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Scientists' Warning of Threats to Mountains

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54 **Abstract**

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

75

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

78

79 **Main text**

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

111 Mountains cover a large part of the Earth's terrestrial surface and host a larger proportion
112 of biodiversity than expected by area (Körner et al., 2011). They hold an estimated one-third of

113 terrestrial species diversity (Körner, 2004), and represent 18 of the 36 global biodiversity
114 hotspots (Chape et al., 2005). Nevertheless, even in remote areas human impact is strong, as
115 mountains are part of the global socio-ecological systems which have been shaped by
116 geological forces and by human activities (Turner et al., 1990). In mountains, these impacts and
117 the resulting threats remain largely understudied (Schmeller et al., 2018). Generally, people are
118 unaware of the threats to mountain ecosystems and the services mountains provide to humanity.
119 Mountain ecosystems sequester CO₂, clean waters and the air, regulate climate, provide
120 biomedical resources, and regulate floods (Martín-López et al., 2019). Mountains also provide
121 for the livelihoods of more than half of humanity (Grêt-Regamey et al., 2012; Grêt-Regamey and
122 Weibel, 2020). All these goods and services are provided by mountain ecosystems through
123 complex processes that are maintained by communities of species interacting with each other
124 and with the abiotic environment (Bestion et al., 2021). These mountain communities are
125 comprised of prokaryotic and eukaryotic microbes, fungi, plankton species, woody and non-
126 woody plants, as well as invertebrates and vertebrates. By destructing, rebuilding, changing, and
127 shaping the environment, these species produce organic matter and oxygen as well as bind
128 CO₂.

129 The mountain environment is characterized by extreme temperature regimes, severe
130 weather events and short growing seasons at high altitudes to which species have adapted
131 (Körner, 2019; Payne et al., 2020). In temperate mountains, comparably few species have been
132 able to widely colonize the diverse habitats with montane conditions during the short time
133 window given by the recent demise of glaciers at the end of the last glacial period about 11,000
134 years ago (McCain and Colwell, 2011; Schabetsberger et al., 2013; Valbuena-Ureña et al.,
135 2018). Mountain ecosystems have evolved in partial isolation, separated by a variety of
136 biogeographic barriers. The gradients and dynamics in climate, hydrology, and water chemistry
137 contributed to the formation of a high diversity of microhabitats, harboring numerous species in
138 comparably small areas (McCain and Colwell, 2011), which also explains the high levels of
139 endemism detected in mountains (Rahbek et al., 2019a; b; Swanson et al., 1988). With
140 increasing elevation, montane climates become more extreme, providing habitat for fewer
141 species. System redundancies (i.e. different species with similar functions), available in
142 ecosystems at low altitudes, are increasingly scarce in mountain ecosystems with increasing
143 elevation. Such redundancies usually provide stability to ecosystems (Fonseca and Ganade,
144 2001). The absence of these redundancies renders mountain ecosystem particularly vulnerable
145 to the impacts of global change (Moser et al., 2019). However, multiple threats to mountains are
146 arising from climate change alone. Moreover, interactions with socio-cultural, economic and

147 political developments, such as the exploitation of mountains, e.g. for timber, food production,
148 including fish and livestock, tourism, and hydro-electricity, exacerbate these threats, calling for
149 urgent consideration by policymakers (Figure 1).

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

161 **Climate Change in Mountains**

162 Mountains are defined by rugged terrain and unique climate regimes distinguishing them
163 from lowlands (Körner et al., 2017). The climatic complexity created by mountain topography
164 also influences insolation and air circulation (Dobrowski et al., 2009). Elevation gradients in
165 particular, have a strong impact on many abiotic variables in mountains, and their geographic
166 location is the main control on moisture gradients or seasonality in climate (Körner, 2007). On a
167 regional scale, mountain climate is influenced by large-scale synoptic patterns, proximity to
168 oceans, and the range's longitudinal or latitudinal orientation (Del Barrio et al., 1990). In synergy
169 with climate change impacts, we see important changes in precipitations, temperatures, and
170 frequency of extreme events, such as droughts and floods. Therefore, climate change might be
171 considered the most basic and far-reaching threat to mountains, impacting mountain biodiversity
172 and ecosystems way more intensively as compared to lowland regions (Rangwala and Miller,
173 2012; Scarano, 2019).

174 Precipitation dynamics are not the same in all mountains, and for example, mountains in
175 tropical regions show precipitation maxima at lower and mid-elevations. Temperate mountains
176 typically have an orographic effect and show increased precipitation towards the top, largely
177 driven by different seasonal dynamics in precipitation intensity (Roe, 2005). These precipitation
178 regimes are also regulated by geology, soils, vegetation, and human land use, leading to a large
179 variety of hydrological behaviors and stream flow regimes in global mountain catchments
180 (Dierauer et al., 2018; Zuecco et al., 2018). Climate change-driven precipitation regimes and

181 their increasing variability, especially in mountains, determine long-term change on soil moisture
182 conditions and are important controls on water levels and on the hydroperiods of shallow lakes,
183 ponds and wetlands (Catalan and Bartumeus, 2006; Stephan et al., 2021). As such they are
184 particularly important variables for mountain habitats. Climate change will increase the
185 unpredictability of precipitation patterns (Myhre et al., 2019). Generally, water availability and its
186 predictability is expected to decrease in the future due to lower water storage capacities in areas
187 with glacier cover and higher outflows of excess water during periods of extreme precipitation
188 and melting events (Rajczak and Schär, 2017). These changes will jeopardize the role of
189 mountains as global water towers and the drinking water supply for billions of people (Viviroli et
190 al., 2007) as well as for plants and animals.

