes however, having only one border entry point has been the major driver of this massive invasion in the country (Dorjee et al. 2020). One hundred and sixty-six introduced invasive plant species reported from Nepal are scattered from 100 to 4300 m amsl (Bhattarai et al. 2014). In Myanmar invasive trees like *Prosopis* spp., *Acacia* spp., *Leucaena leucocephala*, and *Eucalyptus* spp. etc. were introduced through seed exchange schemes for testing, greening and other economic commitments. Water hyacinth, water lily, canna, kyetsu-kanakho (*Jatropha* sp.), and many bamboo species, etc. are now potential invaders and drivers of terrestrial and aquatic biodiversity loss. In aquatic ecosystems invasive fish species, like common carp, brown trout, and rainbow trout, are frequently reported from numerous localities (Gupta and Everard 2019). Nineteen non-native species, comprising 13% of total abundance, were distributed among the three habitats (including PF). At present, ant invasions are limited to lower mountain ranges. Nineteen invasive species of ants contributing to 13% of the total ant species abundance were reported from lower Shivaliks having the potential to invade Himalayan highlands (Bharti et al. 2016). China's border road initiative (BRI) that is overlaid over 27 of 35 acknowledged global biodiversity hotspots and associated infrastructure designed to enhance trade and transportation in this region is expected to accelerate the rate of invasions (Liu et al. 2019).

Nutrient loading/pollution

The Environmental Performance Index (EPI), 2018 ranked Nepal 180 among180 countries for its worsening air quality (Uprety et al. 2019). The capital city of Kathmandu was identified as one of the most polluted cities having the fine Particulate Matter (PM2.5) levels at 140 µg/m^3 (Saud and Paudel 2018). Emissions and impacts of Short-lived climate pollutants (SLCPs) including black carbon (BC), methane (CH_4), and tropospheric ozone (O_3) in Nepal from biomass burning and fuel combustion along with CH_4 emissions from agriculture and waste sites has resulted in several non-communicable and respiratory diseases including allergies (Nakarmi et al. 2020). Air quality in fast growing urban areas in IHR is also compromised and not good for human health. The air quality in Bhutan is also unsafe as per WHO and fresh records specify the country's annual mean concentration for PM2.5 at 38 µg/m^3 that is above the recommended maximum of 10 µg/m^3 (WHO 2020). Increasing forest fires significantly affects the air quality, however, lack of real-time air quality monitoring is a serious cause of concern across the region (Somvanshi 2021). *Acidovorax, Geobacillus*, and *Caulobacter* bacterial genera were predominantly reported from the upstream areas of river Bagmati in Nepal due to untreated sewage discharge. Human pathogens and gut bacteria *Clostridium*, *Prevotella*, *Arcobacter*, *Lactobacillus*, *Enterococcus* and *Streptococcus* reported from downstream areas are risks for human health (Pantha et al. 2021). Red algal bloom reported from the fishponds in eastern, western, and Central regions of Nepal have also affected native fish yield (Mandal et al. 2016, 2018). The quality of the water of Punatshang Chu, Thimphu Chu and Pa Chu rivers of Bhutan is affected by polluted river banks, solid waste management issues, and discharge of untreated domestic wastewaters (Pradhan and Mandal 2015). Water pollution in Bhutan results in the loss of native fishes and aquatic diversity (Tariq et al. 2021). The Himalayas is projected to act as a cold trap for many air as well as semi-volatile organic pollutants and also mercury (Loewen et al. 2005). DDT, hexachlorocyclohexanes (HCHs) and polycyclic aromatic hydrocarbons (PAHs) have been already observed in the East Rongbuk Glacier of Mt. Everest in Nepal (Wang et al. 2008). There is a growing pollution risk from increasing road networks, market availability, and tourism as evidenced by the presence of of microplastics in snow and stream water samples. This raises alarms and the need for comprehensive studies and ban on plastics in the region (Napper et al. 2020).

