# Scientists' warning of threats to mountains

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## Abstract

Mountains are an essential component of the global life-support system. They are characterized by a rugged, heterogenous landscape with rapidly changing environmental conditions providing myriad ecological niches over relatively small spatial scales. Although montane species are well adapted to life at extremes, they are highly vulnerable to human derived ecosystem threats. Here we build on the manifesto 'World Scientists' Warning to Humanity', issued by the Alliance of World Scientists, to outline the major threats to mountain ecosystems. We highlight climate change as the greatest threat to mountain ecosystems, which are more impacted than their lowland counterparts. We further discuss the cascade of "knock-on" effects of climate change such as increased UV radiation, altered hydrological cycles, and altered pollution profiles; highlighting the biological and socio-economic consequences. Finally, we present how intensified use of mountains leads to overexploitation and abstraction of water, driving changes in carbon stock, reducing biodiversity, and impacting ecosystem functioning. These perturbations can provide opportunities for invasive species, parasites and pathogens to colonize these fragile habitats, driving further changes and losses of micro- and macro-biodiversity, as well further impacting ecosystem services. Ultimately, imbalances in the normal functioning of mountain ecosystems will lead to changes in vital biological, biochemical, and chemical processes, critically reducing ecosystem health with widespread repercussions for animal and human wellbeing. Developing tools in species/habitat conservation and future restoration is therefore essential if we are to effectively mitigate against the declining health of mountains.

**Keywords:** Pollution, climate change, environmental health, sustainable development goals, policy

## Main text

Following the onset of the industrial revolution and the use of fossil energy, humans can indisputably be seen as major geological agents (Gałuszka et al., 2014) and as global pathogen vectors (Small et al., 2019). Due to the increase in human activities over the last 300 years, human impact has become at least as strong a force as natural processes (Crutzen, 2006), marking the geological era of the Anthropocene (Gałuszka et al., 2014). Already in 1972, scientists lined out that there are limits to human population growth (Meadows et al., 1972). Twenty years later, scientists warned about ozone depletion in the stratosphere, availability of drinking water, climate change, exponential human population growth, and degradation of the environment and biodiversity (Scientists, 1992). This early warning remained largely unheard and unrecognized, and the progress of humanity towards a sustainable lifestyle has been largely insufficient. This insufficiency ushered in a second warning to humanity 25 years later, arguing that our life-support system is on the brink of collapse (Ripple et al., 2017). Scientists are now largely aware of humanity approaching important tipping points (Lenton, 2011) and planetary boundaries (Steffen et al., 2015). A policy-led reaction was the development of 17 Sustainable Development Goals (https://sdgs.un.org/goals) and 20 Aichi targets (https://www.cbd.int/sp/targets/), the creation of the Intergovernmental Panel for Climate Change (IPCC) and the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES, Schmeller et al., 2017). However, all recent global reviews of the state of the planet conducted by the United Nations, IPCC and IPBES univocally lay out the dire state of Earth (Bridgewater et al., 2019). The direct drivers of the observed changes, as outlined in the global assessment on biodiversity and ecosystem services by IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019), include climate change, pollution, and increasing demands for energy and materials due to a growing human population. As a response, the UN Convention on Biological Diversity (CBD), developed a global biodiversity framework with 21 targets and 10 milestones to be achieved by 2030 to 'living in harmony with nature' by 2050 (CBD/WG2020/3/3). Goals include reducing threats to biodiversity (8 targets), meeting people's needs through sustainable use and benefit-sharing (5 targets), developing tools and solutions for implementation and mainstreaming (8 targets; CBD/WG2020/3/3). In line with these goals and targets, IPBES, during its 8$^{th}$ plenary, decided to advance with an assessment on the transformative change needed to indicate ways out of the current global crisis (Schmeller and Bridgewater, 2021).

Mountains cover a large part of the Earth's terrestrial surface and host a larger proportion of biodiversity than expected by area (Körner et al., 2011). They hold an estimated one-third of terrestrial species diversity (Körner, 2004), and represent 18 of the 36 global biodiversity hotspots (Chape et al., 2005). Nevertheless, even in remote areas human impact is strong, as mountains are part of the global socio-ecological systems which have been shaped by geological forces and by human activities (Turner et al., 1990). In mountains, these impacts and the resulting threats remain largely understudied (Schmeller et al., 2018). Generally, people are unaware of the threats to mountain ecosystems and the services mountains provide to humanity. Mountain ecosystems sequester $CO_2$, clean waters and the air, regulate climate, provide biomedical resources, and regulate floods (Martín-López et al., 2019). Mountains also provide for the livelihoods of more than half of humanity (Grêt-Regamey et al., 2012; Grêt-Regamey and Weibel, 2020). All these goods and services are provided by mountain ecosystems through complex processes that are maintained by communities of species interacting with each other and with the abiotic environment (Bestion et al., 2021). These mountain communities are comprised of prokaryotic and eukaryotic microbes, fungi, plankton species, woody and non-woody plants, as well as invertebrates and vertebrates. By destructing, rebuilding, changing, and shaping the environment, these species produce organic matter and oxygen as well as bind $CO_2$.

The mountain environment is characterized by extreme temperature regimes, severe weather events and short growing seasons at high altitudes to which species have adapted (Körner, 2019; Payne et al., 2020). In temperate mountains, comparably few species have been able to widely colonize the diverse habitats with montane conditions during the short time window given by the recent demise of glaciers at the end of the last glacial period about 11,000 years ago (McCain and Colwell, 2011; Schabetsberger et al., 2013; Valbuena-Ureña et al., 2018). Mountain ecosystems have evolved in partial isolation, separated by a variety of biogeographic barriers. The gradients and dynamics in climate, hydrology, and water chemistry contributed to the formation of a high diversity of microhabitats, harboring numerous species in comparably small areas (McCain and Colwell, 2011), which also explains the high levels of endemism detected in mountains (Rahbek et al., 2019a; b; Swanson et al., 1988). With increasing elevation, montane climates become more extreme, providing habitat for fewer species. System redundancies (i.e. different species with similar functions), available in ecosystems at low altitudes, are increasingly scarce in mountain ecosystems with increasing elevation. Such redundancies usually provide stability to ecosystems (Fonseca and Ganade, 2001). The absence of these redundancies renders mountain ecosystem particularly vulnerable to the impacts of global change (Moser et al., 2019). However, multiple threats to mountains are arising from climate change alone. Moreover, interactions with socio-cultural, economic and political developments, such as the exploitation of mountains, e.g. for timber, food production, including fish and livestock, tourism, and hydro-electricity, exacerbate these threats, calling for urgent consideration by policymakers (Figure 1).

Here, we highlight the diversity of global threats impacting mountain ecosystems. We focus on the direct drivers climate change, pollution, and land use following earlier science-policy reports (IPBES 2019) to compel stakeholders and decision makers of the urgency to act on all of these different threats. We detail how different drivers interact, creating pressures that degrade and destroy valuable mountain ecosystems and their biodiversity. We further outline, how this impacts the services provided by mountains and creates emerging risks for humans. We treat threats to mountains largely equally, as a ranking of threats in regard to their severity appears elusive based on current knowledge. Finally, we provide recommendations for mitigation actions to be taken to preserve mountains, their biodiversity and the ecosystem services they provide to humanity, as well as describing ways of averting detrimental trajectories.

## Climate Change in Mountains

Mountains are defined by rugged terrain and unique climate regimes distinguishing them from lowlands (Körner et al., 2017). The climatic complexity created by mountain topography also influences insolation and air circulation (Dobrowski et al., 2009). Elevation gradients in particular, have a strong impact on many abiotic variables in mountains, and their geographic location is the main control on moisture gradients or seasonality in climate (Körner, 2007). On a regional scale, mountain climate is influenced by large-scale synoptic patterns, proximity to oceans, and the range's longitudinal or latitudinal orientation (Del Barrio et al., 1990). In synergy with climate change impacts, we see important changes in precipitations, temperatures, and frequency of extreme events, such as droughts and floods. Therefore, climate change might be considered the most basic and far-reaching threat to mountains, impacting mountain biodiversity and ecosystems way more intensively as compared to lowland regions (Rangwala and Miller, 2012; Scarano, 2019).

Precipitation dynamics are not the same in all mountains, and for example, mountains in tropical regions show precipitation maxima at lower and mid-elevations. Temperate mountains typically have an orographic effect and show increased precipitation towards the top, largely driven by different seasonal dynamics in precipitation intensity (Roe, 2005). These precipitation regimes are also regulated by geology, soils, vegetation, and human land use, leading to a large variety of hydrological behaviors and stream flow regimes in global mountain catchments (Dierauer et al., 2018; Zuecco et al., 2018). Climate change-driven precipitation regimes and their increasing variability, especially in mountains, determine long-term change on soil moisture conditions and are important controls on water levels and on the hydroperiods of shallow lakes, ponds and wetlands (Catalan and Bartumeus, 2006; Stephan et al., 2021). As such they are particularly important variables for mountain habitats. Climate change will increase the unpredictability of precipitation patterns (Myhre et al., 2019). Generally, water availability and its predictability is expected to decrease in the future due to lower water storage capacities in areas with glacier cover and higher outflows of excess water during periods of extreme precipitation and melting events (Rajczak and Schär, 2017). These changes will jeopardize the role of mountains as global water towers and the drinking water supply for billions of people (Viviroli et al., 2007) as well as for plants and animals.

Trends in warming of mountain surface air temperatures become more and more apparent (López-Moreno et al., 2008; Niedrist et al., 2018; Niedrist and Füreder, 2021), and high-latitude mountains are projected to warm much faster than temperate and tropical mountains (Negi et al., 2021; Nogues-Bravo et al., 2007). Further, warming is accentuated at higher altitudes (Pepin et al., 2015). The intensity of warming depends on the mountain climatic zone, elevation and season (Pepin and Lundquist, 2008). In the Alps, the mean annual temperature has already increased by 1.5 - 2°C since 1970, and future projections predict an additional rise of 0.25 - 0.36 °C per decade within the next century (Einhorn et al., 2015). Similar increases have been projected in other mountain ranges (Urrutia and Vuille, 2009; Valdivia et al., 2013). Increasing temperatures have decreased the annual snow deposition volume with most impacts observed at mid- and lower elevations (Laternser and Schneebeli, 2003), has caused important shifts to earlier snow melt (Kapnick and Hall, 2012), earlier lake-ice melt (Franssen and Scherrer, 2008), and globally accelerated the deglaciation process (Zemp et al., 2015). Yearly, world-wide cumulative glacier mass balance data have been showing significant decreasing trends in glacier thickness (Ripple et al., 2021). The shorter period of snow cover will therefore also shorten the time during which the Albedo effect is active and during which 85% to 90% of sunlight is reflected. Hence, further acceleration of the temperature rise in alpine mountain regions needs to be expected. Droughts and extreme precipitation events will globally increase in mountains (Gobiet et al., 2014; Urrutia and Vuille, 2009; Valdivia et al., 2013). For the European Alps, climate projections predict more summer droughts and more extreme rainfall events (Rajczak and Schär, 2017). Subtropical mountains tend to experience more frequent summer droughts (McCullough et al., 2016), while for example the Hindu Kush and the Himalaya have been experiencing increased amounts of extreme rainfall events (Hartmann and Andresky, 2013; Wester et al., 2019). Droughts in mountains also lead to an increase of the probability of wildfires in mountain grasslands and forest as the probability of ignition of dry plant material by lightning increases (Stephens et al., 2018). Such wildfires are difficult to extinguish due to the difficult terrain and result in the loss of very large areas (i.e. thousands of hectare) of mountain vegetation with large and long-lasting effects on mountain ecosystems due to low pre-fire production of seeds due to drought and the generally low recovery speed with increasing altitude (Werner et al., 2022).

