Chapter

Climate Change and Its Impact on Mountainous Plant Species: A Review

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Abstract

Climate change poses unprecedented threats to ecosystems worldwide, and mountainous regions with rare ecosystems, unique landscapes, a large number of endemic species, and enormous plant biodiversity are highly sensitive to the effects of climate change. Early spring and late autumn events are major phenological changes observed in plants in response to climate change, and such changes mainly disturb the interaction between plants and their pollinators, thereby affecting the fitness and survival of both species. Climate warming is causing plant species to shift upward along the elevational gradient in the mountain, resulting in species accumulation at higher elevations and range contraction of several alpine plant species. Further, climate warming is augmenting the plant invasion by removing climatic barriers, thus threatening the diversity of native plant species. Moreover, climate warming is contributing to habitat fragmentation and loss and accelerating the associated impacts. All these impacts of climate change can potentially alter the composition, structure, and function of pristine mountain ecosystems, which leads to irreversible biodiversity losses. Thus, various climate change mitigation strategies, such as conventional mitigation strategies, negative emissions technologies, and radiative forcing or geoengineering technologies, are suggested to stabilize climate warming, thereby conserving irreversible global biodiversity loss.

Keywords: climate change, habitat fragmentation, habitat shift, mountain ecosystem, phenology, plant invasion

1. Introduction

Climate change refers to long-term alterations in local, regional, or global weather patterns (e.g., changes in temperature, precipitation, humidity, and atmospheric pressure) due to natural and anthropogenic activities. An increase in global air and oceanic temperature, the retreating of the global ice sheets, a rise in sea level, extreme weather events such as prolonged drought, frequent heat waves, erratic rainfall, an increase in flooding events, and the frequent occurrence of pests and diseases are the consequences of the climatic change evident at national and international levels. These events are posing unprecedented threats to the agroeconomy, the livelihood of marginal populations, global biodiversity, and

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the structure, composition, and functions of various ecosystems across the globe. Climate change, therefore, has become a formidable intergovernmental challenge that impacts various domains of the environment, ecology, sociopolitics, and socioeconomy [1].

Mountains are unique ecosystems recognized for their complexity and diversity [2]. They harbor about 23% of the Earth's forests and 30% of all land, along with high levels of biodiversity and endemism [3]. Approximately 1/4th of the global human population inhabits mountainous regions across the globe, and many of them are poor [3]. Thus, the biodiversity of the mountains is pivotal for the sustainable development and survival of human societies [4]. Mountains possess the most distinct climatic gradients on earth and are one of the key "experimental fields of nature" because of the sharp environmental gradients they cover and the spatial fragmentation they generate at the otherwise global occurrence of habitat types and wilderness [5]. An average temperature decrease of −6°C is observed in mountains with every 1000 meters increase in elevation due to adiabatic lapse rate, and inversely, precipitation increases with increasing elevation because air masses cool and condense if it is elevated to higher elevations [6]. Thus, temperature and soil moisture are the major factors that determine the zonation of ecosystems along mountain gradients [5]. Such a type of zonation is the unique feature that differentiates mountain forests from other forests. The definition of mountain forest is obscure; however, a reasonable definition according to Price et al. [7] is "forests on land with an elevation of 2500 m above sea level or higher, irrespective of slope, or on land with an elevation of 300–2500 m and a slope with sharp changes in elevation within a short distance." However, mountain environments are highly sensitive to climate change [8, 9] and experience climate warming at a rapid pace compared to the Northern Hemisphere [10] or the lowlands [11]. Also, the future air temperatures of these regions are predicted to be higher than present-day temperatures [10, 12]. The macroclimate warming on mountains has accelerated the rate of species accumulation and potentially jeopardized the primary function of mountains, which is to act as long-term refugia for biodiversity [13].