Tourism

Twenty-nine times more tourists came in 2001 to Tibet autonomous region than in 1990 and these numbers have grown exponentially in the last twenty years (Baiping et al. 2004). Surging tourist numbers in the Himalaya call for a proactive response, including regulating the numbers of tourists on arrival, the imposition of an environmental tax on tourists, and other controls and sanctions (Pandit 2013). Despite having diverse places to attract tourists, the region is challenged by common antagonistic environmental complications due to tourism that includes solid waste disposal, increasing pressure on local water resources, and an additional burden on natural resources (Brown 1997). According to the Working Group, II Sustainable Tourism in the Indian Himalayan Region report by NITI Aayog in 2018, the leisure industry and hospitality sector is extremely profitable livelihood in IHR that contributes more than US$ 71.5 billion to the GDP. The tourism industry in Bhutan contributes more than 15% of the annual GDP and is the largest convertible foreign exchange income (Hoy et al. 2016). In another survey led by the World Bank in 2015 following the criteria of 'Ease of Doing Business and 'Environmental compliance'', it was stated that tourism across IHR and in other countries of the regions is also not sustainable (Gayatri 2018). Deforestation due to increasing tourist demand for fuelwood in the trekking route to Mt. Everest Base camp has required strict guidelines to regulate and protect the unique ecosystems and biodiversity within sustainable limits (Laiolo 2004). Monetary pressure from tourism has affected the structure and functioning of villages, and their livestock composition is expected to surpass natural thresholds for Sagarmatha National Park (Padoa-Schioppa and Baietto 2008). Tourism-related developments in Sagarmatha National Park have enhanced human-animal conflicts due to the coexistence of livestock with Snow Leopards, Himalayan tahr, and also musk deer populations (Ale et al. 2007). Tourism in Gilgit Baltistan in Pakistan has resulted in enhanced deforestation, biodiversity loss, solid waste, pollution, loss to cultural and heritage sites (Saqib et al. 2019). There is significant interest of policymakers and conservationists in ecotourism, but unfortunately, there is inadequate and mixed observed evidence for ecotourism contributing to positive biodiversity results in the long-term. Brandt et al. (2019) assessed the influence of ecotourism from 2000 to 2017 on deforestation rates and trajectories in 15 ecotourism centers for non-ecotourism Himalayan temperate forests zones of four Himalayan countries. In Nepal and Bhutan changes in deforestation rates due to ecotourism and corresponding non-ecotourism zones were not considerably different and the extent of likely outcomes was also insignificant. However, in China deforestation rates were lower in ecotourism zones than in none ecotourism zones. Though Bhutan's tourism's policy has significantly limited the ecological and cultural influence from West, as tourism is growing, the agreement between India and Bhutan, that permits unrestricted entry of Indian tourists affects the traditional and ecological bearing as well as carrying capacity of the fragile landscapes in the region (Brunet et al. 2001).

Diseases

Ishtiaq et al. (2017) was first to report the recurring occurrence of avian haemosporidians in migratory as well as native birds of western Himalaya, India. This helped support the evolutionary study on avian malaria and its spread in diverse Himalayan bird communities. The presence of gastrointestinal parasites (*Baylisascaris transfuga*, *Ancylostoma* spp. and cyst of *Eimeria* spp.) in Himalayan black bear in Kashmir was also reported but due to limited data on diseases in wild animals it was difficult to assess its larger impact on local populations (Sheikh et al. 2017). Similarly, Sarcoptic mange due to *Sarcoptes scabiei* was reported from several Himalayan ungulates and their predators (leopard, snow leopard etc.). There is dearth of information for potentially damaging diseases observed in secluded and fragmented populations of Himalayan Serow, *Capricornis thar*, *Himalayan Goral*, *Naemorhedus goral* populations in Western Himlayas (Geladi et al. 2017). The first report on fungus affecting the large tracts of natural forests was reported from Himachal Pradesh where root rot disease in deodar (*Cedrus deodara*) due to *Phytophthora cinnamomi* resulted in extensive loss of mature as well as regenerating trees resulting in the death of 200 deodar trees, and additional 150–200 that decayed (Singh and Lakhanpal 2000). The multifaceted interaction of environmental strain, reduced natural course of regeneration and many insect pests have led to dieback and death of oak trees across the region. Stem and wood-boring beetles, especially the Cerambycid wood borer, *Aphrodisium hardwickianum*, have significantly affected the death of *Q. leucotrichophora* as well as another Cerambycid, *Rosalia laterifolia* which affects *Q. dilatata* resulting in 28% tree death (Singh 2011).