191 Trends in warming of mountain surface air temperatures become more and more
192 apparent (López-Moreno et al., 2008; Niedrist et al., 2018; Niedrist and Füreder, 2021), and
193 high-latitude mountains are projected to warm much faster than temperate and tropical
194 mountains (Negi et al., 2021; Nogues-Bravo et al., 2007). Further, warming is accentuated at
195 higher altitudes (Pepin et al., 2015). The intensity of warming depends on the mountain climatic
196 zone, elevation and season (Pepin and Lundquist, 2008). In the Alps, the mean annual
197 temperature has already increased by 1.5 - 2°C since 1970, and future projections predict an
198 additional rise of 0.25 - 0.36 °C per decade within the next century (Einhorn et al., 2015). Similar
199 increases have been projected in other mountain ranges (Urrutia and Vuille, 2009; Valdivia et
200 al., 2013). Increasing temperatures have decreased the annual snow deposition volume with
201 most impacts observed at mid- and lower elevations (Laternser and Schneebeli, 2003), has
202 caused important shifts to earlier snow melt (Kapnick and Hall, 2012), earlier lake-ice melt
203 (Franssen and Scherrer, 2008), and globally accelerated the deglaciation process (Zemp et al.,
204 2015). Yearly, world-wide cumulative glacier mass balance data have been showing significant
205 decreasing trends in glacier thickness (Ripple et al., 2021). The shorter period of snow cover will
206 therefore also shorten the time during which the Albedo effect is active and during which 85% to
207 90% of sunlight is reflected. Hence, further acceleration of the temperature rise in alpine
208 mountain regions needs to be expected. Droughts and extreme precipitation events will globally
209 increase in mountains (Gobiet et al., 2014; Urrutia and Vuille, 2009; Valdivia et al., 2013). For
210 the European Alps, climate projections predict more summer droughts and more extreme rainfall
211 events (Rajczak and Schär, 2017). Subtropical mountains tend to experience more frequent
212 summer droughts (McCullough et al., 2016), while for example the Hindu Kush and the Himalaya
213 have been experiencing increased amounts of extreme rainfall events (Hartmann and Andresky,
214 2013; Wester et al., 2019). Droughts in mountains also lead to an increase of the probability of

215 wildfires in mountain grasslands and forest as the probability of ignition of dry plant material by
216 lightning increases (Stephens et al., 2018). Such wildfires are difficult to extinguish due to the
217 difficult terrain and result in the loss of very large areas (i.e. thousands of hectare) of mountain
218 vegetation with large and long-lasting effects on mountain ecosystems due to low pre-fire
219 production of seeds due to drought and the generally low recovery speed with increasing altitude
220 (Werner et al., 2022).

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

243 Generally, decreasing amounts of annual snow and retreating glaciers have been and
244 will continue to profoundly reshape mountain freshwater habitats and also the terrestrial
245 communities depending on them, threatening mountain species and communities (Jacobsen and
246 Dangles, 2017; Sommaruga, 2015), but also providing new habitats for colonization (Ficetola et
247 al., 2021). Impacts on lowland human populations include difficult to predict water supply (Huss
248 et al., 2017; Viviroli et al., 2007) and destruction of infrastructure through more frequent extreme

249 floods and/or landslides. Climate change will drive the disappearance of many intermediate and
250 ephemeral habitats in mountains due to droughts, with potential severe consequences for
251 mountain biodiversity and biological processes e.g. carbon storage. Climate change will also
252 impact the water regime of many peatlands. Due to the importance of mountain peat- and
253 wetlands as global carbon sinks, the loss of these habitats may further accentuate climate
254 change (De Jong et al., 2010) and UVR impacts (Barnes et al. 2019).

255 **Pollutants in Mountains**

256 Sources of pollution are manifold in mountain ecosystems (Lei and Wania, 2004; Noyes
257 et al., 2009; Shunthirasingham et al., 2010) and we generally lack a global approach to observe
258 environmental pollution and its impact (Brack et al., 2022). Global atmospheric transport of
259 micropollutants (Hussain et al., 2019; Wania and Mackay, 1993; Yang et al., 2010) and local
260 human activities such as mining, logging, agriculture, pastoralism and tourism are the main
261 pollution sources in mountain environments. Increasing pastoralism and livestock units have
262 been shown to put the health of mountain lakes at risk by introducing highly toxic organic
263 pollutants into mountain lakes (Machate et al., 2022). Further, fish stocking introduced heavy
264 metals such as mercury in mountain ecosystems (Hansson et al., 2017b). Other sources of
265 pollution include extreme weather events releasing legacy pollutants from mining, tourists
266 introducing UV blockers as part of personal care products, and atmospheric transport of
267 pollutants releasing a plethora of different molecules (Gross, 2022; Le Roux et al., 2020; Pozo et
268 al., 2007). Mountains are also at risk of acidification when they are located downwind of Nitrogen
269 or Sulphur emission sources and buffering capacity of freshwater is low. In addition, seasonal
270 events such as snowmelt can change pH up to a full unit (Nodvin et al., 1995). Acidic pulses
271 may co-occur with spikes of toxic element concentrations in water (Havas and Rosseland,
272 1995). Further, higher rates of erosion and weathering, as a result of more frequent events of
273 heavy precipitation, may also lead to a higher import of base cations and increase the pH of
274 mountain freshwater and soil (Kopáček et al., 2017). Finally, global change-driven eutrophication
275 and elevated temperatures lead to an increased growth of cyanobacteria, which can produce
276 toxins (e.g. cyanotoxins), with known negative impacts on human health (Catherine et al., 2013;
277 Funari and Testai, 2008; Zanchett and Oliveira-Filho, 2013).