Climate influences the vegetation patterns (structure, distribution, and ecology) of forests around the world [14]. Global warming of 1–2°C is sufficient to impact most landscapes and ecosystems by altering species composition, productivity, and biodiversity [15]. When environmental conditions alter, living organisms either escape, adapt, or become extinct [5]. In the case of plants, they mostly change their phenology [16] and shift their distributional range to higher latitudes and/or elevations [17, 18] to track climatic niches in response to climate change. Changes in flowering phenology often lead to plant-pollinator mismatches, which impact the reproduction, dispersal, fitness, and survival of the plants and associated pollinators and other species. The latitudinal or elevational shifts of plant species change the native species composition, increase the probability of the spread of alien invasive species (e.g., *Eupatorium, Lantana*, and *Parthenium* spp.) in the native ecosystems, and risk biodiversity. These events potentially accelerate competition among native and non-native plant species, which can lead to habitat fragmentation, biodiversity loss, and eventually the extinction of native flora. Therefore, this chapter delves into the influence of climate change on the phenology, habitat shifting, plant invasion, habitat fragmentation, and their consequences on native mountain biodiversity and ecosystems, along with the prospect of the preservation of mountain ecosystems and their unique plant diversity.

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2. Climate change influencing plant phenology

Phenology is the study of the timing of various seasonal events in an organism's life cycle [19], including the response of organisms to climatic or seasonal changes (such as variation in temperature, precipitation, and duration of sunlight) in the environment in which they live [20]. Plants are adapted to the annual-seasonal cycle of a particular region, and seasonal atmospheric variations regulate the different stages of a plant's life cycle, such as the appearance of leaves and buds, first bloom or flowering, pollination, fertilization, seed dispersal, leaf senescence, and germination [20]. Temperature and photoperiod are the two major environmental factors that cause and control phenological patterns, especially in higher-latitude ecosystems [11–23]. The global climate warming phenomenon has drastically changed the various biological processes [24–26], including phenology [27, 28]. Thus, phenological events are sensitive and the most prominent indicators of climate change [29–32]. However, according to the study on Mediterranean shrubland and Mediterranean mountain forest, rainfall and water availability also affect plant phenology in addition to temperature [33]. Nonetheless, the early arrival of the growing season of vegetation, the early bud break, leaf flush or flowering during spring, and late leaf senescence and fruit maturation during autumn are the most widely studied impacts of climate change on plant phenology [34–37].

The climate warming in the Himalaya is higher than the average global temperature increase [38], and such warming immensely impacts the biodiversity in mountainous regions [39]. These regions are the "natural laboratory," which is ideal for studying the influence of climate change on floral phenology [40]. Variation in flowering phenology in response to climate change in mountainous regions has attracted many ecologists [40], and their studies have found that the mean flowering time of the mountain plant species is sensitive to temperature changes [41] as well as to changes in elevation, temperature, and precipitation along the elevation gradient of the mountains [42]. The temperate plant species in the Himalaya showed a mean phenological advancement of 1.9 days in spring events and a mean delay of 1.4 in autumn events per decade, and the average growing season length was extended by 3.3 days per decade [43]. Studies on flowering phenology in temperate mountains (e.g., the Alps) also indicated that spring phenology has preponded over the last few decades [44–46], and spring flowering times became earlier in the southern subtropical Nanling region of southern China in response to climate warming [47]. Field-based observations in the Himalaya showed that some species of *Rhododendron* are flowering a month earlier than in the past [48]. A similar result of 15 days early flowering in *Rhododendron arboreum* Smith compared to previous reports was observed in Kumaun Region of Central Himalaya (India) [49]. These shifts in peak flowering dates in *R. arboretum* over the past 100 years were due to the elevated seasonal and annual average maximum temperatures [50]. The mean flowering time in *Rhododendron* spp. advances 2.27 days per 1°C rise in mean annual temperature [41]. Periodic leafing and bud break in trees in the Himalayan forests has also advanced by 0.20 days per year for the past 30 years, and these changes are related to an increase in atmospheric temperature at the rate of 0.038°C per year [51].

The phenological responses of various plant species to climate change can cause asynchronous ecological interactions that threaten the structure and function of the ecosystem [52, 53]. Early and late flowering of the plants impact their ability to adapt to the surrounding environment, which determines the survival and death of the plant species [54]. Plant species can adapt to the changing environment if the changes in their flowering phenology can track the rate of climate change; however, if the flowering phenological changes of the species cannot track the rate of climate change, such species cannot adapt and are eliminated [40]. Thus, the phenological alterations affect the demography, fitness, and survival of the plant species [55, 56]. Further, the survival of plant species depends on the reproductive success of pollinators [40]. Therefore, the risk of plant-pollinator mismatches increases with changing flowering phenology, which threatens the stability of the plant community and impacts ecosystem structure and functions [57]. For example, the changes in the timing of flowering of *Corydalis yanhusuo* W. T. Wang gave rise to a phenological mismatch with bumblebees (pollinators), which resulted in a low seed setting rate [58]. These observations indicate the inimical impact of climate warming on the phenology of plants [59, 60]. Thus, plant phenology is becoming an instrumental tool to monitor the effects of climate warming on vegetation shifts, which have detrimental impacts on biodiversity and ecosystem functioning [61, 62].