Climate change

According to regional climate models, the Himalayas are warming more rapidly than the global averages and are predicted to further increase and degrade natural ecosystems (Kulkarni et al. 2013; Bhatta et al. 2015; Adler et al. 2022). The fragile mountainous terrain and landscapes makes the region susceptible to frequent and large-scale climate fluctuations (Chhogyel and Kumar 2018). Increasing glacier retreat due to global warming has resulted in rapid expansion of 118 lakes that urgently need risk assessment and conservation planning (Nie et al. 2017). Warming in the region has also resulted in rising water levels of HAWs, such as Tsomoriri in Ladakh, that has inundated significant breeding grounds of the endangered migratory Black-necked Crane and Barheaded Goose (Bassi et al. 2014). Regional circulation models indicate that climate change will significantly affect Himalayan highlands, especially the Tibetan Plateau (Sivakumar and Stefanski 2011). Enormous shifts in bioclimatic settings are expected across the Kailash sacred landscape by 2050, which will substantially affect all bioclimatic zones and ecoregions. More than 76% of the total area is expected to change to an altered stratum, 55% in a dissimilar bioclimatic zone, while 36.6% in a diverse ecoregion. Upward shifting of bioclimatic zones by 357 m amsl and 371 m amsl for ecoregions will have reduced the areas in the highest altitudes and ecoregions. The lower tropical and sub-tropical zones and ecoregions is expected to increase upwards and numerous strata of high value may disappear. These changes will affect the flow of ecosystem services, creating new conservation and sustainable development challenges in the region (Zomer et al. 2014). High altitude alpine and subalpine ecosystems are projected to be the most vulnerable ecosystems as some species will not have the habitat required for upward migration (Zomer et al. 2015). Climate modeling for the Protected Area Network (PAN) in Yunnan province of China predicts 45% of the network will shift to a divergent zone with 83% to a changed stratum by 2050. (Zomer et al. 2015). Water stress in the region will also affect plant phenology, seed setting, soil seed bank, and regeneration of keystone forest species (Singhet al. 2010). The Medicine Mountains (a portion of the Hengduan Mountains) in Tibet autonomous region, having high medicinal plant diversity to support the requirements of Tibetan medicine, will be affected by climate warming (Salick et al. 2009). Degradation of keystone *Quercus* species in moist temperate mixed broad-leaved forests and *Hippophae* species growing in riparian buffers will not only affect the Nitrogen cycle but also hydrological balances in the entire region resulting in loss of natural spring-sheds, riparian buffer health, and jeopardizing the provisioning subsistence support to local communities (Shrestha et al. 2018; Dhyani et al. 2018, 2020a, b). Despite being a carbon–neutral country Bhutan, is facing the brunt of climate change with clear indications of higher warming during winters at higher elevations > 4000 a msl (Mahagaonkar et al. 2017). The agricultural production and food security of Bhutan is compromised due to unusual outbreaks of pests and diseases, unpredictable rainfall, rainstorms, hail storms, all due to climate change (Chhogyel and Kumar 2018). Climate change is expected to enhance the present niches of invasive alien plant species in the Kailash Sacred Landscape, which will affect the native scrublands and subtropical needle-leaved Himalayan forests in Nepal, China, and India (Thapa et al. 2018). Lamsal et al. (2018) reported that climate change impact on *Ageratum conyzoides* and *Parthenium hysterophorus* will lead to the loss of their suitable niches by 2070, whereas *Ageratina adenophora*, *Chromolaena odorata*, and *Lantana camara* will further gain suitable niches. Suitable bioclimatic niches of diverse *Rhododendron* species are also projected to shrink substantially and affect other species and pollinator diversity (Kumar 2012). The habitat suitability for Chinese caterpillar fungus (*Ophiocordyceps sinensis*), will be affected by climate change and a reduction of 0.11–4.87% in its present habitats is expected in coming decades (Shrestha and Bawa 2014). However, the population of the species will also decline further due to overexploitation of the species in alpine areas of India, Nepal, Tibet, and Bhutan (Hopping et al. 2018). Aryal et al. (2014) reported grasslands, and forests in the Mustang district (> 35,000 m amsl) of Nepal have already reduced by 11% and 42%, correspondingly, between 1979 and 2009, while, the imberline has shifted towards higher altitudes. Hence, blue sheep populations have started grazing at lower altitudes followed by snow leopard resulting in the crop, livestock depredation, and human-wildlife conflicts adversely affecting local livelihoods (Aryal et al. 2014).