278 The scavenging of atmospheric organic and inorganic pollutants is pronounced at high
279 altitudes and can take the form of dry and wet deposition of aerosols to the ground surface (Daly
280 and Wania, 2005; Le Roux et al., 2016; Le Roux et al., 2020). Atmospheric pollutants in
281 mountains include trace elements (Camarero et al., 2009) (Yang et al., 2010), organic and

282 synthetic pollutants (i.e. current-use and legacy pesticides), polycyclic aromatic hydrocarbons
283 (PAHs), endocrine disrupting compounds (EDCs; Rockström et al., 2009; Meire et al., 2012),
284 and polychlorinated biphenyls (PCBs) or microplastics (Allen et al., 2019; Brahney et al., 2020;
285 Reid et al., 2019). These compounds are introduced into the atmosphere via evaporation, or
286 binding to particles light enough to be carried by wind. Volatile compounds tend to evaporate in
287 warmer environments at lower altitudes and condensation progressively takes place with
288 decreasing temperature as air masses travel over mountain slopes (Blais et al., 1998). Less
289 volatile compounds, such as most of the currently used agricultural pesticides, are not prone to
290 directly evaporate into the atmosphere, but are still transported into the mountain environment
291 as they bind to soil particles, which can be uplifted and carried over longer distance during more
292 extreme wind events (Silva et al., 2018). As a consequence, organic and inorganic
293 micropollutants can be introduced to mountains via the atmosphere and over long distances
294 (Camarero et al., 2009; Bradford et al., 2010; 2013; Fig. 2).

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

305 Despite the accumulated knowledge on global pollution, we still know little about the toxic
306 cocktail accumulating in mountains and its impact on biodiversity (but see Catalan, 2015). There
307 are very few studies that analyzed a broad set of pollutants or even conduct non-target
308 monitoring in a mountain context (Machate et al., 2022), rendering our current knowledge on
309 global mountain pollution patterns largely incomplete. We also know little about each
310 (detectable) compound's physico-chemical characteristics, e.g. the water-air constant (K_{wa}),
311 without which it is difficult to make predictions on future pollution patterns in mountains.
312 Generally, the introduction of new pollutants and changes in pollutant mobilization due to climate
313 change may challenge mountain ecosystem health and increase the vulnerability of species and
314 humans to pathogens, increasing health risks (Brack et al., 2022; Schmeller et al., 2020; 2018).
315 Concerns about adverse toxic effects have especially been raised about, but are not limited to,

316 pollutants introduced from local activities (Machate et al., 2022). In the future, these health risks
317 might further increase, by shifting e.g. pastures to higher altitudes (Mayer et al., 2022), where
318 ecosystems are already under high pressures due to climate change (Herzog and Seidl, 2018)).
319 Tourism and expansion of infrastructure create yet additional pressures on mountain
320 biodiversity.

321 **Vegetation and land use changes in Mountains**

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

349 **Introduced species in mountains**

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

358 For example, tourism drives fish stocking of naturally fishless lakes. In such naturally
359 fishless mountain lakes fish introductions have an outsized impact and drive profound ecological
360 change as a highly efficient aquatic predator is introduced in a naïve environment (Miró and
361 Ventura, 2020). Stocking montane lakes with fish for subsistence purposes has been occurring
362 since the Neolithic, through fish translocations from nearby lakes and rivers. However, before
363 1950 such introductions had limited geographic extent and their impacts were rather local
364 (Moser et al., 2019). Since 1950, introductions of fish increased dramatically as a consequence
365 of the increasing popularity of recreational angling, both in large and relatively small lakes as
366 well as in adjacent wetlands (Hansson et al., 2017b). In addition, the use of small fish, mainly
367 minnows *Phoxinus* sp. (Fam. Cyprinidae), as live baits for trout fishing is causing a new and
368 detrimental wave of invasion (Miró and Ventura, 2015). These introduced fish dramatically affect
369 native communities of mountain lakes. Initially considered ecologically harmless and
370 economically beneficial, introductions continued even when their serious ecological
371 consequences became clear (Knapp et al., 2001). Supported by institutional stocking campaigns
372 and non-authorized translocations by anglers, fish spread rapidly in mountain deep-ponds and
373 lakes of all sizes, as well as in all the colonizable downstream habitats (Ventura et al., 2017),
374 with a long list of negative impacts: i) decline/elimination of native species (e.g., invertebrates
375 and amphibians; (Knapp et al., 2001; Tiberti et al., 2014); ii) cascading effects in the trophic
376 network (Schindler et al., 2001), affecting the chemical/microbiological quality of waters, and the
377 ecological linkages with surrounding terrestrial habitats (Epanchin et al., 2010); iii) impacts such
378 as predation, competition, transmission of pathogens and hybridization on native fish inhabiting
379 downstream habitats (Adams et al., 2001), and iv) further collateral introductions of fish used as
380 live bait (Miró and Ventura, 2015). Hence, fish stocking in mountain lakes is particularly
381 detrimental to water quality and biodiversity, especially as now nearly all these ecosystems are

382 affected, including large lakes, small lakes, ponds, connecting streams and their adjacent
383 mountain wetlands (Ventura et al., 2017).

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

401 **Water abstraction from Mountains**

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

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

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

433 **Threats to and from Mountain Micro-Biodiversity**

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

444 Despite their small size, microbial communities drive major processes in and on animals,
445 plants, as well as in ecosystems (Bates et al., 2022; Bernardo-Cravo et al., 2020; Lin et al.,
446 2021). In a nutrient poor environment such as mountains, microbial communities likely play an
447 important role in synthesizing vital nutrients, thereby increasing energy uptake and growth of
448 plants and animals (Bernardo-Cravo et al., 2020; Schmeller et al., 2020; Sentenac et al., 2022).
449 Similarly, micro-organisms stabilize whole ecosystems by buffering against change through the

450 maintenance of biodiversity and ecosystem processes. For example, the interactions between
451 micro-organisms and plankton constitute the basis of aquatic food webs and determine the
452 functioning of biogeochemical cycles, accounting for more than half of global carbon fixation
453 (Cavicchioli et al., 2019; Purcell et al., 2022). Any kind of disturbance to microbial communities
454 can therefore impact on mountain species and ecosystems.