3. Climate change causing habitat shifts

Climate change is altering the environmental conditions of the habitats of plant and animal species, causing them to shift their habitat range in search of their climatic niche for survival [63]. Plant species either change elevational range or latitudinal range in response to climate change [64]. However, the tolerance level of individual species to environmental change determines the need for a shift and its extent [63]. It has been predicted that climate warming will shift the distributions of plants and animals toward the pole along the latitudinal gradient and toward higher elevation along the elevational gradient in the track of isotherms [65]. For example, a meta-analysis of more than 1700 plant species indicated that climate change is attributing to the advance of spring events by 2.3 days per decade and an average range shift of 6.1 m/decade toward the pole [17]. Several studies in the Alps indicated upslope elevational shifts of species in response to climate change, and they were able to track their ecological niche with rising global temperatures [66–69]. A study on changes in the optimum elevation of 171 forest plants between 1905–1985 and 1986–2005 indicated the upslope migration of plant species across six mountain ranges in France [66]. A study on Mt. Gongga (China) also depicted an upward shift of 53 plant species in response to climate change [70]. In the Nordic region (Northern Europe), the distribution of cereal and grass is likely to shift by up to 92.8 and 178.7 km, depending on the intensity of climate change [71], and some crop species have already been introduced to new areas [72]. Our study on large cardamom (*Amomum subulatum* Roxb., a commercially important spice crop of Sikkim, India) also indicated that cultivars previously grown at low elevations (below 975 m asl) are shifted to high elevations (above 975 m), and climate change is augmenting this elevational shift [73].

The plant diversity of the Alpine region in the mountain range is higher than the global average [74, 75]; thus, the Alpine meadows are included under the 200 critical global ecoregions [76]. However, plant species in the GLORIA (Global Observation Research Initiative in Alpine Environments) network of mountains in Europe have shifted their elevational distributions to higher elevations between 2001 and 2008, with an average shift of 2.7 m/year [77]. Telwala et al. [78] suggested that the winter temperature of alpine regions of Sikkim Himalaya (India) has become warmer than the winter temperature of the last two centuries, and the upper elevation limit of the species was shifted to 23–998 m with an average upward displacement rate of

27.5 ± 22.1 m per decade. About 87% of the 124 endemic plant species have shifted their geographic range in the region, which caused an increase in species richness in the upper alpine zone compared to the nineteenth century, and the plant assemblages and community structure of the region were substantially different compared to the last century [78]. The species richness of vascular plants on Mount Schrankogel, which is a major GLORIA site located in the Tyrolean Alps (Austria), increased by 11.8% within a decade [79]. Similarly, Parolo and Rossi [80] also reported that plant species richness in the Italian Alps was higher between the years 2003–2005 compared to 1954–1958. In addition to elevational shifts of mountain species [69], climate change can also cause contraction of the elevational ranges of mountain plants, which accelerates the threat of local extinctions of the endemic alpine species [80–84]. Such redistribution of plant species to new areas may alter the existing native plant communities and increase competition for space and nutrients for survival, which may disturb the prevalent structure and function of the mountain. Besides competition for resources and space, such exotic species expanding the elevational area and becoming invasive could disturb the functioning of the mountain ecosystem and increase the loss of mountain biodiversity [85, 86].