Ultraviolet radiation (UVR) both affects and is affected by climate change. These modifications of UV exposure are affecting how people and ecosystems respond to UV, with more pronounced effects in the future (Barnes et al. 2019). UVR reaching mountain ecosystems increases with elevation (Sommaruga et al., 1999). In many high mountain freshwaters, the limited catchment sources of DOC, which results in crystal clear water, facilitates the penetration of radiation far into the water column (Catalan and Donato Rondon, 2016; Laurion et al., 2000; Rose et al., 2009). High levels of UVR in the UV-B spectrum (wavelength range 280-320 nm) have been studied with regard to their effects on aquatic organisms at higher elevations. Colored dissolved organic carbon (DOC) and phytoplankton may attenuate the penetration of UV underwater, shielding freshwater species from negative effects of this radiation (Sommaruga et al., 1999). Variability in UVR reaching mountain freshwaters depends on factors such as cloud cover and air pollution (Brooks et al., 2005; de Oliveira et al., 2021; Diamond et al., 2005; Obertegger and Flaim, 2021; Sommaruga, 2001). Long-term changes in UV-B in turn are due to changes in atmospheric ozone levels, and despite the recovery of atmospheric ozone layers since the Montreal protocol was implemented (Barnes et al., 2019), new reports of ongoing lower stratospheric ozone depletion (Ball et al., 2018) and new ozone depleting agents in the atmosphere have been issued (Fang et al., 2019). We may also see potential opposite effects of global warming in mountains, as for aquatic or semi-aquatic species UVR stress may increase due to earlier snow and ice-cover melt, but may decrease due to higher DOC import from catchment reforestation (Sommaruga et al., 1999). The impact of UVR and stress avoidance behavior remains an understudied field, but may drive further changes in mountain biodiversity and perturb mountain ecosystems (Häder et al., 2011).

Generally, decreasing amounts of annual snow and retreating glaciers have been and will continue to profoundly reshape mountain freshwater habitats and also the terrestrial communities depending on them, threatening mountain species and communities (Jacobsen and Dangles, 2017; Sommaruga, 2015), but also providing new habitats for colonization (Ficetola et al., 2021). Impacts on lowland human populations include difficult to predict water supply (Huss et al., 2017; Viviroli et al., 2007) and destruction of infrastructure through more frequent extreme floods and/or landslides. Climate change will drive the disappearance of many intermediate and ephemeral habitats in mountains due to droughts, with potential severe consequences for mountain biodiversity and biological processes e.g. carbon storage. Climate change will also impact the water regime of many peatlands. Due to the importance of mountain peat- and wetlands as global carbon sinks, the loss of these habitats may further accentuate climate change (De Jong et al., 2010) and UVR impacts (Barnes et al. 2019).

## Pollutants in Mountains

Sources of pollution are manifold in mountain ecosystems (Lei and Wania, 2004; Noyes et al., 2009; Shunthirasingham et al., 2010) and we generally lack a global approach to observe environmental pollution and its impact (Brack et al., 2022). Global atmospheric transport of micropollutants (Hussain et al., 2019; Wania and Mackay, 1993; Yang et al., 2010) and local human activities such as mining, logging, agriculture, pastoralism and tourism are the main pollution sources in mountain environments. Increasing pastoralism and livestock units have been shown to put the health of mountain lakes at risk by introducing highly toxic organic pollutants into mountain lakes (Machate et al., 2022). Further, fish stocking introduced heavy metals such as mercury in mountain ecosystems (Hansson et al., 2017b). Other sources of pollution include extreme weather events releasing legacy pollutants from mining, tourists introducing UV blockers as part of personal care products, and atmospheric transport of pollutants releasing a plethora of different molecules (Gross, 2022; Le Roux et al., 2020; Pozo et al., 2007). Mountains are also at risk of acidification when they are located downwind of Nitrogen or Sulphur emission sources and buffering capacity of freshwater is low. In addition, seasonal events such as snowmelt can change pH up to a full unit (Nodvin et al., 1995). Acidic pulses may co-occur with spikes of toxic element concentrations in water (Havas and Rosseland, 1995). Further, higher rates of erosion and weathering, as a result of more frequent events of heavy precipitation, may also lead to a higher import of base cations and increase the pH of mountain freshwater and soil (Kopáček et al., 2017). Finally, global change-driven eutrophication and elevated temperatures lead to an increased growth of cyanobacteria, which can produce toxins (e.g. cyanotoxins), with known negative impacts on human health (Catherine et al., 2013; Funari and Testai, 2008; Zanchett and Oliveira-Filho, 2013).

The scavenging of atmospheric organic and inorganic pollutants is pronounced at high altitudes and can take the form of dry and wet deposition of aerosols to the ground surface (Daly and Wania, 2005; Le Roux et al., 2016; Le Roux et al., 2020). Atmospheric pollutants in mountains include trace elements (Camarero et al., 2009) (Yang et al., 2010), organic and synthetic pollutants (i.e. current-use and legacy pesticides), polycyclic aromatic hydrocarbons (PAHs), endocrine disrupting compounds (EDCs; Rockström et al., 2009; Meire et al., 2012), and polychlorinated biphenyls (PCBs) or microplastics (Allen et al., 2019; Brahney et al., 2020; Reid et al., 2019). These compounds are introduced into the atmosphere via evaporation, or binding to particles light enough to be carried by wind. Volatile compounds tend to evaporate in warmer environments at lower altitudes and condensation progressively takes place with decreasing temperature as air masses travel over mountain slopes (Blais et al., 1998). Less volatile compounds, such as most of the currently used agricultural pesticides, are not prone to directly evaporate into the atmosphere, but are still transported into the mountain environment as they bind to soil particles, which can be uplifted and carried over longer distance during more extreme wind events (Silva et al., 2018). As a consequence, organic and inorganic micropollutants can be introduced to mountains via the atmosphere and over long distances (Camarero et al., 2009; Bradford et al., 2010; 2013; Fig. 2).

Transfer of inorganic and organic pollutants to mountain freshwaters can also originate from legacy and recent local human activities. Fish stocking (Hansson et al., 2017b), present and historic mining activities (Hansson et al., 2017a) or forestry, agriculture and tourism (Alpers et al., 2016) introduce pollutants or mobilize their catchment sources such as soils and sediments. Evidence for the introduction of potentially harmful trace elements (PHTE, for example the metals As, Hg, Pb, Se, Sb, Zn, Cu) from distant or local sources is found in mountain lake sediments, peatlands and in snow (Bacardit and Camarero, 2010). Furthermore, glacier melt and snowmelt can mobilize legacy atmospheric pollution and catchment sources of pollutants (Bogdal et al., 2009; Meyer and Wania, 2008), which may increase exposure of mountain species to micropollutants.

Despite the accumulated knowledge on global pollution, we still know little about the toxic cocktail accumulating in mountains and its impact on biodiversity (but see Catalan, 2015). There are very few studies that analyzed a broad set of pollutants or even conduct non-target monitoring in a mountain context (Machate et al., 2022), rendering our current knowledge on global mountain pollution patterns largely incomplete. We also know little about each (detectable) compound’s physico-chemical characteristics, e.g. the water-air constant ($K_{wa}$), without which it is difficult to make predictions on future pollution patterns in mountains. Generally, the introduction of new pollutants and changes in pollutant mobilization due to climate change may challenge mountain ecosystem health and increase the vulnerability of species and humans to pathogens, increasing health risks (Brack et al., 2022; Schmeller et al., 2020; 2018). Concerns about adverse toxic effects have especially been raised about, but are not limited to, pollutants introduced from local activities (Machate et al., 2022). In the future, these health risks might further increase, by shifting e.g. pastures to higher altitudes (Mayer et al., 2022), where ecosystems are already under high pressures due to climate change (Herzog and Seidl, 2018)). Tourism and expansion of infrastructure create yet additional pressures on mountain biodiversity.

## Vegetation and land use changes in Mountains

Recent mountain vegetation is largely shaped by historical and current land use (Körner et al., 1997; Lavorel et al., 2017), with the degree of influence depending mainly on the accessibility of the area (Tasser and Tappeiner, 2002). Vegetation and changes in rates of carbon sequestration due to shifts in land use can occur through a change in land cover, through intensification or extensification of existing land use practices (Niedertscheider et al., 2017) and acidification (Bowman et al., 2012). Most of these changes are driven by pastoral activities, such as livestock grazing, which is the major agricultural activity in most mountains. Pastoral activities in many mountain regions have a long history. However, especially for European countries it is known that livestock units are increasing, partly as a result of the EU subvention policy, partly as strategy to evade climate change impacts and reduced availability of fodder in lowlands (Mayer et al. 2022). Another (illegal) activity related to pastoralism is slash and burn to avoid expansion of forest areas. The clearing intensity and frequency increases with increasing pastoral pressure. In addition, novel non-native crops have been planted to increase local food availability under optimal environmental conditions. However, plantations of species that are well-adapted to the environment of a particular mountain range, such as cardamom in the Hindu Kush region (Eklabya et al., 2000), provide a larger genetic reservoir and thus a greater buffer against environmental pressures such as climate change (Kelty, 2006). Other land use changes include logging of forest stands (Latty et al., 2004), afforestation (Liu et al., 2021), vegetation regrowth in abandoned lands (Aide et al., 2019). All these changes intervene deeply in the existing ecosystem (Hinojosa et al., 2016), altering and threatening underlying processes and associated ecosystem services (Chiang et al., 2014; Faccioni et al., 2019; Tasser and Tappeiner, 2002). An emerging land-use trend is the growing impact of tourism on ecosystems, where damage to vegetation can occur (Rodway-Dyer and Ellis, 2018) and is playing an increasing role in mountain regions (Niu and Cheng, 2019). In the Dongling Mountains (China), tourism led to a lower species richness, heterogeneity and evenness in impacted subalpine meadows (Zhang et al., 2012). Increasing pressures from land use changes will further accentuate the impacts of climate change and pollution on mountain biodiversity and the health of mountain ecosystems.