455 Pathogens, and other microorganisms, can be easily introduced to mountains through
456 pastoralism, tourism or wind drift. However, we remain largely oblivious to how the complexity of
457 the abiotic and biotic environment in mountain ecosystems influences beneficial microbe-species
458 interactions (e.g. microbial loop, mycoloop; (Kagami et al., 2014), host-pathogen interactions
459 (Frenken et al., 2017; Haver et al., 2021; Fisher and Garner, 2020) and health risks for the
460 human population (Schmeller et al., 2018). For example, the transport of microbial pathogens is
461 of special concern for human and livestock health, but also for wildlife and keystone species
462 groups such as amphibians. In particular, fungi and bacteria with resistant aerosolised spores
463 are capable of long-distance transport of e.g. dust (Dadam et al., 2019; Sultan et al., 2005).
464 Global dust dispersion is a natural phenomenon, and occurs when topsoil is transported into the
465 troposphere and carried over long distances by wind currents. However, global warming and
466 changes in land use practices (e.g. deforestation and overgrazing) have accelerated
467 desertification in many areas, resulting in increased dust dispersion even to remote places
468 (Moulin and Chiapello, 2006; Tegen et al., 2004), particularly to high elevation sites (Dong et al.,
469 2020). Further anthropogenic impacts via air pollution can intensify both the abundance and
470 community composition of aerial microbes (Yan et al., 2016), but also for vector-borne diseases
471 (Caminade et al., 2019): Malaria has been found at higher altitudes in mountains in Ethiopia and
472 Colombia (Siraj et al., 2014), incidences of Malaria and Dengue are increasing in Nepal's
473 mountains (Dhimal et al., 2015a), altitudinal upward shifts of Dengue and Chikungunya (Dhimal
474 et al., 2015b), and also ticks have been reported, the latter e.g. leading to increased occurrence
475 of Lyme borreliosis in the Alps (Garcia-Vozmediano et al., 2020).

476 Recent data also suggest that we currently see an increase in eutrophication of mountain
477 lakes globally with an upsurge of the diversity of Cyanobacteria (Ho et al., 2019). Cyanobacteria
478 produce a range of toxins (e.g. microcystins, cyanotoxins, Catherine et al., 2013), which have an
479 important impact on the quality of water (Du et al., 2019; Ho et al., 2019), therewith increasing
480 risks of intoxications for humans and livestock. Epilithic biofilms are a highly reactive component
481 in freshwater systems that play a crucial role in the provision of many ecosystem services
482 (Catalan and Donato Rondon, 2016). Especially in smaller mountain lakes, streams and other
483 waterbodies, epilithic biofilms must be considered the major player in carbon cycling and

484 ecosystem productivity (Vadeboncoeur et al., 2008). A better understanding of the risks of
485 proliferation of potentially harmful microbial groups, pathogenic fungi, bacteria and protists due
486 to human-driven input of phosphorus, nitrogen through atmospheric fertilization and microbial
487 pollution is necessary to improve our predictive abilities for human and wildlife risks. For
488 mountain ecosystems, in particular, our predictive abilities are poor for forecasting pathogen
489 proliferation, the dynamics of potentially harmful microorganisms, and for identifying threatened
490 species and habitats. In a mountain context that could mean that resources of clean drinking
491 water will diminish at a much faster rate than currently predicted (Schmeller et al., 2018) and the
492 important ecosystem services such as CO₂ sequestration and nitrogen retention will be
493 suboptimal or absent (Saunders and Kalff, 2001).

494 **Threats to Mountain Macro-Biodiversity**

495 Mountain areas host many species that live in a delicate balance or at the edge of their
496 distribution and are therefore very susceptible to environmental changes and local extinction.
497 Top predators, such as large carnivores, but also large herbivores play important roles in
498 maintaining mammal, avian, invertebrate, and herpetofauna abundance and richness. Many of
499 these species are threatened with extinction (Ripple et al., 2014) and nearing global collapse
500 (Ripple et al., 2015). Threats to macro-biodiversity in mountains come from chemical pollution,
501 nutrient influx through atmospheric processes and local sources such as livestock (Machate et
502 al., 2022), introduction of non-native taxa, but most importantly from overexploitation and habitat
503 loss (Maxwell et al., 2016). These threats drive the decline of already threatened species
504 (Maxwell et al., 2016) and will change the communities of species, which do not all have the
505 same possibilities of dispersal, recovery and reproduction to avoid disturbances (Kerr and
506 Deguise, 2004; Pimm, 2008). For example, among aquatic organisms, the possibility of dispersal
507 and life traits such as the mode of reproduction are very different among taxonomic groups.
508 Some zooplankton species can reproduce sexually or parthenogenetically, and can produce
509 resting eggs, which can survive for a long time in sediment egg banks (Brendonck and De
510 Meester, 2003; Nielsen et al., 2012). Benthic invertebrates increase their dispersal capacity by
511 producing winged adults. Both strategies may allow a speedy recovery through hatching from
512 resting stages or recolonization by flying. Complete recovery after local extinction, however, is
513 unlikely, and restoration and recovery processes in mountains take a long time (Tiberti et al.,
514 2019). For example, recovery from fish impacts took 11-20 years to obtain a similar food web
515 structure. In the same studies, it was evident that recolonization efficiency of species with a
516 parthenogenetic reproduction mode was higher than for sexual reproduction (Knapp and
517 Sarnelle, 2008; Knapp et al., 2001). In any case, for many species dispersal and recolonization

518 can be limited, when the remaining seed pool is not abundant or found too distant or beyond
519 barriers in the land- or waterscape in mountains, due to their relief. Hence, connectivity between
520 different populations of the same mountain species is reduced, hampering recolonization after
521 disturbance (Heino, 2013). Further, upward shifts of distribution areas are not the same for all
522 mountain species, disrupting long-established communities and their interactions. For example,
523 we understand only inadequately, if the observed upward shift of some mountain plant species
524 due to climate change is met by associated microbes and invertebrates (Grabherr et al., 1994;
525 Steinbauer et al., 2018). Other factors leading to unequal dispersal of formerly associated
526 species might be driven by reduced oxygen availability with increasing elevation (Jacobsen,
527 2020), differences in temperature and drought tolerance (Forero-Medina et al., 2011;
528 Schai-Braun et al., 2021), different adaptation abilities through e.g. seasonality or phenology
529 (Parmesan and Yohe, 2003), or different abilities to change depth distribution. Dysfunctional
530 ecosystems, with lower resilience to further impacts, are the likely outcome (Körner, 2019; Pecl
531 et al., 2017). Due to the non-linear loss of biodiversity (Trisos et al., 2020), the expected
532 extinction of endemic plant and animal species after tipping points have been met (Dullinger et
533 al., 2012), may further increase the dysfunctioning of mountain ecosystems. When this will
534 happen and what will be the outcome will be difficult to predict due to the multitude of factors
535 impacting different species in a community.