Along with the redistribution of native plants along mountain slopes, non-native plant species also tend to shift upward and expand their elevational range to colonize new habitats in the mountain ecosystem [87–90]. This habitat expansion or redistribution of non-native plant species toward the higher elevation of the mountain exerts an additional threat to native plants by increasing competition between them and non-native plant species at higher elevations [91]. Native and non-native species follow distinct patterns of distribution along the elevational gradients of the mountain because they have different ecological backgrounds and evolutionary histories [92, 93]. Thus, the direction and magnitude of elevational range shifts for native and non-native plant species differ significantly under changing macroclimates. However, several controversial results on species redistributions have also been reported in the past few decades, both at regional [66, 94] and global levels [95]. Apart from rising temperatures, changes in precipitation and the functional traits of plant species, such as their ability to disperse and colonize new areas, also contribute to the upward shift of species along an elevational gradient [70]. For example, studies in California [94] and the Mediterranean mountains of southern Europe [77] found that changes in precipitation patterns contributed more than temperature increases to the elevational shifts of plant species. Therefore, it is crucial to determine the major abiotic and biotic factors responsible for species redistribution. Nonetheless, the distinct macroclimatic gradients along the slope from the bottom of the valley to the top of the mountains act as a natural experimental field to investigate the effect of climate change on biodiversity [96, 97].

4. Climate change and plant invasion

Invasive plants are non-native plant species that are intentionally or inadvertently introduced into new geographic areas, eventually posing a threat to native plant diversity. Species with a broader physiological niche can tolerate a wide range of environments, and such species have a high potential to become invasive [98]. Biological invasions aided by climate change can exert extremely critical environmental impacts [99] and thus significantly contribute to environmental change across the globe [100]. Climate change intensifies the risks and losses in ecosystems through different mechanisms, including the removal of climatic barriers, thereby augmenting the spread of invasive species [101, 102]. Compared to native plants, invasive plant species tend to shift their niche rapidly and are likely to adapt to new dwelling environments quickly [101, 103]. In addition, a rise in atmospheric carbon dioxide (CO_2) concentration and global warming favors the survival of invasive plant species over native plant species [104]. For example, the range of alien evergreen plants in Swiss forests has expanded in response to a decrease in the frequency of frost intervals due to climate warming [105]. Therefore, vegetation communities across the globe are expected to change because of the increases in global temperature [106].

Climate change has already elevated the spread of invasive species [107] and accelerated the expansion of native species [108], transforming them into invasive ones. For example, *Yushania maling* (Gamble) R.B. Majumdar & Karthik, which is native to the temperate zones of the Eastern Himalaya [109, 110], whose occurrence in Darjeeling district of West Bengal, India, was first recorded during the 1980s [111]. It has spread rapidly in the forest areas, potentially due to climate change causing a threat to the native floral diversity and ecosystems [109, 110, 112, 113]; thus, it is now considered a native invasive species in the region [109, 110, 113]. In mountain ecosystems, non-native invasive species are abundant between low and mid-elevations; however, anthropogenic activities and ongoing climate change are likely to accelerate their spread and dominance at high elevations [114]. Priyanka and Joshi [115] also suggested that most parts of the western and southern regions of the western Himalaya (India) tend to become suitable for the expansion of invasive pant *Lantana camara* L. in the future due to increased warming. In Kashmir (part of the western Himalaya), the invasive species are already augmenting the homogenization of the terrestrial ecosystems [116]. These invasive species are invading protected areas of the region and disturbing the habitat and food availability of the native wildlife [117, 118]. Such reports indicate that the mountainous regions are vulnerable to plant invasion due to climate change, specifically climate warming.

Invasive plant species are known to alter the diversity and composition of the native flora and form nearly mono-specific stands (homogenization). They also impact a wide range of abiotic and biotic factors that could potentially change the function and services contributed by the invaded ecosystems. Invasive plant species can directly impact the activity, productivity, and survival of native biota [119]. They have superior potential to compete for space and resources and a more efficient capacity to utilize resources than the native species. Thus, they have a major influence on resources (e.g., nutrients) and space in new habitats, as well as modify ecological processes, thereby outcompete native species and degrade the habitats of native biota in the ecosystems [120]. In brief, invasive plant species displace native plant species from their original habitats, degrade ecosystems, have a negative impact on human health [121, 122], homogenize the world's biological systems, and cause global biodiversity loss. Therefore, climate change-driven biological invasions could potentially disrupt the diversity, composition, structure, function, and services of mountain ecosystems and cause a severe impact on mountain biodiversity.