## Introduced species in mountains

Biological invasions are increasingly exacerbated by human activities and are responsible for significant biodiversity decline as well as high economic losses to society (Diagne et al., 2021). In addition, they are exacerbated by globalization and climate change (Seebens et al., 2021). The harsh environmental conditions (e.g., high UV-B, low temperatures, variable water availability, poor soil) may limit alien plant invasion and expansion, especially in high mountain areas (Watermann et al., 2020). However, remote mountain areas have been reportedly impacted by the introduction of alien species (Pauchard et al., 2009), partly also through tourism (Hemp, 2008).

For example, tourism drives fish stocking of naturally fishless lakes. In such naturally fishless mountain lakes fish introductions have an outsized impact and drive profound ecological change as a highly efficient aquatic predator is introduced in a naïve environment (Miró and Ventura, 2020). Stocking montane lakes with fish for subsistence purposes has been occurring since the Neolithic, through fish translocations from nearby lakes and rivers. However, before 1950 such introductions had limited geographic extent and their impacts were rather local (Moser et al., 2019). Since 1950, introductions of fish increased dramatically as a consequence of the increasing popularity of recreational angling, both in large and relatively small lakes as well as in adjacent wetlands (Hansson et al., 2017b). In addition, the use of small fish, mainly minnows *Phoxinus* sp. (Fam. Cyprinidae), as live baits for trout fishing is causing a new and detrimental wave of invasion (Miró and Ventura, 2015). These introduced fish dramatically affect native communities of mountain lakes. Initially considered ecologically harmless and economically beneficial, introductions continued even when their serious ecological consequences became clear (Knapp et al., 2001). Supported by institutional stocking campaigns and non-authorized translocations by anglers, fish spread rapidly in mountain deep-ponds and lakes of all sizes, as well as in all the colonizable downstream habitats (Ventura et al., 2017), with a long list of negative impacts: i) decline/elimination of native species (e.g., invertebrates and amphibians; (Knapp et al., 2001; Tiberti et al., 2014); ii) cascading effects in the trophic network (Schindler et al., 2001), affecting the chemical/microbiological quality of waters, and the ecological linkages with surrounding terrestrial habitats (Epanchin et al., 2010); iii) impacts such as predation, competition, transmission of pathogens and hybridization on native fish inhabiting downstream habitats (Adams et al., 2001), and iv) further collateral introductions of fish used as live bait (Miró and Ventura, 2015). Hence, fish stocking in mountain lakes is particularly detrimental to water quality and biodiversity, especially as now nearly all these ecosystems are affected, including large lakes, small lakes, ponds, connecting streams and their adjacent mountain wetlands (Ventura et al., 2017).

For timber production, fast growing tree species of the genera *Pinus* and *Eucalyptus* have also been introduced in many mountain forests. These exotic tree plantations are subject to serious criticism due to their negative impact on water balance, soil fertility, and native biodiversity (Fahey and Jackson, 1997; Hofstede et al., 2002; Lundgren, 1978). A significant loss of soil carbon and a major reduction in taxonomic and functional diversity of soil invertebrates has been observed in pine tree plantations compared to native forests of very similar soil origins and topographies (Cifuentes-Croquevielle et al., 2020). These impacts may further be exaggerated by fast rotation speeds, which would not permit to increase floristic and hence also faunistic biodiversity (Hall et al., 2012). These changes therefore have the potential to aggravate both climate change impacts and biodiversity loss (but see (Balthazar et al., 2015). Further, exotic tree species can become highly invasive under the right environmental conditions, which might also be met by future climate change. Invasibility is also driven by seeds from exotic tree plantations leading to colonisation and replacement of surrounding natural vegetation (van Wilgen, 2012). Reversing impacts associated with those self-sown invasive stands has be proven to be very difficult (van Wilgen and Richardson, 2012), also because waste of e.g. pine harvesting is left at sites or even delivered to nearby rivers, delaying the natural regeneration of indigenous vegetation (Balthazar et al., 2015).

## Water abstraction from Mountains

Most valley bottoms have been heavily altered by human activities that impact freshwater systems (Finlayson and D'Cruz, 2005). These activities include land drainage, dredging, flood protection, water abstraction for hydroelectric powerplants, and inter-basin water transfer, building dams to create reservoirs, and digging new canals for navigation. In mountains, which are increasingly used as recreational area, food and water source, but also as hydroelectric powerplants, water abstraction has been increased to excessive levels. Hydrological interventions include (hydroelectric) dams, pipelines and derivation channels, agricultural ponds, irrigation and snowmaking reservoirs, quarries, water removal, and flow regime alterations. Among their very many consequences, these interventions may lead to the gradual drying up of natural aquatic ecosystems due to excessive water extraction and diversion, as well as changes in the water level of (dammed) lakes, in the flow regime of streams, and in hydrological connectivity. These consequences in turn impact on the structure and function of the unique biodiversity that is characteristic of these habitats, and which includes many endemic and threatened species absent from the lowlands (Fait et al., 2020; Mayerhofer et al., 2021;

Schabetsberger et al., 2013). Importantly, ongoing modifications in high-mountain freshwater ecosystems may also directly and profoundly impact on the wellbeing and livelihoods of peoples (Schmeller et al., 2018).

Recent reports indicate that biodiversity in freshwater ecosystems is declining even faster than in oceans and forests and that the extent of human alteration and impairment of aquatic ecosystems is massive (Tickner et al., 2020). Mountain aquatic systems are no exception, particularly in high-mountain areas (Catalan et al., 2017). Human alterations to alpine aquatic ecosystems are of particular concern given that mountain aquatic habitats provide essential ecosystem services such as drinking water and renewable energy to much of humanity, and that they are of high aesthetic, recreational, and conservation value, particularly in their function as biodiversity reservoirs (Fait et al., 2020). Water abstraction in concert with climate driven changes in hydrological regimes will lead to a gradual drying up of aquatic mountain ecosystems, likely causing massive water shortages in cities that depend on drinking water from mountains (Viviroli et al., 2020; United Nations Environment Programme 2022). The desertification of these ecosystems will also be detrimental to their unique mountain biodiversity, leading to an irreversible degradation of these sensitive ecosystems, if no or too little action for their preservation are put in place immediately (Immerzeel et al., 2020).

## Threats to and from Mountain Micro-Biodiversity

The unseen diversity of micro-organisms and their microbiomes, comprising the community of fungi, yeasts, bacteria, viruses and protists, and the impacts of climate change on them have already been subject to a previous warning (Cavicchioli et al., 2019). In short, micro-biodiversity plays a central role and is of global importance in climate change biology, particularly in extreme environments such as mountain ecosystems (Schmeller et al., 2018). Climate change impacts, relevant also for humanity, depend heavily on the responses of microorganisms, which are essential for achieving an environmentally sustainable future (Cavicchioli et al., 2019). Despite their importance, we still know little about the microbial communities or microbiomes, especially in mountain ecosystems (Kammerlander et al., 2015; Schmeller et al., 2018).

Despite their small size, microbial communities drive major processes in and on animals, plants, as well as in ecosystems (Bates et al., 2022; Bernardo-Cravo et al., 2020; Lin et al., 2021). In a nutrient poor environment such as mountains, microbial communities likely play an important role in synthesizing vital nutrients, thereby increasing energy uptake and growth of plants and animals (Bernardo-Cravo et al., 2020; Schmeller et al., 2020; Sentenac et al., 2022). Similarly, micro-organisms stabilize whole ecosystems by buffering against change through the maintenance of biodiversity and ecosystem processes. For example, the interactions between micro-organisms and plankton constitute the basis of aquatic food webs and determine the functioning of biogeochemical cycles, accounting for more than half of global carbon fixation (Cavicchioli et al., 2019; Purcell et al., 2022). Any kind of disturbance to microbial communities can therefore impact on mountain species and ecosystems.

Pathogens, and other microorganisms, can be easily introduced to mountains through pastoralism, tourism or wind drift. However, we remain largely oblivious to how the complexity of the abiotic and biotic environment in mountain ecosystems influences beneficial microbe-species interactions (e.g. microbial loop, mycoloop; (Kagami et al., 2014), host-pathogen interactions (Frenken et al., 2017; Haver et al., 2021; Fisher and Garner, 2020) and health risks for the human population (Schmeller et al., 2018). For example, the transport of microbial pathogens is of special concern for human and livestock health, but also for wildlife and keystone species groups such as amphibians. In particular, fungi and bacteria with resistant aerosolised spores are capable of long-distance transport of e.g. dust (Dadam et al., 2019; Sultan et al., 2005). Global dust dispersion is a natural phenomenon, and occurs when topsoil is transported into the troposphere and carried over long distances by wind currents. However, global warming and changes in land use practices (e.g. deforestation and overgrazing) have accelerated desertification in many areas, resulting in increased dust dispersion even to remote places (Moulin and Chiapello, 2006; Tegen et al., 2004), particularly to high elevation sites (Dong et al., 2020). Further anthropogenic impacts via air pollution can intensify both the abundance and community composition of aerial microbes (Yan et al., 2016), but also for vector-borne diseases (Caminade et al., 2019): Malaria has been found at higher altitudes in mountains in Ethiopia and Colombia (Siraj et al., 2014), incidences of Malaria and Dengue are increasing in Nepal´s mountains (Dhimal et al., 2015a), altitudinal upward shifts of Dengue and Chikungunya (Dhimal et al., 2015b), and also ticks have been reported, the latter e.g. leading to increased occurrence of Lyme borreliosis in the Alps (Garcia-Vozmediano et al., 2020).

Recent data also suggest that we currently see an increase in eutrophication of mountain lakes globally with an upsurge of the diversity of Cyanobacteria (Ho et al., 2019). Cyanobacteria produce a range of toxins (e.g. microcystins, cyanotoxins, Catherine et al., 2013), which have an important impact on the quality of water (Du et al., 2019; Ho et al., 2019), therewith increasing risks of intoxications for humans and livestock. Epilithic biofilms are a highly reactive component in freshwater systems that play a crucial role in the provision of many ecosystem services (Catalan and Donato Rondon, 2016). Especially in smaller mountain lakes, streams and other waterbodies, epilithic biofilms must be considered the major player in carbon cycling and ecosystem productivity (Vadeboncoeur et al., 2008). A better understanding of the risks of proliferation of potentially harmful microbial groups, pathogenic fungi, bacteria and protists due to human-driven input of phosphorus, nitrogen through atmospheric fertilization and microbial pollution is necessary to improve our predictive abilities for human and wildlife risks. For mountain ecosystems, in particular, our predictive abilities are poor for forecasting pathogen proliferation, the dynamics of potentially harmful microorganisms, and for identifying threatened species and habitats. In a mountain context that could mean that resources of clean drinking water will diminish at a much faster rate than currently predicted (Schmeller et al., 2018) and the important ecosystem services such as $CO_2$ sequestration and nitrogen retention will be suboptimal or absent (Saunders and Kalff, 2001).