536 **Threats to mountain ecosystem services**

537 Negative impacts on mountain biodiversity threatens ecosystem integrity and functioning,
538 and hence also the multiple ecosystem services provided to local communities, populations
539 downstream and local stakeholders, including tourists (Grêt-Regamey et al., 2012; Martín-López
540 et al., 2019; Schirpke et al., 2019). The capacity of mountain ecosystems to provide ecosystem
541 services is deteriorating due to biodiversity loss driven by global change (Palomo, 2017). There
542 is an alarming set of negative consequences from those changes, in stark contrast to the few
543 positive effects that have been reported (Hobbs et al., 2009). These changes will jeopardize
544 water use of at least 1.9 billion people (Immerzeel et al., 2020). Moreover, as a result of glacier
545 decline, water availability will be severely reduced in the dry season, affecting millions of farmers
546 globally (Biemans et al., 2019). Mountains will therefore not remain the reliable and highly
547 important source of water they have been for thousands of years. Even in humid mountain
548 regions, such as the European Alps, droughts have become a problem (Stephan et al., 2021)
549 due to the increasing irregularity of water discharging rates and increasing flood events (Ragetti
550 et al., 2021). The irregularity of water discharging rates in combination with land use and land
551 cover changes can also have synergistic effects on ecosystem functioning, rendering mountains

552 more vulnerable to climate change impacts (Chiang et al., 2014). For the central mountain range
553 of Taiwan, it was shown that these combined effects lead to a relocation or loss of ecosystem
554 services and therefore need to be considered in conservation planning (Lin et al., 2019; Lin et
555 al., 2017).

556 Net primary production (NPP), the amount of biomass or carbon produced by primary
557 producers per unit area and time, is the basis of all ecosystem services and is being altered due
558 to climate change (Haberl et al., 2007; Kastner et al., 2022; Melillo et al., 1993). Overall, there is
559 evidence that increasing temperatures and CO₂ concentrations have increased the NPP of
560 forests when water was not a limiting factor (Boisvenue and Running, 2006). In the Alps,
561 changes in NPP of grasslands on which cattle depend show contrasting regional trends (Jäger
562 et al., 2020). A study combining experimentation and meta-analysis reported stabilization of NPP
563 of grasslands under climate change due to changes in species and increasing allocation towards
564 belowground biomass to resist drought (Liu et al., 2018). Despite a limited body of evidence,
565 local models predict that NPP will increase under climate change in the forests of the mountain
566 region of Changbai in China (Gao et al., 2020).

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

580 **Conclusions**

581 Mountain ecosystems are complex, dynamic, exceptionally fragile and are highly
582 sensitive to global change. They are therefore considered sentinels of change (Schmeller et al.,
583 2018). We are only beginning to understand the functional ecology of mountain ecosystems, but
584 international research already suggests that changing species communities will be detrimental to
585 the environment, to biodiversity and therefore to a critical part of Earth's life-support system.

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

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

615 In this light, and in that of the challenging objectives set by global agendas, including the
616 UN Sustainable Development Agenda, the Convention on Biological Diversity, the recently
617 launched EU Biodiversity Strategy for 2030 or the UN Decade on Ecosystem Restoration 2021-
618 2030, investments are needed for the delivery of policy-relevant science on mountain
619 ecosystems (Körner, 2019), closely following recommendations given in the global biodiversity

620 framework (CBD/WG2020/3/3). Only if we maintain a high ecosystem resilience will we be able
621 to maintain ecosystem functioning and ecosystem services. Threats to mountains are numerous
622 and the repercussions to humanity demand conservation and restoration of mountain
623 ecosystems, as they are an essential and highly sensitive part of the global life-support system.
624

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637

638 **References**

- 639 Acevedo-Whitehouse K, Duffus ALJ. Effects of environmental change on wildlife health.
640 Philosophical Transactions of the Royal Society B-Biological Sciences 2009; 364: 3429-
641 3438.
- 642 Adams SB, Frissell CA, Rieman BE. Geography of invasion in mountain streams: consequences
643 of headwater lake fish introductions. *Ecosystems* 2001; 4: 296-307.
- 644 Aide TM, Grau HR, Graesser J, Andrade-Nuñez MJ, Aráoz E, Barros AP, et al. Woody
645 vegetation dynamics in the tropical and subtropical Andes from 2001 to 2014: Satellite
646 image interpretation and expert validation. *Global Change Biology* 2019; 25: 2112-2126.
- 647 Allen S, Allen D, Phoenix VR, Le Roux G, Jiménez PD, Simonneau A, et al. Atmospheric
648 transport and deposition of microplastics in a remote mountain catchment. *Nature*
649 *Geoscience* 2019; 12: 339-344.
- 650 Allison EA. The spiritual significance of glaciers in an age of climate change. *Wiley*
651 *Interdisciplinary Reviews: Climate Change* 2015; 6: 493-508.
- 652 Bacardit M, Camarero L. Atmospherically deposited major and trace elements in the winter
653 snowpack along a gradient of altitude in the Central Pyrenees: the seasonal record of
654 long-range fluxes over SW Europe. *Atmospheric Environment* 2010; 44: 582-595.
- 655 Ball WT, Alsing J, Mortlock DJ, Staehelin J, Haigh JD, Peter T, et al. Evidence for a continuous
656 decline in lower stratospheric ozone offsetting ozone layer recovery. *Atmospheric*
657 *Chemistry and Physics* 2018; 18: 1379-1394.
- 658 Balthazar V, Vanacker V, Molina A, Lambin EF. Impacts of forest cover change on ecosystem
659 services in high Andean mountains. *Ecological Indicators* 2015; 48: 63-75.
- 660 Barnes PW, Williamson CE, Lucas RM, Robinson SA, Madronich S, Paul ND, et al. Ozone
661 depletion, ultraviolet radiation, climate change and prospects for a sustainable future.
662 *Nature Sustainability* 2019; 2: 569-579.
- 663 Bates KA, Sommer U, Hopkins KP, Shelton JMG, Wierzbicki C, Sergeant C, et al. Microbiome
664 function predicts amphibian chytridiomycosis disease dynamics. *Microbiome* 2022; 10:
665 44.