Recommendations

From the above synthesis key approaches emerge to reduce the intensity of drivers and improving ecosystem conditions in the region for human well-being. Trans-boundary response strategies suitable to the local context of the region could buffer some of these impacts but certainly not all of them (Dhyani et al. 2022). These emerging concerns and solutions can be researched, strengthened and mainstreamed in policy planning to ensure that the high value Himalayan ecosystems are restored and protected before actual collapse (Table 1).

Table 1 Key approaches to reduce the intensity of drivers and improving ecosystem conditions in the region for human well-being across the Himalayas

Serial no.	Approach	Long term benefits
1	IUCN Red list of ecosystem assessment at biome level or at national level to assess the threats can also contribute to monitor the status of ecosystems, as per Convention on Biodiversity (CBD) decision on Monitoring as well as SEEA for ecosystem accounting	Status for developing future conservation strategy as a pressing need for different countries and ecosystems in the region
2	Carrying capacity or bearing capacity assessment of major tourist destinations and expanding urban sprawls by understanding the demand supply gap developed due to rampant sprawling and exponential population pressure	To ensure and facilitate suitable sustainable tourism practices
3	Transboundary cooperation to form an active coalition that meets regularly	To monitor and discuss the impact of drivers especially climate change impacts, forest fires, hydropower projects, road construction and broadening, mining and non-sustainable extraction of wild species and green approaches
4	Comprehensive and integrated land use structure acceptable across transboundary landscapes that respects and acknowledges local land rights	Conservation of the biophysical environment, increasing the sustainable productivity of natural resources
5	Reducing and reversing migration of marginalized communities by ensuring better livelihoods, education, and medical health care opportunities in remote valleys	Improving socio-economic conditions can help to ensure sustainable harvesting practices and reducing wildlife killing and trafficking in the region
6	Comprehensive conservation strategies must go beyond protecting intact primary forests and ensure that low-intensity agricultural lands are not extensively converted (Elsen et al. 2017)	Given that forest reserves alone may inadequately conserve threatened biodiversity,
7	Greater integration of diverse knowledge types (scientific, traditional, and participatory) and institutions (formal and informal, government and community)	For better planning in order to reconcile several functions and community expectations at the landscape level (Bawa and Seidler 2015)
8	Subsidies and increasing availability of modern energy and livelihood opportunities	To help rural poor households to ensure their reduced reliance on the forests and also ensuring reduced migration from Himalayas
9	Focusing on areas having high-invasion rates of pests and weeds, and species with high invasive potentials across transboundary areas	To help sustainable implementation and the development of early, economical, and effective biosecurity strategies
10	Increased investment in enforcement, education and outreach, small livestock development, improved crop productivity, demarcation of no-take areas for wildlife and biological monitoring of targeted species	To reduce wildlife hunting and trade from Himalayan nations (Rao et al. 2011). Also ensuring transboundary surveillance to reduce wildlife trafficking