## Threats to Mountain Macro-Biodiversity

Mountain areas host many species that live in a delicate balance or at the edge of their distribution and are therefore very susceptible to environmental changes and local extinction. Top predators, such as large carnivores, but also large herbivores play important roles in maintaining mammal, avian, invertebrate, and herpetofauna abundance and richness. Many of these species are threatened with extinction (Ripple et al., 2014) and nearing global collapse (Ripple et al., 2015). Threats to macro-biodiversity in mountains come from chemical pollution, nutrient influx through atmospheric processes and local sources such as livestock (Machate et al., 2022), introduction of non-native taxa, but most importantly from overexploitation and habitat loss (Maxwell et al., 2016). These threats drive the decline of already threatened species (Maxwell et al., 2016) and will change the communities of species, which do not all have the same possibilities of dispersal, recovery and reproduction to avoid disturbances (Kerr and Deguise, 2004; Pimm, 2008). For example, among aquatic organisms, the possibility of dispersal and life traits such as the mode of reproduction are very different among taxonomic groups. Some zooplankton species can reproduce sexually or parthenogenetically, and can produce resting eggs, which can survive for a long time in sediment egg banks (Brendonck and De Meester, 2003; Nielsen et al., 2012). Benthic invertebrates increase their dispersal capacity by producing winged adults. Both strategies may allow a speedy recovery through hatching from resting stages or recolonization by flying. Complete recovery after local extinction, however, is unlikely, and restoration and recovery processes in mountains take a long time (Tiberti et al., 2019). For example, recovery from fish impacts took 11-20 years to obtain a similar food web structure. In the same studies, it was evident that recolonization efficiency of species with a parthenogenetic reproduction mode was higher than for sexual reproduction (Knapp and Sarnelle, 2008; Knapp et al., 2001). In any case, for many species dispersal and recolonization can be limited, when the remaining seed pool is not abundant or found too distant or beyond barriers in the land- or waterscape in mountains, due to their relief. Hence, connectivity between different populations of the same mountain species is reduced, hampering recolonization after disturbance (Heino, 2013). Further, upward shifts of distribution areas are not the same for all mountain species, disrupting long-established communities and their interactions. For example, we understand only inadequately, if the observed upward shift of some mountain plant species due to climate change  is met by associated microbes and invertebrates (Grabherr et al., 1994; Steinbauer et al., 2018). Other factors leading to unequal dispersal of formerly associated species might be driven by reduced oxygen availability with increasing elevation (Jacobsen, 2020), differences in temperature and drought tolerance (Forero-Medina et al., 2011; Schai-Braun et al., 2021), different adaptation abilities through e.g. seasonality or phenology (Parmesan and Yohe, 2003), or different abilities to change depth distribution. Dysfunctional ecosystems, with lower resilience to further impact  s, are the likely outcome (Körner, 2019; Pecl et al., 2017). Due to the non-linear loss of biodiversity (Trisos et al., 2020), the expected extinction of endemic plant and animal species after tipping points have been met (Dullinger et al., 2012), may further increase the dysfunctioning of mountain ecosystems. When this will happen and what will be the outcome will be difficult to predict due to the multitude of factors impacting different species in a community.

## Threats to mountain ecosystem services

Negative impacts on mountain biodiversity threatens ecosystem integrity and functioning, and hence also the multiple ecosystem services provided to local communities, populations downstream and local stakeholders, including tourists (Grêt-Regamey et al., 2012; Martín-López et al., 2019; Schirpke et al., 2019). The capacity of mountain ecosystems to provide ecosystem services is deteriorating due to biodiversity loss driven by global change (Palomo, 2017). There is an alarming set of negative consequences from those changes, in stark contrast to the few positive effects that have been reported (Hobbs et al., 2009). These changes will jeopardize water use of at least 1.9 billion people (Immerzeel et al., 2020). Moreover, as a result of glacier decline, water availability will be severely reduced in the dry season, affecting millions of farmers globally (Biemans et al., 2019). Mountains will therefore not remain the reliable and highly important source of water they have been for thousands of years. Even in humid mountain regions, such as the European Alps, droughts have become a problem (Stephan et al., 2021) due to the increasing irregularity of water discharging rates and increasing flood events (Ragettli et al., 2021). The irregularity of water discharging rates in combination with land use and land cover changes can also have synergistic effects on ecosystem functioning, rendering mountains more vulnerable to climate change impacts (Chiang et al., 2014). For the central mountain range of Taiwan, it was shown that these combined effects lead to a relocation or loss of ecosystem services and therefore need to be considered in conservation planning (Lin et al., 2019; Lin et al., 2017).

Net primary production (NPP), the amount of biomass or carbon produced by primary producers per unit area and time, is the basis of all ecosystem services and is being altered due to climate change (Haberl et al., 2007; Kastner et al., 2022; Melillo et al., 1993). Overall, there is evidence that increasing temperatures and $CO_2$ concentrations have increased the NPP of forests when water was not a limiting factor (Boisvenue and Running, 2006). In the Alps, changes in NPP of grasslands on which cattle depend show contrasting regional trends (Jäger et al., 2020). A study combining experimentation and meta-analysis reported stabilization of NPP of grasslands under climate change due to changes in species and increasing allocation towards belowground biomass to resist drought (Liu et al., 2018). Despite a limited body of evidence, local models predict that NPP will increase under climate change in the forests of the mountain region of Changbai in China (Gao et al., 2020).

Further, as glaciers retreat and permafrost thaw, the decreased land-surface stability results in increased hazards in the form of landslides and rock fall, increasing risks for wildlife, tourists and livestock (Huss et al., 2017; Temme, 2015). Glacial lake outburst floods may also intensify due to glacier retreat and glacial lake formation, with potentially devastating consequences for populations downstream (Harrison et al., 2018; Milner et al., 2017; Vuille et al., 2018). Cultural ecosystem services are also impacted by climate change. For example, glaciers are considered sacred or have a strong symbolic meaning for several mountain communities, and thus spirituality is being affected (Allison, 2015) and has been documented in various countries in Africa, Asia, and the Americas (Allison, 2015; Mölg et al., 2008; Shijin and Dahe, 2015). Overall, the documented threats to mountain ecosystem services are a major concern worldwide, as they could lead to increased poverty, lower food production, higher health risks and a general decrease of human wellbeing, which may often affect not only mountains but also the populations living downstream.

## Conclusions

Mountain ecosystems are complex, dynamic, exceptionally fragile and are highly sensitive to global change. They are therefore considered sentinels of change (Schmeller et al., 2018). We are only beginning to understand the functional ecology of mountain ecosystems, but international research already suggests that changing species communities will be detrimental to the environment, to biodiversity and therefore to a critical part of Earth's life-support system.

Climate change might be considered the most impactful driver of change in mountain ecosystem, but all the outlined threats to mountains act in synergy. Climate change is modifying and will continue to modify the occurrence of extreme events, the amount of precipitations (rain and snow), as well as freeze and thaw cycles, with impacts on the onset of snow melt (and thus length of growing season) and water temperatures, aggravating impacts from inappropriate land use practices. Global change with all the different pressures outlined above causes imbalances in the functioning of mountain ecosystems, which lead to changes in vital biological, biochemical, and chemical processes, critically reducing ecosystem health with repercussions for animal and human health and wellbeing (Acevedo-Whitehouse and Duffus, 2009; Bradshaw et al., 2021; Lerner and Berg, 2017).

Humanity has a wide range of options in its hand to mitigate human-driven impacts on mountains and to change the current trajectory as humanity is at the nexus of it all. All relevant actors need to coordinate their efforts in extensive collaborations to achieve the necessary conservation measures: in mountain areas with a protection status conservation policy needs reinforcement; for mountain areas without a protection status, evaluation of its status, importance and future perspective need to be used to prioritize (i) protective measures, (ii) re-evaluations of impacts of touristic and pastoral activities, (iii) evaluation of sustainability management of natural resources, and (iv) development of early-warning systems of ecosystem degradation and biodiversity loss. These measures will then be able to inform about trajectories towards detrimental outcomes (pathogen emergence, ecosystem services; (Huber et al., 2013). As mountain stakeholders are numerous, regional networks and coordination mechanisms must urgently be installed, and a broad communication strategy needs to be developed to raise awareness about the threats to mountains and their complex consequences (Brunner and Grêt-Regamey, 2016; Drexler et al., 2016). These consequences may have also an important social component, as people may move out of mountain areas, if the conditions for cultivation and exploitation are unfavourable, not providing for their livelihood. These different aspects need to be included in comprehensive mountain ecosystem management plans, considering the cumulative and hierarchical context of disturbance regimes to prevent reductions in ecological variability and ecosystem resilience (Chiang et al., 2014).

In this light, and in that of the challenging objectives set by global agendas, including the UN Sustainable Development Agenda, the Convention on Biological Diversity, the recently launched EU Biodiversity Strategy for 2030 or the UN Decade on Ecosystem Restoration 2021-2030, investments are needed for the delivery of policy-relevant science on mountain ecosystems (Körner, 2019), closely following recommendations given in the global biodiversity framework (CBD/WG2020/3/3). Only if we maintain a high ecosystem resilience will we be able to maintain ecosystem functioning and ecosystem services. Threats to mountains are numerous and the repercussions to humanity demand conservation and restoration of mountain ecosystems, as they are an essential and highly sensitive part of the global life-support system.

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**References**

Acevedo-Whitehouse K, Duffus ALJ. Effects of environmental change on wildlife health. Philosophical Transactions of the Royal Society B-Biological Sciences 2009; 364: 3429-3438.

Adams SB, Frissell CA, Rieman BE. Geography of invasion in mountain streams: consequences of headwater lake fish introductions. Ecosystems 2001; 4: 296-307.

Aide TM, Grau HR, Graesser J, Andrade-Nuñez MJ, Aráoz E, Barros AP, et al. Woody vegetation dynamics in the tropical and subtropical Andes from 2001 to 2014: Satellite image interpretation and expert validation. Global Change Biology 2019; 25: 2112-2126.

Allen S, Allen D, Phoenix VR, Le Roux G, Jiménez PD, Simonneau A, et al. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nature Geoscience 2019; 12: 339-344.

Allison EA. The spiritual significance of glaciers in an age of climate change. Wiley Interdisciplinary Reviews: Climate Change 2015; 6: 493-508.

Bacardit M, Camarero L. Atmospherically deposited major and trace elements in the winter snowpack along a gradient of altitude in the Central Pyrenees: the seasonal record of long-range fluxes over SW Europe. Atmospheric Environment 2010; 44: 582-595.

Ball WT, Alsing J, Mortlock DJ, Staehelin J, Haigh JD, Peter T, et al. Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery. Atmospheric Chemistry and Physics 2018; 18: 1379-1394.

Balthazar V, Vanacker V, Molina A, Lambin EF. Impacts of forest cover change on ecosystem services in high Andean mountains. Ecological Indicators 2015; 48: 63-75.