666 Bernardo-Cravo A, Schmeller DS, Chatzinotas A, Vredenburg VT, Loyau A. Environmental
667 Factors and Host Microbiomes Shape Host-Pathogen Dynamics. *Trends in Parasitology*
668 2020; 36: 29-36.

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

673 Biemans H, Siderius C, Lutz A, Nepal S, Ahmad B, Hassan T, et al. Importance of snow and
674 glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability* 2019;
675 2: 594-601.

676 Blais JM, Schindler DW, Muir DC, Kimpe LE, Donald DB, Rosenberg B. Accumulation of
677 persistent organochlorine compounds in mountains of western Canada. *Nature* 1998;
678 395: 585-588.

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

681 Bowman WD, Murgel J, Blett T, Porter E. Nitrogen critical loads for alpine vegetation and soils in
682 Rocky Mountain National Park. *Journal of Environmental Management* 2012; 103: 165-
683 171.

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

687 Bradford DF, Stanley K, McConnell LL, Tallent-Halsell NG, Nash MS, Simonich SM. Spatial
688 patterns of atmospherically deposited organic contaminants at high elevation in the
689 southern Sierra Nevada mountains, California, USA. *Environ Toxicol Chem* 2010; 29:
690 1056-66.

691 Bradford DF, Stanley KA, Tallent NG, Sparling DW, Nash MS, Knapp RA, et al. Temporal and
692 spatial variation of atmospherically deposited organic contaminants at high elevation in
693 Yosemite National Park, California, USA. *Environmental toxicology and chemistry* 2013;
694 32: 517-525.

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

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

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

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

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

707 Brunner SH, Grêt-Regamey A. Policy strategies to foster the resilience of mountain social-
708 ecological systems under uncertain global change. *Environmental Science & Policy*
709 2016; 66: 129-139.

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

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

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

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

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

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

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

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

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

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

737 Cifuentes-Croquevielle C, Stanton DE, Armesto JJ. Soil invertebrate diversity loss and functional
738 changes in temperate forest soils replaced by exotic pine plantations. *Scientific Reports*
739 2020; 10: 7762.

740 Crutzen PJ. The “anthropocene”. *Earth system science in the anthropocene*. Springer, 2006, pp.
741 13-18.

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

745 Daly GL, Wania F. Organic contaminants in mountains. *Environmental science & technology*
746 2005; 39: 385-398.

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

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

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

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

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

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

763 Diamond SA, Trenham PC, Adams MJ, Hossack BR, Knapp RA, Stark SL, et al. Estimated
764 ultraviolet radiation doses in wetlands in six national parks. *Ecosystems* 2005; 8: 462-
765 477.

766 Dierauer JR, Whitfield PH, Allen DM. Climate controls on runoff and low flows in mountain
767 catchments of Western North America. *Water Resources Research* 2018; 54: 7495-
768 7510.

769 Dobrowski SZ, Abatzoglou JT, Greenberg JA, Schladow S. How much influence does
770 landscape-scale physiography have on air temperature in a mountain environment?
771 *Agricultural and Forest Meteorology* 2009; 149: 1751-1758.

772 Dong Z, Brahney J, Kang S, Elser J, Wei T, Jiao X, et al. Aeolian dust transport, cycle and
773 influences in high-elevation cryosphere of the Tibetan Plateau region: New evidences
774 from alpine snow and ice. *Earth-Science Reviews* 2020; 211: 103408.

775 Drexler C, Braun V, Christie D, Claramunt B, Dax T, Jelen I, et al. Mountains for Europe's
776 Future—A strategic research agenda. Bern, Switzerland: Mountain Research Initiative,
777 Institute of Interdisciplinary Mountain Research 2016.

778 Du X, Liu H, Yuan L, Wang Y, Ma Y, Wang R, et al. The Diversity of Cyanobacterial Toxins on
779 Structural Characterization, Distribution and Identification: A Systematic Review. *Toxins*
780 2019; 11: 530.

781 Dullinger S, Gattringer A, Thuiller W, Moser D, Zimmermann NE, Guisan A, et al. Extinction debt
782 of high-mountain plants under twenty-first-century climate change. *Nature climate*
783 *change* 2012; 2: 619-622.

784 Einhorn B, Eckert N, Chaix C, Ravanel L, Deline P, Gardent M, et al. Climate change and
785 natural hazards in the Alps. Observed and potential impacts on physical and socio-
786 economic systems. *Journal of Alpine Research| Revue de géographie alpine* 2015.

787 Eklabya S, Rita S, Singh KK, Sharma G. A Boon for Mountain Populations. *Mountain Research*
788 *and Development* 2000; 20: 108-111.

789 Epanchin PN, Knapp RA, Lawler SP. Nonnative trout impact an alpine-nesting bird by altering
790 aquatic-insect subsidies. *Ecology* 2010; 91: 2406-2415.

791 Faccioni G, Sturaro E, Ramanzin M, Bernués A. Socio-economic valuation of abandonment and
792 intensification of Alpine agroecosystems and associated ecosystem services. *Land Use*
793 *Policy* 2019; 81: 453-462.