Table 1 (continued)

Serial no.	Approach	Long term benefits
11	Promoting action research and community engagement including citizen science. Species-specific conservation strategies are urgently needed, particularly for leopards and elephants to reduce conflict (Acharya et al. 2016)	For long-term conservation and management of biodiversity by identifying vulnerable areas for regular monitoring and implementation of mitigation efforts through risk assessment; understanding the ranging pattern of wildlife species developing and implementing adaptive management strategies in some of the identified vulnerable areas through community engagement (Sambandam et al. 2016)

Conclusions

The Himalayas, the water tower for a large part of Asia and a store house of diverse nature's contributions for human well-being for larger population of this planet, is one of the most vulnerable regions of the world. From this review it is clear that impact of a range of mega drivers and their combined impacts on the region are severe and enhanced human-induced pressure has significantly accelerated the degradation of the natural ecosystems, air and aquatic environments and the consequences are already highly visible. This comprehensive overview also clearly shows that a number of indicators may be an early warning of hidden ecosystem collapse of the fragile and sensitive Himalayan ecosystem and increasing disaster risks and extreme climate events are going to exponentially enhance this further. There is strong evidence that ecosystem functions are declining rapidly and affecting human well-being both in immediate vicinity of upstream areas as well as larger population living in downstream region. Transboundary response strategies are able to buffer some of these impacts but certainly not all of them. With growing concern about increasing vulnerability to the region from current and future climate change impacts, it is clear that these drivers and their profound impact will compromise the services and benefits for human populations directly and indirectly dependent on Himalayan ecosystems in coming years. Hence, the review proposes planning and undertaking ecosystem health assessment at biome, national as well as regional level. This can be undertaken by involving diverse stakeholders, experts and organisations including government departments of the countries in the region following the IUCN Red List of Ecosystem Assessment approach well supported by ample technical and financial measures. RLE is now a crucial requirement to be included in National Biodiversity Strategy and Action Plans (NBSAPs) as a key condition included in Kunming-Montreal Global Biodiversity framework under Goal A and the UN-SEEA. Only through these proactive measures of integrated ecosystem health assessments that are critical for the region and nations prioritized planning in conservation and restoration of ecosystems can be undertaken. RLE assessments in the region will help conserving thousands of species that are still data deficient and not evaluated as per IUCN Red list of Species. Understanding ecosystem risks can be helpful to conserve species under the broader umbrella of ecosystems by ensuring their habitat suitability in the changing climate following in-situ or ex-situ conservation efforts. With a focus on Kunming-Montreal Global Biodiversity framework under Goal A and the UN-SEEA ensuring that biodiversity hotspot values, ecosystems and species are conserved through international, transboundary cooperation should be an important strategy. This should involve not only experts, academicians, researchers, forest managers, government line departments but also marginalized, indigenous and local communities under a strengthened participatory programme to help countries in the region have evidence-based decision making for achieving relevant biodiversity, climate, restoration and sustainable development goals for long-term resilience building.

Acknowledgements Author is immensely grateful to the editor Prof. Nigel Stork and an anonymous reviewer for their constructive comments and suggestions to substantially improve the manuscript. The author acknowledges the Knowledge Resource Center, CSIR-NEERI for checking plagiarism using licensed version of i-thenticate software under the number CSIR-NEERI/KRC/2022/JULY/WTMD/2 and AcSIR PhD scholar Ms. Radhika Sood for providing pictures of Cordyceps collection.

Author contribution SD conceptualized, reviewed, researched, developed main manuscript text, prepared the figures, reviewed, revised and finalized the manuscript for submission.

Funding No funding support was received at any stage of research, drafting or development of this manuscript.

Declarations

Conflict of interest I declare that the author has no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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