Barnes PW, Williamson CE, Lucas RM, Robinson SA, Madronich S, Paul ND, et al. Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. Nature Sustainability 2019; 2: 569-579.

Bates KA, Sommer U, Hopkins KP, Shelton JMG, Wierzbicki C, Sergeant C, et al. Microbiome function predicts amphibian chytridiomycosis disease dynamics. Microbiome 2022; 10: 44.

Bernardo-Cravo A, Schmeller DS, Chatzinotas A, Vredenburg VT, Loyau A. Environmental Factors and Host Microbiomes Shape Host-Pathogen Dynamics. Trends in Parasitology 2020; 36: 29-36.

Bestion E, Haegeman B, Alvarez Codesal S, Garreau A, Huet M, Barton S, et al. Phytoplankton biodiversity is more important for ecosystem functioning in highly variable thermal environments. Proceedings of the National Academy of Sciences 2021; 118: e2019591118.

Biemans H, Siderius C, Lutz A, Nepal S, Ahmad B, Hassan T, et al. Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability 2019; 2: 594-601.

Blais JM, Schindler DW, Muir DC, Kimpe LE, Donald DB, Rosenberg B. Accumulation of persistent organochlorine compounds in mountains of western Canada. Nature 1998; 395: 585-588.

Boisvenue C, Running SW. Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. Global Change Biology 2006; 12: 862-882.

Bowman WD, Murgel J, Blett T, Porter E. Nitrogen critical loads for alpine vegetation and soils in Rocky Mountain National Park. Journal of Environmental Management 2012; 103: 165-171.

Brack W, Barcelo Culleres D, Boxall ABA, Budzinski H, Castiglioni S, Covaci A, et al. One planet: one health. A call to support the initiative on a global science–policy body on chemicals and waste. Environmental Sciences Europe 2022; 34: 21.

Bradford DF, Stanley K, McConnell LL, Tallent-Halsell NG, Nash MS, Simonich SM. Spatial patterns of atmospherically deposited organic contaminants at high elevation in the southern Sierra Nevada mountains, California, USA. Environ Toxicol Chem 2010; 29: 1056-66.

Bradford DF, Stanley KA, Tallent NG, Sparling DW, Nash MS, Knapp RA, et al. Temporal and spatial variation of atmospherically deposited organic contaminants at high elevation in Yosemite National Park, California, USA. Environmental toxicology and chemistry 2013; 32: 517-525.

Bradshaw CJA, Ehrlich PR, Beattie A, Ceballos G, Crist E, Diamond J, et al. Underestimating the Challenges of Avoiding a Ghastly Future. Frontiers in Conservation Science 2021; 1.

Brahney J, Hallerud M, Heim E, Hahnenberger M, Sukumaran S. Plastic rain in protected areas of the United States. Science 2020; 368: 1257-1260.

Brendonck L, De Meester L. Egg banks in freshwater zooplankton: evolutionary and ecological archives in the sediment. Hydrobiologia 2003; 491: 65-84.

Bridgewater P, Loyau A, Schmeller DS. The seventh plenary of the intergovernmental platform for biodiversity and ecosystem services (IPBES-7): a global assessment and a reshaping of IPBES. Biodiversity and Conservation 2019; 28: 2457-2461.

Brooks PD, O'Reilly CM, Diamond SA, Campbell DH, Knapp R, Bradford D, et al. Spatial and temporal variability in the amount and source of dissolved organic carbon: implications for ultraviolet exposure in amphibian habitats. Ecosystems 2005; 8: 478-487.

Brunner SH, Grêt-Regamey A. Policy strategies to foster the resilience of mountain social-ecological systems under uncertain global change. Environmental Science & Policy 2016; 66: 129-139.

Camarero L, Botev I, Muri G, Psenner R, Rose N, Stuchlík E. Trace elements in alpine and arctic lake sediments as a record of diffuse atmospheric contamination across Europe. Freshwater Biology 2009; 54: 2518-2532.

Caminade C, McIntyre KM, Jones AE. Impact of recent and future climate change on vector-borne diseases. Annals of the New York Academy of Sciences 2019; 1436: 157.

Catalan J. Tracking long-range atmospheric transport of trace metals, polycyclic aromatic hydrocarbons, and organohalogen compounds using lake sediments of mountain regions. Environmental contaminants. Springer, 2015, pp. 263-322.

Catalan J, Camarero, L., Felip, M., Pla, S., Ventura, M., Buchaca, T., , Bartumeus F, Guillermo de Mendoza, Miró, A., Casamayor, E.O., Medina-Sánchez, J.M., Bacardit, M., Altuna, M., Bartrons, M., Díaz de Quijano, D. High mountain lakes: extreme habitats and witnesses of environmental changes. Limnetica 2006; 25: 551-584.

Catalan J, Donato Rondon JC. Perspectives for an integrated understanding of tropical and temperate high-mountain lakes. Journal of Limnology 2016; 75: 215-234.

Catalan J, Ninot JM, Aniz MM. High Mountain Conservation in a Changing World. Vol 62. Cham: Springer, 2017.

Catherine Q, Susanna W, Isidora E-S, Mark H, Aurelie V, Jean-François H. A review of current knowledge on toxic benthic freshwater cyanobacteria–ecology, toxin production and risk management. Water research 2013; 47: 5464-5479.

Cavicchioli R, Ripple WJ, Timmis KN, Azam F, Bakken LR, Baylis M, et al. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol 2019.

Chape S, Harrison J, Spalding M, Lysenko I. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philosophical Transactions of the Royal Society B: Biological Sciences 2005; 360: 443-455.

Chiang L-C, Lin Y-P, Huang T, Schmeller DS, Verburg PH, Liu Y-L, et al. Simulation of ecosystem service responses to multiple disturbances from an earthquake and several typhoons. Landscape and urban planning 2014; 122: 41-55.

Cifuentes-Croquevielle C, Stanton DE, Armesto JJ. Soil invertebrate diversity loss and functional changes in temperate forest soils replaced by exotic pine plantations. Scientific Reports 2020; 10: 7762.

Crutzen PJ. The “anthropocene”. Earth system science in the anthropocene. Springer, 2006, pp. 13-18.

Dadam D, Robinson RA, Clements A, Peach WJ, Bennett M, Rowcliffe JM, et al. Avian malaria-mediated population decline of a widespread iconic bird species. Royal Society open science 2019; 6: 182197.

Daly GL, Wania F. Organic contaminants in mountains. Environmental science & technology 2005; 39: 385-398.

De Jong R, Blaauw M, Chambers FM, Christensen TR, De Vleeschouwer Fo, Finsinger W, et al. Climate and peatlands. Changing Climates, Earth Systems and Society. Springer Netherlands, 2010, pp. 85-121.

de Oliveira DG, Schneider G, Itokazu AG, Costa GB, Rörig LR, Simonassi JC, et al. Effects of ultraviolet radiation removal on algal communities in three high-elevation Brazilian (ultra) oligotrophic lakes. Phycologia 2021; 60: 497-512.

Del Barrio G, Creus J, Puigdefábregas J. Thermal seasonality of the high mountain belts of the Pyrenees. Mountain Research and Development 1990: 227-233.

Dhimal M, Ahrens B, Kuch U. Climate change and spatiotemporal distributions of vector-borne diseases in Nepal–a systematic synthesis of literature. PloS one 2015a; 10: e0129869.

Dhimal M, Gautam I, Joshi HD, O’Hara RB, Ahrens B, Kuch U. Risk factors for the presence of chikungunya and dengue vectors (Aedes aegypti and Aedes albopictus), their altitudinal distribution and climatic determinants of their abundance in central Nepal. PLoS Neglected Tropical Diseases 2015b; 9: e0003545.

Diagne C, Leroy B, Vaissière A-C, Gozlan RE, Roiz D, Jarić I, et al. High and rising economic costs of biological invasions worldwide. Nature 2021; 592: 571-576.

Diamond SA, Trenham PC, Adams MJ, Hossack BR, Knapp RA, Stark SL, et al. Estimated ultraviolet radiation doses in wetlands in six national parks. Ecosystems 2005; 8: 462-477.

Dierauer JR, Whitfield PH, Allen DM. Climate controls on runoff and low flows in mountain catchments of Western North America. Water Resources Research 2018; 54: 7495-7510.
Dobrowski SZ, Abatzoglou JT, Greenberg JA, Schladow S. How much influence does landscape-scale physiography have on air temperature in a mountain environment? Agricultural and Forest Meteorology 2009; 149: 1751-1758.
Dong Z, Brahney J, Kang S, Elser J, Wei T, Jiao X, et al. Aeolian dust transport, cycle and influences in high-elevation cryosphere of the Tibetan Plateau region: New evidences from alpine snow and ice. Earth-Science Reviews 2020; 211: 103408.
Drexler C, Braun V, Christie D, Claramunt B, Dax T, Jelen I, et al. Mountains for Europe‘s Future–A strategic research agenda. Bern, Switzerland: Mountain Research Initiative, Institute of Interdisciplinary Mountain Research 2016.
Du X, Liu H, Yuan L, Wang Y, Ma Y, Wang R, et al. The Diversity of Cyanobacterial Toxins on Structural Characterization, Distribution and Identification: A Systematic Review. Toxins 2019; 11: 530.
Dullinger S, Gattringer A, Thuiller W, Moser D, Zimmermann NE, Guisan A, et al. Extinction debt of high-mountain plants under twenty-first-century climate change. Nature climate change 2012; 2: 619-622.
Einhorn B, Eckert N, Chaix C, Ravanel L, Deline P, Gardent M, et al. Climate change and natural hazards in the Alps. Observed and potential impacts on physical and socio-economic systems. Journal of Alpine Research| Revue de géographie alpine 2015.
Eklabya S, Rita S, Singh KK, Sharma G. A Boon for Mountain Populations. Mountain Research and Development 2000; 20: 108-111.
Epanchin PN, Knapp RA, Lawler SP. Nonnative trout impact an alpine-nesting bird by altering aquatic-insect subsidies. Ecology 2010; 91: 2406-2415.
Faccioni G, Sturaro E, Ramanzin M, Bernués A. Socio-economic valuation of abandonment and intensification of Alpine agroecosystems and associated ecosystem services. Land Use Policy 2019; 81: 453-462.
Fahey B, Jackson R. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. Agricultural and Forest Meteorology 1997; 84: 69-82.
Fait P, Demierre E, Ilg C, Oertli B. Small mountain reservoirs in the Alps: New habitats for alpine freshwater biodiversity? Aquatic Conservation: Marine and Freshwater Ecosystems 2020; 30: 617-630.
Fang X, Pyle JA, Chipperfield MP, Daniel JS, Park S, Prinn RG. Challenges for the recovery of the ozone layer. Nature Geoscience 2019; 12: 592-596.
Ficetola GF, Marta S, Guerrieri A, Gobbi M, Ambrosini R, Fontaneto D, et al. Dynamics of ecological communities following current retreat of glaciers. Annual Review of Ecology, Evolution, and Systematics 2021; 52: 405-426.
Finlayson C, D'Cruz R. Inland water systems. Ecosystems and human well-being: Current state and trends. Island Press, 2005, pp. 551-583.
Fisher MC, Garner TW. Chytrid fungi and global amphibian declines. Nature Reviews Microbiology 2020; 18: 332-343.
Fonseca CR, Ganade G. Species functional redundancy, random extinctions and the stability of ecosystems. Journal of Ecology 2001; 89: 118-125.
Forero-Medina G, Joppa L, Pimm SL. Constraints to Species' Elevational Range Shifts as Climate Changes. Conservation Biology 2011; 25: 163-171.
Franssen HH, Scherrer S. Freezing of lakes on the Swiss plateau in the period 1901–2006. International Journal of Climatology: A Journal of the Royal Meteorological Society 2008; 28: 421-433.