5. Habitat fragmentation and biodiversity loss due to climate change

Global biodiversity is under severe threat due to increasing anthropogenic activities (e.g., habitat destruction) and climate change. Habitat fragmentation or habitat loss of plants is generally attributed to human-induced causes such as change in land-use patterns, deforestation, overexploitation, intentional forest fires, and pollution. However, climate change also causes fragmentation of favorable habitats, leading to a decline in the habitat quality of the species [123]. Habitat fragmentation produces small populations with widening spatial isolation, which potentially accelerates the risk of extinction [124–126]. Mantyka-Pringle [127] suggested that recent climate and climate change are key factors that determine the negative effects of habitat loss, and raising temperatures is the major determinant of habitat loss and fragmentation effects, while change in precipitation over the past 100 years is of secondary importance. Further, habitat loss and fragmentation effects were highest in regions with high maximum temperatures [127], suggesting that climate change is contributing to enhanced habitat fragmentation across the globe. In landscapes undergoing habitat fragmentation, certain species will obviously be affected by habitat loss, and in such a scenario, associated or dependent species may also be lost, causing populations to decline [128–130]. Nonetheless, there has been massive biodiversity loss over the past few decades that can potentially initiate the sixth mass extinction crisis due to the environmental changes induced by anthropogenic activities [131].

Climate change is considered a major factor in the decline of global biodiversity. At a basic level, climate change is influencing the reduction of genetic diversity in populations due to rapid migration and directional selection, which can further affect the resilience and functioning of the ecosystem [132]. At the community level, the "web of interactions" among different populations is likely to be modified due to the various effects of climate change [133, 134]. As described in the sections above, climate change alters phenological events, thereby disrupting plant-pollinator interactions [57]. This can cause the extinction of both pollinators and plants, with expected impacts on the structure of plant-pollinator networks [135, 136]. Based on the study of 9650 inter-specific systems, which include pollinators and parasites, about 6300 species are expected to disappear along with the extinction of their associated species [137]. Several climatic variables determine the geographical distribution ranges of various species, and therefore, species shift their distribution range depending upon their dispersal capacities and go locally extinct in response to climate change [138, 139]. Such redistribution of species reduces biodiversity at low elevations and latitudes and causes habitat fragmentation and range contraction of several native species in alpine and polar ecosystems, paving the way for their disappearance from the ecosystem. Further, a global rise in temperature favors the survival of invasive alien plant species over native plant species [106]. These invasive plant species are known to alter the environment they invade, have efficient dispersal and reproductive capacity, and thus outcompete the native plant species in terms of space and resource utilization. They homogenize the diversity and composition of the invaded region, resulting in the loss of native biodiversity. Most of the studies at present indicate that habitat loss and fragmentation have a greater impact on species and ecosystems than climate warming [140–143]. However, in due course, the effect of climate change is expected to increase and contribute more to determining population trends than habitat fragmentation and loss [144]. Based on this chapter, the consequences of climate change on mountainous plant species and the different ways in which climate change leads to biodiversity loss are summarized in **Figure 1**.

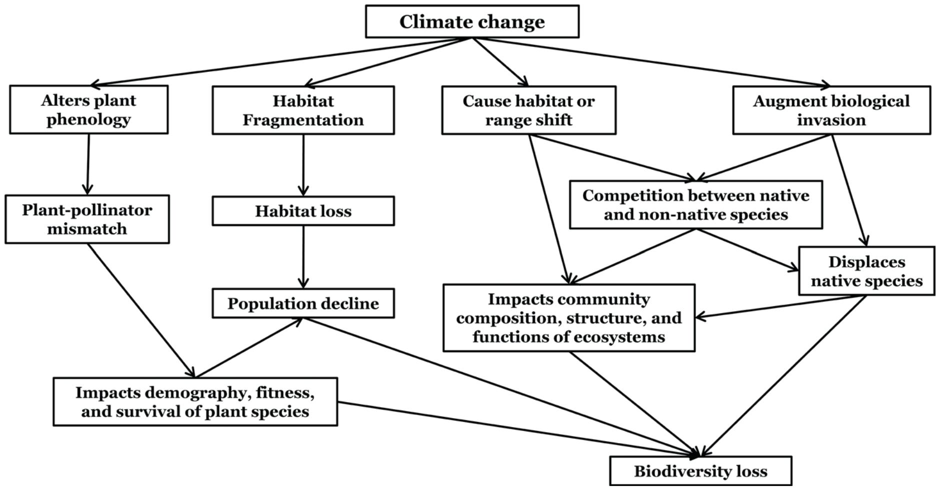

Figure 1.
Impact of climate change on mountainous plant species leading to biodiversity loss.