794 Fahey B, Jackson R. Hydrological impacts of converting native forests and grasslands to pine
795 plantations, South Island, New Zealand. *Agricultural and Forest Meteorology* 1997; 84:
796 69-82.

797 Fait P, Demierre E, Ilg C, Oertli B. Small mountain reservoirs in the Alps: New habitats for alpine
798 freshwater biodiversity? *Aquatic Conservation: Marine and Freshwater Ecosystems*
799 2020; 30: 617-630.

800 Fang X, Pyle JA, Chipperfield MP, Daniel JS, Park S, Prinn RG. Challenges for the recovery of
801 the ozone layer. *Nature Geoscience* 2019; 12: 592-596.

802 Ficetola GF, Marta S, Guerrieri A, Gobbi M, Ambrosini R, Fontaneto D, et al. Dynamics of
803 ecological communities following current retreat of glaciers. *Annual Review of Ecology,*
804 *Evolution, and Systematics* 2021; 52: 405-426.

805 Finlayson C, D'Cruz R. Inland water systems. *Ecosystems and human well-being: Current state*
806 *and trends*. Island Press, 2005, pp. 551-583.

807 Fisher MC, Garner TW. Chytrid fungi and global amphibian declines. *Nature Reviews*
808 *Microbiology* 2020; 18: 332-343.

809 Fonseca CR, Ganade G. Species functional redundancy, random extinctions and the stability of
810 ecosystems. *Journal of Ecology* 2001; 89: 118-125.

811 Forero-Medina G, Joppa L, Pimm SL. Constraints to Species' Elevational Range Shifts as
812 Climate Changes. *Conservation Biology* 2011; 25: 163-171.

813 Franssen HH, Scherrer S. Freezing of lakes on the Swiss plateau in the period 1901–2006.
814 *International Journal of Climatology: A Journal of the Royal Meteorological Society* 2008;
815 28: 421-433.

816 Frenken T, Alacid E, Berger SA, Bourne EC, Gerphagnon M, Grossart H-P, et al. Integrating
817 chytrid fungal parasites into plankton ecology. Research gaps and needs. *Environmental*
818 *Microbiology* 2017; 19: 3802–3822.

819 Funari E, Testai E. Human health risk assessment related to cyanotoxins exposure. *Critical*
820 *reviews in toxicology* 2008; 38: 97-125.

821 Gałuszka A, Migaszewski ZM, Zalasiewicz J. Assessing the Anthropocene with geochemical
822 methods. Geological Society, London, Special Publications 2014; 395: 221-238.

823 Gao W-Q, Lei X-D, Fu L-Y. Impacts of climate change on the potential forest productivity based
824 on a climate-driven biophysical model in northeastern China. *Journal of Forestry*
825 *Research* 2020; 31: 2273-2286.

826 Garcia-Vozmediano A, Krawczyk AI, Sprong H, Rossi L, Ramassa E, Tomassone L. Ticks climb
827 the mountains: ixodid tick infestation and infection by tick-borne pathogens in the
828 Western Alps. *Ticks and Tick-borne Diseases* 2020; 11: 101489.

829 Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M. 21st century climate change
830 in the European Alps—A review. *Science of the Total Environment* 2014; 493: 1138-
831 1151.

832 Grabherr G, Gottfried M, Pauli H. Climate effects on mountain plants. *Nature* 1994; 369: 448-
833 448.

834 Grêt-Regamey A, Brunner SH, Kienast F. Mountain ecosystem services: who cares? *Mountain*
835 *Research and Development* 2012; 32: S23-S34.

836 Grêt-Regamey A, Weibel B. Global assessment of mountain ecosystem services using earth
837 observation data. *Ecosystem Services* 2020; 46: 101213.

838 Gross M. Anthropocene at altitude. *Current Biology* 2022; 32: R441-R444.

839 Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzer C, et al. Quantifying and
840 mapping the human appropriation of net primary production in earth's terrestrial
841 ecosystems. *Proceedings of the National Academy of Sciences* 2007; 104: 12942-12947.

842 Häder DP, Helbling EW, Williamson CE, Worrest RC. Effects of UV radiation on aquatic
843 ecosystems and interactions with climate change. *Photochemical & Photobiological*
844 *Sciences* 2011; 10: 242-260.

845 Hall JM, Van Holt T, Daniels AE, Balthazar V, Lambin EF. Trade-offs between tree cover, carbon
846 storage and floristic biodiversity in reforesting landscapes. *Landscape Ecology* 2012; 27:
847 1135-1147.

848 Hansson SV, Claustres A, Probst A, De Vleeschouwer F, Baron S, Galop D, et al. Atmospheric
849 and terrigenous metal accumulation over 3000 years in a French mountain catchment:
850 Local vs distal influences. *Anthropocene* 2017a; 19: 45-54.

851 Hansson SV, Sonke J, Galop D, Bareille G, Jean S, Le Roux G. Transfer of marine mercury to
852 mountain lakes. *Scientific Reports* 2017b; 7: 12719.

853 Harrison S, Kargel JS, Huggel C, Reynolds J, Shugar DH, Betts RA, et al. Climate change and
854 the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere*
855 2018; 12: 1195-1209.

856 Hartmann H, Andresky L. Flooding in the Indus River basin—a spatiotemporal analysis of
857 precipitation records. *Global and planetary change* 2013; 107: 25-35.

858 Havas M, Rosseland BO. Response of zooplankton, benthos, and fish to acidification: an
859 overview. *Water, Air, and Soil Pollution* 1995; 85: 51-62.

860 Haver M, Le Roux G, Friesen J, Loyau A, Vredenburg VT, Schmeller DS. The role of abiotic
861 variables in an emerging global amphibian fungal disease in mountains. *Science of The*
862 *Total Environment* 2021: 152735.

863 Heino J. The importance of metacommunity ecology for environmental assessment research in
864 the freshwater realm. *Biological Reviews* 2013; 88: 166-178.