Frenken T, Alacid E, Berger SA, Bourne EC, Gerphagnon M, Grossart H-P, et al. Integrating chytrid fungal parasites into plankton ecology. Research gaps and needs. Environmental Microbiology 2017; 19: 3802–3822.
Funari E, Testai E. Human health risk assessment related to cyanotoxins exposure. Critical reviews in toxicology 2008; 38: 97-125.
Gałuszka A, Migaszewski ZM, Zalasiewicz J. Assessing the Anthropocene with geochemical methods. Geological Society, London, Special Publications 2014; 395: 221-238.
Gao W-Q, Lei X-D, Fu L-Y. Impacts of climate change on the potential forest productivity based on a climate-driven biophysical model in northeastern China. Journal of Forestry Research 2020; 31: 2273-2286.
Garcia-Vozmediano A, Krawczyk AI, Sprong H, Rossi L, Ramassa E, Tomassone L. Ticks climb the mountains: ixodid tick infestation and infection by tick-borne pathogens in the Western Alps. Ticks and Tick-borne Diseases 2020; 11: 101489.
Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M. 21st century climate change in the European Alps—A review. Science of the Total Environment 2014; 493: 1138-1151.
Grabherr G, Gottfried M, Pauli H. Climate effects on mountain plants. Nature 1994; 369: 448-448.
Grêt-Regamey A, Brunner SH, Kienast F. Mountain ecosystem services: who cares? Mountain Research and Development 2012; 32: S23-S34.
Grêt-Regamey A, Weibel B. Global assessment of mountain ecosystem services using earth observation data. Ecosystem Services 2020; 46: 101213.
Gross M. Anthropocene at altitude. Current Biology 2022; 32: R441-R444.
Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, et al. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 2007; 104: 12942-12947.
Häder DP, Helbling EW, Williamson CE, Worrest RC. Effects of UV radiation on aquatic ecosystems and interactions with climate change. Photochemical & Photobiological Sciences 2011; 10: 242-260.
Hall JM, Van Holt T, Daniels AE, Balthazar V, Lambin EF. Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. Landscape Ecology 2012; 27: 1135-1147.
Hansson SV, Claustres A, Probst A, De Vleeschouwer F, Baron S, Galop D, et al. Atmospheric and terrigenous metal accumulation over 3000 years in a French mountain catchment: Local vs distal influences. Anthropocene 2017a; 19: 45-54.
Hansson SV, Sonke J, Galop D, Bareille G, Jean S, Le Roux G. Transfer of marine mercury to mountain lakes. Scientific Reports 2017b; 7: 12719.
Harrison S, Kargel JS, Huggel C, Reynolds J, Shugar DH, Betts RA, et al. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. The Cryosphere 2018; 12: 1195-1209.
Hartmann H, Andresky L. Flooding in the Indus River basin—a spatiotemporal analysis of precipitation records. Global and planetary change 2013; 107: 25-35.
Havas M, Rosseland BO. Response of zooplankton, benthos, and fish to acidification: an overview. Water, Air, and Soil Pollution 1995; 85: 51-62.
Haver M, Le Roux G, Friesen J, Loyau A, Vredenburg VT, Schmeller DS. The role of abiotic variables in an emerging global amphibian fungal disease in mountains. Science of The Total Environment 2021: 152735.
Heino J. The importance of metacommunity ecology for environmental assessment research in the freshwater realm. Biological Reviews 2013; 88: 166-178.
Hemp A. Introduced plants on Kilimanjaro: tourism and its impact. Plant Ecology 2008; 197: 17-29.

Herzog F, Seidl I. Swiss alpine summer farming: current status and future development under climate change. The Rangeland Journal 2018; 40: 501-511.

Hinojosa L, Napoléone C, Moulery M, Lambin EF. The “mountain effect” in the abandonment of grasslands: Insights from the French Southern Alps. Agriculture, Ecosystems & Environment 2016; 221: 115-124.

Ho JC, Michalak AM, Pahlevan N. Widespread global increase in intense lake phytoplankton blooms since the 1980s. Nature 2019; 574: 667-670.

Hobbs RJ, Higgs E, Harris JA. Novel ecosystems: implications for conservation and restoration. Trends in ecology & evolution 2009; 24: 599-605.

Hofstede RGM, Groenendijk JP, Coppus R, Fehse JC, Sevink J. Impact of Pine Plantations on Soils and Vegetation in the Ecuadorian High Andes. Mountain Research and Development 2002; 22: 159-167, 9.

Huber R, Rigling A, Bebi P, Brand FS, Briner S, Buttler A, et al. Sustainable land use in mountain regions under global change: synthesis across scales and disciplines. Ecology and Society 2013; 18.

Huss M, Bookhagen B, Huggel C, Jacobsen D, Bradley RS, Clague JJ, et al. Toward mountains without permanent snow and ice. Earth's Future 2017; 5: 418-435.

Hussain BA, Westgate JN, Hayward SJ, Shunthirasingham C, Brown TN, Hung H, et al. Polycyclic aromatic hydrocarbons and polychlorinated biphenyls in soils and atmosphere of Western Canadian mountains: The role of source proximity, precipitation, forest cover and mountain cold-trapping. Atmospheric Environment: X 2019; 1: 100004.

Immerzeel WW, Lutz A, Andrade M, Bahl A, Biemans H, Bolch T, et al. Importance and vulnerability of the world’s water towers. Nature 2020; 577: 364-369.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Brondizio ES, Settele J, Díaz S, Ngo HT, editors. IPBES Secretariat, Bonn, Germany, 2019, pp. 1148.

Jacobsen D. The dilemma of altitudinal shifts: caught between high temperature and low oxygen. Frontiers in Ecology and the Environment 2020; 18: 211-218.

Jacobsen D, Dangles O. Ecology of high altitude waters: Oxford University Press, 2017.

Jäger H, Peratoner G, Tappeiner U, Tasser E. Grassland biomass balance in the European Alps: current and future ecosystem service perspectives. Ecosystem Services 2020; 45: 101163.

Kagami M, Miki T, Takimoto G. Mycoloop: chytrids in aquatic food webs. Frontiers in microbiology 2014; 5: 166.

Kammerlander B, Breiner H-W, Filker S, Sommaruga R, Sonntag B, Stoeck T. High diversity of protistan plankton communities in remote high mountain lakes in the European Alps and the Himalayan mountains. FEMS microbiology ecology 2015; 91: fiv010.

Kapnick S, Hall A. Causes of recent changes in western North American snowpack. Climate Dynamics 2012; 38: 1885-1899.

Kastner T, Matej S, Forrest M, Gingrich S, Haberl H, Hickler T, et al. Land use intensification increasingly drives the spatiotemporal patterns of the global human appropriation of net primary production in the last century. Global Change Biology 2022; 28: 307-322.

Kelty MJ. The role of species mixtures in plantation forestry. Forest Ecology and Management 2006; 233: 195-204.

Kerr JT, Deguise I. Habitat loss and the limits to endangered species recovery. Ecology Letters 2004; 7: 1163-1169.

Knapp R, Sarnelle O. Recovery after local extinction: factors affecting re-establishment of alpine lake zooplankton. Ecological Applications 2008; 18: 1850 - 1859.

Knapp RA, Matthews KR, Sarnelle O. Resistance and Resilience of Alpine Lake Fauna to Fish Introductions. Ecological Monographs 2001; 71: 401-421.

Kopáček J, Fluksová H, Hejzlar J, Kaňa J, Porcal P, Turek J. Changes in surface water chemistry caused by natural forest dieback in an unmanaged mountain catchment. Science of the Total Environment 2017; 584: 971-981.

Körner C. Mountain biodiversity, its causes and function. AMBIO: A Journal of the Human Environment 2004; 33: 11-17.

Körner C. The use of 'altitude'in ecological research. Trends in ecology & evolution 2007; 22: 569-574.

Körner C. Mountain biodiversity, its causes and function: an overview. Mountain biodiversity 2019: 3-20.

Körner C, Jetz W, Paulsen J, Payne D, Rudmann-Maurer K, Spehn EM. A global inventory of mountains for bio-geographical applications. Alpine Botany 2017; 127: 1-15.

Körner C, Paulsen J, Spehn EM. A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. Alpine Botany 2011; 121: 73-78.

Körner W, Dupouey JL, Dambrine E, Benoit M. Influence of Past Land Use on the Vegetation and Soils of Present Day Forest in the Vosges Mountains, France. Journal of Ecology 1997; 85: 351-358.

Laternser M, Schneebeli M. Long-term snow climate trends of the Swiss Alps (1931–99). International Journal of Climatology: A Journal of the Royal Meteorological Society 2003; 23: 733-750.

Latty EF, Canham CD, Marks PL. The effects of land-use history on soil properties and nutrient dynamics in northern hardwood forests of the Adirondack Mountains. Ecosystems 2004; 7: 193-207.

Laurion I, Ventura M, Catalan J, Psenner R, Sommaruga R. Attenuation of ultraviolet radiation in mountain lakes: Factors controlling the among-and within-lake variability. Limnology and Oceanography 2000; 45: 1274-1288.

Lavorel S, Grigulis K, Leitinger G, Kohler M, Schirpke U, Tappeiner U. Historical trajectories in land use pattern and grassland ecosystem services in two European alpine landscapes. Regional Environmental Change 2017; 17: 2251-2264.

Le Roux G, Hansson SV, Claustres A. Inorganic chemistry in the mountain critical zone: are the mountain water towers of contemporary society under threat by trace contaminants? Developments in Earth Surface Processes. 21. Elsevier, 2016, pp. 131-154.

Le Roux G, Hansson SV, Claustres A, Binet S, De Vleeschouwer F, Gandois L, et al. Trace Metal Legacy in Mountain Environments. Biogeochemical Cycles, 2020, pp. 191-206.

Lei YD, Wania F. Is rain or snow a more efficient scavenger of organic chemicals? Atmospheric Environment 2004; 38: 3557-3571.

Lenton TM. Early warning of climate tipping points. Nature Climate Change 2011; 1: 201-209.