6. Climate change mitigation and future prospective

As of now, the discussion in this chapter has strongly indicated that climate warming is the major driver of climate change-related biological consequences like change in plant phenology, upward elevational shift, plant invasion, habitat fragmentation, and biodiversity loss. Therefore, global climate change mitigation strategies should focus primarily on minimizing or stabilizing the global temperature increase in order to regulate the biological issues that arise due to climate change. There is ample literature that provides knowledge about the initiation of global summits and conventions aimed at framing policies to regulate climate change and biodiversity loss. Therefore, this section directly focuses on the three widely discussed climate change mitigation strategies suggested recently by Fawzy et al. [145]:

Conventional mitigation strategies: energy-related emissions of various gases are the major driver for raising the concentration of atmospheric greenhouse gases. Therefore, conventional mitigation strategies prioritize the use of decarbonization technologies and techniques that decrease carbon dioxide (CO_2) emissions. Conventional mitigation strategies are deployed in four main sectors: on the supply side (power sector) and on the demand side (industry, buildings, and transportation sectors). Mitigation efforts on the supply side include decarbonization through the utilization of renewable energy, fuel switching to low-carbon fuels such as natural gas and renewable fuels, carbon capture and storage, and nuclear power. On the demand side, mitigation efforts include gaining efficiency through the utilization of sector-specific technologies; energy-efficient methods that reduce the consumption of energy; and the inclusion of renewable power technologies that are within the energy matrix of sectors on the demand side [146, 147]. Most of the conventional mitigation technologies are well established and have an acceptable level of managed risk.

Negative emissions technologies or carbon dioxide removal methods: include the techniques deployed to capture and sequester atmospheric CO_2 [148]. For example, wetland construction and restoration, afforestation and reforestation, direct air carbon capture and storage, bioenergy carbon capture and storage, enhanced weathering, ocean alkalinity enhancement, soil carbon sequestration, etc. To date, afforestation and reforestation, as well as bioenergy carbon capture and storage, are included in the IPCC assessments [149]. However, a study suggested that negative emissions technologies are still in their infancy; therefore, climate policy should remain focused on conventional mitigation technologies, while further financial resources should be invested to accelerate the progress of negative emissions technologies [150].

Radiative forcing geoengineering technologies: focus on the reduction or stabilization of atmospheric temperature by altering the radiation balance of the earth through managing solar and terrestrial radiation. Unlike the above two strategies, this technique suggests stabilizing temperature without changing the concentration of greenhouse gases. For example: cirrus cloud thinning, marine sky brightening, stratospheric aerosol injection, space-based mirrors, surface-based brightening, etc. However, these strategies are still theoretical, in the early stages of trial, and uncertain and risky in terms of large-scale practical utilization. Therefore, radiative forcing geoengineering techniques are still not included in climate policy frameworks [151, 152].

7. Conclusion

Climate change is one of the major issues facing our planet in the anthropocene. Mountainous regions of the world harbor unique ecosystems and high biodiversity and are considered the refugia of biodiversity. However, these regions of the world are highly sensitive to climate change; therefore, the impact of climate change is highly visible on mountains as compared to lowlands. Climate warming, or an increase in the global earth's temperature, is the major climatic change that is impacting the entire world and the mountains in particular. The phenological changes, such as early spring events and late autumn events, are evidently disturbing the various plant-animal interactions, such as plant-pollinator interactions. Raising temperatures are compelling various plant species to shift their geographic ranges in search of suitable climatic niches. Climate warming is further removing climatic barriers for invasive alien plant species and increasing the possibilities of their invasions in new areas. Climate change, along with other anthropogenic activities, is contributing to major habitat fragmentation or loss for several plant species. All these responses of mountainous plants to climate change would alter the species composition, structure, and functioning of the mountain ecosystems, eventually leading to the extinction and biodiversity loss of native plant species. Therefore, it is pivotal to mitigate climate change in order to conserve the sixth biodiversity extinction because the economy and livelihood of people living on mountains directly or indirectly depend on the biodiversity and services provided by mountain ecosystems. The major focus of climate change mitigation should be reducing or stabilizing the global temperature because global warming is the major driver of most of the biological changes caused by climate change. Conventional mitigation strategies, negative emissions technologies, carbon dioxide removal methods, and radiative forcing geoengineering technologies are the major strategies that can be explored further for climate change mitigation.

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Conflict of interest

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