Lerner H, Berg C. A Comparison of Three Holistic Approaches to Health: One Health, EcoHealth, and Planetary Health. Frontiers in Veterinary Science 2017; 4.

Lin Y-P, Chen C-J, Lien W-Y, Chang W-H, Petway J, Chiang L. Landscape Conservation Planning to Sustain Ecosystem Services under Climate Change. Sustainability 2019; 11: 1393.

Lin Y-P, Wunderlich RF, Lin C-M, Uphoff N, Schmeller DS, Shipin OV, et al. Topsoil microbial community structure responds to land cover type and environmental zone in the Western Pacific region. Science of The Total Environment 2021; 764: 144349.

Lin YP, Lin W-C, Wang Y-C, Lien W-Y, Huang TH, Hsu CC, et al. Systematically designating conservation areas for protecting multiple ecosystem services. Environmental Modelling & Software 2017; 90: 126-146.

Liu H, Mi Z, Lin L, Wang Y, Zhang Z, Zhang F, et al. Shifting plant species composition in response to climate change stabilizes grassland primary production. Proceedings of the National Academy of Sciences 2018; 115: 4051-4056.

Liu X, Dou L, Ding X, Sun T, Zhang H. Influences of different afforestation systems on the soil properties of limestone mountains in the mid-eastern region of China. Catena 2021; 201: 105198.

López-Moreno JI, Beniston M, García-Ruiz JM. Environmental change and water management in the Pyrenees: Facts and future perspectives for Mediterranean mountains. Global and Planetary Change 2008; 61: 300-312.

Lundgren B. Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands: Swedish University of Agricultural Sciences, 1978.

Machate O, Schmeller DS, Loyau A, Paschke A, Krauss M, Carmona E, et al. Complex chemical cocktail, containing insecticides diazinon and permethrin, drives acute toxicity to crustaceans in mountain lakes. Science of The Total Environment 2022: 154456.

Martín-López B, Leister I, Lorenzo Cruz P, Palomo I, Grêt-Regamey A, Harrison PA, et al. Nature's contributions to people in mountains: a review. PloS one 2019; 14: e0217847.

Maxwell SL, Fuller RA, Brooks TM, Watson JEM. Biodiversity: The ravages of guns, nets and bulldozers. Nature 2016; 536: 143-145.

Mayer A, Egger C, Loyau A, Plutzar C, Schmeller DS, Gaube V. Mountain pastures increase the resilience of livestock farming to extreme events in the Ariège department, France. Agronomy for Sustainable Development 2022; 42: 49.

Mayerhofer J, Wächter D, Calanca P, Kohli L, Roth T, Meuli RG, et al. Environmental and Anthropogenic Factors Shape Major Bacterial Community Types Across the Complex Mountain Landscape of Switzerland. Frontiers in Microbiology 2021; 12: 500.

McCain CM, Colwell RK. Assessing the threat to montane biodiversity from discordant shifts in temperature and precipitation in a changing climate. Ecology letters 2011; 14: 1236-1245.

McCullough IM, Davis FW, Dingman JR, Flint LE, Flint AL, Serra-Diaz JM, et al. High and dry: high elevations disproportionately exposed to regional climate change in Mediterranean-climate landscapes. Landscape Ecology 2016; 31: 1063-1075.

Meadows DH, Meadows DL, Randers J, Behrens III WW. The limits to growth: a report to the club of Rome (1972). New York,Washington, DC (USA): Universe Books, Potomac Associates, 1972.

Meire RO, Lee SC, Yao Y, Targino AC, Torres JPM, Harner T. Seasonal and altitudinal variations of legacy and current-use pesticides in the Brazilian tropical and subtropical mountains. Atmospheric Environment 2012; 59: 108-116.

Melillo JM, McGuire AD, Kicklighter DW, Moore B, Vorosmarty CJ, Schloss AL. Global climate change and terrestrial net primary production. Nature 1993; 363: 234-240.

Milner AM, Khamis K, Battin TJ, Brittain JE, Barrand NE, Füreder L, et al. Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences 2017; 114: 9770-9778.

Miró A, Ventura M. Evidence of exotic trout mediated minnow invasion in Pyrenean high mountain lakes. Biological Invasions 2015; 17: 791-803.

Miró A, Ventura M. Introduced fish in Pyrenean high mountain lakes: impact on amphibians and other organisms, and conservation implications. Limnetica 2020; 39: 283-297.

Mölg T, Hardy DR, Cullen NJ, Kaser G. Tropical glaciers, climate change, and society. Darkening peaks: Glacier retreat, science, and society 2008: 168-182.

Moser KA, Baron JS, Brahney J, Oleksy IA, Saros JE, Hundey EJ, et al. Mountain lakes: Eyes on global environmental change. Global and Planetary Change 2019; 178: 77-95.

Moulin C, Chiapello I. Impact of human-induced desertification on the intensification of Sahel dust emission and export over the last decades. Geophysical Research Letters 2006; 33: L18808.

Myhre G, Alterskjær K, Stjern CW, Hodnebrog Ø, Marelle L, Samset BH, et al. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 2019; 9: 16063.

Negi VS, Tiwari DC, Singh L, Thakur S, Bhatt ID. Review and synthesis of climate change studies in the Himalayan region. Environment, Development and Sustainability 2021.

Niedertscheider M, Tasser E, Patek M, Rüdisser J, Tappeiner U, Erb K-H. Influence of Land-Use Intensification on Vegetation C-Stocks in an Alpine Valley from 1865 to 2003. Ecosystems 2017; 20: 1391-1406.

Niedrist G, Psenner R, Sommaruga R. Climate warming increases vertical and seasonal water temperature differences and inter-annual variability in a mountain lake. Climatic Change 2018; 151: 473-490.

Niedrist GH, Füreder L. Real-time warming of alpine streams:(Re) defining invertebrates' temperature preferences. River Research and Applications 2021; 37: 283-293.

Nielsen DL, Smith D, Petrie R. Resting egg banks can facilitate recovery of zooplankton communities after extended exposure to saline conditions. Freshwater Biology 2012; 57: 1306-1314.

Niu L, Cheng Z. Impact of tourism disturbance on forest vegetation in Wutai Mountain, China. Environmental Monitoring and Assessment 2019; 191: 81.

Nodvin S, Van Miegroet H, Lindberg S, Nicholas N, Johnson D. Acidic deposition, ecosystem processes, and nitrogen saturation in a high elevation southern Appalachian watershed. Water, Air, and Soil Pollution 1995; 85: 1647-1652.

Nogues-Bravo D, Araújo MB, M.P. E, Martínez-Rica JP. Exposure of global mountain systems to climate warming during the 21st Century. Global Environmental Change 2007; 17: 420-428.

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, et al. The toxicology of climate change: environmental contaminants in a warming world. Environ Int 2009; 35: 971-86.

Obertegger U, Flaim G. A 40-year perspective of an alpine lake: Is everything the same? Limnologica 2021; 91: 125929.

Palomo I. Climate change impacts on ecosystem services in high mountain areas: a literature review. Mountain Research and Development 2017; 37: 179-187.

Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature 2003; 421: 37-42.

Pauchard A, Kueffer C, Dietz H, Daehler CC, Alexander J, Edwards PJ, et al. Ain't no mountain high enough: plant invasions reaching new elevations. Frontiers in Ecology and the Environment 2009; 7: 479-486.

Payne D, Spehn EM, Prescott GW, Geschke J, Snethlage MA, Fischer M. Mountain Biodiversity Is Central to Sustainable Development in Mountains and Beyond. One earth 2020; 3: 530-533.

Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen I-C, et al. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 2017; 355: eaai9214.

Pepin N, Bradley RS, Diaz H, Baraër M, Caceres E, Forsythe N, et al. Elevation-dependent warming in mountain regions of the world. Nature climate change 2015; 5: 424-430.

Pepin N, Lundquist J. Temperature trends at high elevations: patterns across the globe. Geophysical Research Letters 2008; 35.

Pimm SL. Biodiversity: Climate change or habitat loss - Which will kill more species? Current Biology 2008; 18: R117-R119.

Pozo K, Urrutia R, Barra R, Mariottini M, Treutler H-C, Araneda A, et al. Records of polychlorinated biphenyls (PCBs) in sediments of four remote Chilean Andean Lakes. Chemosphere 2007; 66: 1911-1921.

Purcell AM, Hayer M, Koch BJ, Mau RL, Blazewicz SJ, Dijkstra P, et al. Decreased growth of wild soil microbes after 15 years of transplant-induced warming in a montane meadow. Global Change Biology 2022; 28: 128-139.

Ragettli S, Tong X, Zhang G, Wang H, Zhang P, Stähli M. Climate change impacts on summer flood frequencies in two mountainous catchments in China and Switzerland. Hydrology Research 2021; 52: 4-25.

Rahbek C, Borregaard MK, Antonelli A, Colwell RK, Holt BG, Nogues-Bravo D, et al. Building mountain biodiversity: Geological and evolutionary processes. Science 2019a; 365: 1114-1119.

Rahbek C, Borregaard MK, Colwell RK, Dalsgaard B, Holt BG, Morueta-Holme N, et al. Humboldt's enigma: What causes global patterns of mountain biodiversity? Science 2019b; 365: 1108-1113.

Rajczak J, Schär C. Projections of future precipitation extremes over Europe: A multimodel assessment of climate simulations. Journal of Geophysical Research: Atmospheres 2017; 122: 10,773-10,800.

Rangwala I, Miller JR. Climate change in mountains: a review of elevation-dependent warming and its possible causes. Climatic change 2012; 114: 527-547.

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, et al. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 2019; 94: 849-873.

Ripple W, J., Estes J, A., Beschta R, L., Wilmers C, C., Ritchie E, G., Hebblewhite M, et al. Status and Ecological Effects of the World's Largest Carnivores. Science 2014; 343: 1241484.

Ripple WJ, Newsome TM, Wolf C, Dirzo R, Everatt KT, Galetti M, et al. Collapse of the world's largest herbivores. Science advances 2015; 1: e1400103.

Ripple WJ, Wolf C, Newsome TM, Galetti M, Alamgir M, Crist E, et al. World Scientists' Warning to Humanity: A Second Notice. BioScience 2017: bix125-bix125.

Ripple WJ, Wolf C, Newsome TM, Gregg JW, Lenton TM, Palomo I, et al. World Scientists' Warning of a Climate Emergency 2021. BioScience 2021.

Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, et al. A safe operating space for humanity. Nature 2009; 461: 472-475.

Rodway-Dyer S, Ellis N. Combining remote sensing and on-site monitoring methods to investigate footpath erosion within a popular recreational heathland environment. Journal of Environmental Management 2018; 215: 68-78.

Roe GH. Orographic precipitation. Annu. Rev. Earth Planet. Sci. 2005; 33: 645-671.

Rose KC, Williamson CE, Saros JE, Sommaruga R, Fischer JM. Differences in UV transparency and thermal structure between alpine and subalpine lakes: implications for organisms. Photochemical & Photobiological Sciences 2009; 8: 1244-1256.

Saunders DL, Kalff J. Nitrogen retention in wetlands, lakes and rivers. Hydrobiologia 2001; 443: 205-212.

Scarano FR. Biodiversity Sector: Risks of Temperature Increase to Biodiversity and Ecosystems. In: Nobre CA, Marengo JA, Soares WR, editors. Climate Change Risks in Brazil. Springer International Publishing, Cham, 2019, pp. 131-141.

Schabetsberger R, Kaiser R, Rott E, Lenzenweger R, Traunspurger W, Kotov AA, et al. On the brink – investigating biodiversity in endangered crater lakes of the Amber Mountains National Park (Madagascar). Aquatic Conservation: Marine and Freshwater Ecosystems 2013; 23: 316-331.

Schai-Braun SC, Jenny H, Ruf T, Hackländer K. Temperature increase and frost decrease driving upslope elevational range shifts in Alpine grouse and hares. Global Change Biology 2021; 27: 6602-6614.

Schindler DE, Knapp RA, Leavitt PR. Alteration of Nutrient Cycles and Algal Production Resulting from Fish Introductions intoMountain Lakes. Ecosystems 2001; 4: 308-321.

Schirpke U, Tappeiner U, Tasser E. A transnational perspective of global and regional ecosystem service flows from and to mountain regions. Scientific reports 2019; 9: 1-11.

Schmeller DS, Bridgewater P. The eighth plenary of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES-8): online, nexus, and transformative change. Biodiversity and Conservation 2021; 33: 2857-2862.

Schmeller DS, Courchamp F, Killeen G. Biodiversity loss, emerging pathogens and human health risks. Biodiversity and Conservation 2020: 3095–3102.

Schmeller DS, Loyau A, Bao K, Brack W, Chatzinotas A, De Vleeschouwer F, et al. People, pollution and pathogens – Global change impacts in mountain freshwater ecosystems. Science of The Total Environment 2018; 622-623: 756-763.

Schmeller DS, Niemelä J, Bridgewater P. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES): getting involved. Biodiversity and Conservation 2017; 26: 2271-2275.

Scientists UoC. World scientists' Warning to Humanity. Union of Concerned Scientists, http://www.ucsusa.org/sites/default/files/attach/2017/11/World%20Scientists%27%20Warning%20to%20Humanity%201992, 1992.

Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, et al. Projecting the continental accumulation of alien species through to 2050. Global Change Biology 2021; 27: 970-982.

Sentenac H, Loyau A, Leflaive J, Schmeller DS. The significance of biofilms to human, animal, plant and ecosystem health. Functional Ecology 2022; 33: 294 - 313.

Shijin W, Dahe Q. Mountain inhabitants' perspectives on climate change, and its impacts and adaptation based on temporal and spatial characteristics analysis: a case study of Mt. Yulong Snow, Southeastern Tibetan Plateau. Environmental Hazards 2015; 14: 122-136.

Shunthirasingham C, Oyiliagu CE, Cao X, Gouin T, Wania F, Lee S-C, et al. Spatial and temporal pattern of pesticides in the global atmosphere. Journal of Environmental Monitoring 2010; 12: 1650-1657.

Silva V, Montanarella L, Jones A, Fernández-Ugalde O, Mol HG, Ritsema CJ, et al. Distribution of glyphosate and aminomethylphosphonic acid (AMPA) in agricultural topsoils of the European Union. Science of the Total Environment 2018; 621: 1352-1359.

Siraj A, Santos-Vega M, Bouma M, Yadeta D, Carrascal DR, Pascual M. Altitudinal changes in malaria incidence in highlands of Ethiopia and Colombia. Science 2014; 343: 1154-1158.

Small ST, Labbé F, Coulibaly YI, Nutman TB, King CL, Serre D, et al. Human migration and the spread of the nematode parasite Wuchereria bancrofti. Molecular biology and evolution 2019; 36: 1931-1941.

Sommaruga R. The role of solar UV radiation in the ecology of alpine lakes. Journal of Photochemistry and Photobiology B: Biology 2001; 62: 35-42.

Sommaruga R. When glaciers and ice sheets melt: consequences for planktonic organisms. Journal of plankton research 2015; 37: 509-518.

Sommaruga R, Sattler B, Oberleiter A, Wille A, Wögrath-Sommaruga S, Psenner R, et al. An in situ enclosure experiment to test the solar UVB impact on plankton in a high-altitude mountain lake. II. Effects on the microbial food web. Journal of Plankton Research 1999; 21.

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary boundaries: Guiding human development on a changing planet. Science 2015; 347.

Steinbauer MJ, Grytnes J-A, Jurasinski G, Kulonen A, Lenoir J, Pauli H, et al. Accelerated increase in plant species richness on mountain summits is linked to warming. Nature 2018; 556: 231-234.

Stephan R, Erfurt M, Terzi S, Žun M, Kristan B, Haslinger K, et al. An inventory of Alpine drought impact reports to explore past droughts in a mountain region. Nat. Hazards Earth Syst. Sci. 2021; 21: 2485-2501.

Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, et al. Drought, Tree Mortality, and Wildfire in Forests Adapted to Frequent Fire. BioScience 2018; 68: 77-88.

Sultan B, Labadi K, Guégan J-F, Janicot S. Climate drives the meningitis epidemics onset in West Africa. PLoS medicine 2005; 2: e6.

Swanson F, Kratz T, Caine N, Woodmansee R. Landform effects on ecosystem patterns and processes. BioScience 1988; 38: 92-98.

Tasser E, Tappeiner U. Impact of land use changes on mountain vegetation. Applied Vegetation Science 2002; 5: 173-184.

Tegen I, Werner M, Harrison S, Kohfeld K. Relative importance of climate and land use in determining present and future global soil dust emission. Geophysical Research Letters 2004; 31: L05105.

Temme AJ. Using climber's guidebooks to assess rock fall patterns over large spatial and decadal temporal scales: an example from the swiss alps. Geografiska Annaler: Series A, Physical Geography 2015; 97: 793-807.

Tiberti R, Bogliani G, Brighenti S, Iacobuzio R, Liautaud K, Rolla M, et al. Recovery of high mountain Alpine lakes after the eradication of introduced brook trout Salvelinus fontinalis using non-chemical methods. Biological invasions 2019; 21: 875-894.

Tiberti R, von Hardenberg A, Bogliani G. Ecological impact of introduced fish in high altitude lakes: a case of study from the European Alps. Hydrobiologia 2014; 724: 1-19.

Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, et al. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. BioScience 2020; 70: 330-342.

Trisos CH, Merow C, Pigot AL. The projected timing of abrupt ecological disruption from climate change. Nature 2020; 580: 496-501.

Turner B, Clark W, Kates R, Richards J, Mathews J. The earth as transformed by human action: global and regional changes in the biosphere over the past 300 years. 1990.

United Nations Environment Programme A Scientific Assessment of the Third Pole Environment, Nairobi, 2022.

Urrutia R, Vuille M. Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century. Journal of Geophysical Research: Atmospheres 2009; 114.

Vadeboncoeur Y, Peterson G, Vander Zanden MJ, Kalff J. Benthic algal production across lake size gradients: interactions among morphometry, nutrients, and light. Ecology 2008; 89: 2542-2552.

Valbuena-Ureña E, Oromi N, Soler-Membrives A, Carranza S, Amat F, Camarasa S, et al. Jailed in the mountains: Genetic diversity and structure of an endemic newt species across the Pyrenees. PLOS ONE 2018; 13: e0200214.

Valdivia C, Thibeault J, Gilles JL, García M, Seth A. Climate trends and projections for the Andean Altiplano and strategies for adaptation. Adv. Geosci. 2013; 33: 69-77.

van Wilgen BW. Evidence, Perceptions, and Trade-offs Associated with Invasive Alien Plant Control in the Table Mountain National Park, South Africa. Ecology and Society 2012; 17.

van Wilgen BW, Richardson DM. Three centuries of managing introduced conifers in South Africa: Benefits, impacts, changing perceptions and conflict resolution. Journal of Environmental Management 2012; 106: 56-68.

Ventura M, Tiberti R, Buchaca T, Buñay D, Sabás I, Miró A. Why should we preserve fishless high mountain lakes? In: Catalan J, Ninot JM, Aniz M, editors. High mountain conservation in a changing world. Springer, Cham, 2017, pp. 181-205.

Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resources Research 2007; 43.

Viviroli D, Kummu M, Meybeck M, Kallio M, Wada Y. Increasing dependence of lowland populations on mountain water resources. Nature Sustainability 2020; 3: 917-928.

Vuille M, Carey M, Huggel C, Buytaert W, Rabatel A, Jacobsen D, et al. Rapid decline of snow and ice in the tropical Andes–Impacts, uncertainties and challenges ahead. Earth-Science Reviews 2018; 176: 195-213.

Wania F, Mackay D. Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions. Ambio 1993; 22: 10-18.

Watermann LY, Hock M, Blake C, Erfmeier A. Plant invasion into high elevations implies adaptation to high UV-B environments: a multi-species experiment. Biological Invasions 2020; 22: 1203-1218.

Werner CM, Harrison SP, Safford HD, Bohlman GN, Serata R. Extreme pre-fire drought decreases shrub regeneration on fertile soils. Ecological Applications 2022; 32: e02464.

Wester P, Mishra A, Mukherji A, Shrestha AB. The Hindu Kush Himalaya assessment: mountains, climate change, sustainability and people: Springer Nature, 2019.

Yan D, Zhang T, Su J, Zhao L-L, Wang H, Fang X-M, et al. Diversity and composition of airborne fungal community associated with particulate matters in Beijing during haze and non-haze days. Frontiers in microbiology 2016; 7: 487.

Yang H, Engstrom DR, Rose NL. Recent changes in atmospheric mercury deposition recorded in the sediments of remote equatorial lakes in the Rwenzori Mountains, Uganda. Environmental science & technology 2010; 44: 6570-6575.

Zanchett G, Oliveira-Filho EC. Cyanobacteria and cyanotoxins: from impacts on aquatic ecosystems and human health to anticarcinogenic effects. Toxins 2013; 5: 1896-1917.

Zemp M, Frey H, Gärtner-Roer I, Nussbaumer SU, Hoelzle M, Paul F, et al. Historically unprecedented global glacier decline in the early 21st century. Journal of glaciology 2015; 61: 745-762.

Zhang J-T, Xiang C, Li M. Effects of Tourism and Topography on Vegetation Diversity in the Subalpine Meadows of the Dongling Mountains of Beijing, China. Environmental Management 2012; 49: 403-411.

Zuecco G, Penna D, Borga M. Runoff generation in mountain catchments: long-term hydrological monitoring in the Rio Vauz Catchment, Italy. Cuadernos de investigación geográfica/Geographical Research Letters 2018: 397-428.