865 Hemp A. Introduced plants on Kilimanjaro: tourism and its impact. *Plant Ecology* 2008; 197: 17-
866 29.

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

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

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

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

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

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

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

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

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

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

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

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

897 Jäger H, Peratoner G, Tappeiner U, Tasser E. Grassland biomass balance in the European
898 Alps: current and future ecosystem service perspectives. *Ecosystem Services* 2020; 45:
899 101163.

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

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

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

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

910 Kelty MJ. The role of species mixtures in plantation forestry. *Forest Ecology and Management*
911 2006; 233: 195-204.

912 Kerr JT, Deguise I. Habitat loss and the limits to endangered species recovery. *Ecology Letters*
913 2004; 7: 1163-1169.

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

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

- 918 Kopáček J, Fluksová H, Hejzlar J, Kaňa J, Porcal P, Turek J. Changes in surface water
919 chemistry caused by natural forest dieback in an unmanaged mountain catchment.
920 *Science of the Total Environment* 2017; 584: 971-981.
- 921 Körner C. Mountain biodiversity, its causes and function. *AMBIO: A Journal of the Human*
922 *Environment* 2004; 33: 11-17.
- 923 Körner C. The use of 'altitude' in ecological research. *Trends in ecology & evolution* 2007; 22:
924 569-574.
- 925 Körner C. Mountain biodiversity, its causes and function: an overview. *Mountain biodiversity*
926 2019: 3-20.
- 927 Körner C, Jetz W, Paulsen J, Payne D, Rudmann-Maurer K, Spehn EM. A global inventory of
928 mountains for bio-geographical applications. *Alpine Botany* 2017; 127: 1-15.
- 929 Körner C, Paulsen J, Spehn EM. A definition of mountains and their bioclimatic belts for global
930 comparisons of biodiversity data. *Alpine Botany* 2011; 121: 73-78.
- 931 Körner W, Dupouey JL, Dambrine E, Benoit M. Influence of Past Land Use on the Vegetation
932 and Soils of Present Day Forest in the Vosges Mountains, France. *Journal of Ecology*
933 1997; 85: 351-358.
- 934 Laternser M, Schneebeli M. Long-term snow climate trends of the Swiss Alps (1931–99).
935 *International Journal of Climatology: A Journal of the Royal Meteorological Society* 2003;
936 23: 733-750.
- 937 Latty EF, Canham CD, Marks PL. The effects of land-use history on soil properties and nutrient
938 dynamics in northern hardwood forests of the Adirondack Mountains. *Ecosystems* 2004;
939 7: 193-207.
- 940 Laurion I, Ventura M, Catalan J, Psenner R, Sommaruga R. Attenuation of ultraviolet radiation in
941 mountain lakes: Factors controlling the among-and within-lake variability. *Limnology and*
942 *Oceanography* 2000; 45: 1274-1288.
- 943 Lavorel S, Grigulis K, Leitinger G, Kohler M, Schirpke U, Tappeiner U. Historical trajectories in
944 land use pattern and grassland ecosystem services in two European alpine landscapes.
945 *Regional Environmental Change* 2017; 17: 2251-2264.
- 946 Le Roux G, Hansson SV, Claustres A. Inorganic chemistry in the mountain critical zone: are the
947 mountain water towers of contemporary society under threat by trace contaminants?
948 *Developments in Earth Surface Processes*. 21. Elsevier, 2016, pp. 131-154.
- 949 Le Roux G, Hansson SV, Claustres A, Binet S, De Vleeschouwer F, Gandois L, et al. Trace
950 Metal Legacy in Mountain Environments. *Biogeochemical Cycles*, 2020, pp. 191-206.
- 951 Lei YD, Wania F. Is rain or snow a more efficient scavenger of organic chemicals? *Atmospheric*
952 *Environment* 2004; 38: 3557-3571.
- 953 Lenton TM. Early warning of climate tipping points. *Nature Climate Change* 2011; 1: 201-209.
- 954 Lerner H, Berg C. A Comparison of Three Holistic Approaches to Health: One Health,
955 EcoHealth, and Planetary Health. *Frontiers in Veterinary Science* 2017; 4.
- 956 Lin Y-P, Chen C-J, Lien W-Y, Chang W-H, Petway J, Chiang L. Landscape Conservation
957 Planning to Sustain Ecosystem Services under Climate Change. *Sustainability* 2019; 11:
958 1393.
- 959 Lin Y-P, Wunderlich RF, Lin C-M, Uphoff N, Schmeller DS, Shipin OV, et al. Topsoil microbial
960 community structure responds to land cover type and environmental zone in the Western
961 Pacific region. *Science of The Total Environment* 2021; 764: 144349.
- 962 Lin YP, Lin W-C, Wang Y-C, Lien W-Y, Huang TH, Hsu CC, et al. Systematically designating
963 conservation areas for protecting multiple ecosystem services. *Environmental Modelling*
964 *& Software* 2017; 90: 126-146.
- 965 Liu H, Mi Z, Lin L, Wang Y, Zhang Z, Zhang F, et al. Shifting plant species composition in
966 response to climate change stabilizes grassland primary production. *Proceedings of the*
967 *National Academy of Sciences* 2018; 115: 4051-4056.

968 Liu X, Dou L, Ding X, Sun T, Zhang H. Influences of different afforestation systems on the soil
969 properties of limestone mountains in the mid-eastern region of China. *Catena* 2021; 201:
970 105198.

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

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

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

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

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

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

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

989 McCain CM, Colwell RK. Assessing the threat to montane biodiversity from discordant shifts in
990 temperature and precipitation in a changing climate. *Ecology letters* 2011; 14: 1236-
991 1245.

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

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

998 Meire RO, Lee SC, Yao Y, Targino AC, Torres JPM, Harner T. Seasonal and altitudinal
999 variations of legacy and current-use pesticides in the Brazilian tropical and subtropical
1000 mountains. *Atmospheric Environment* 2012; 59: 108-116.

1001 Melillo JM, McGuire AD, Kicklighter DW, Moore B, Vorosmarty CJ, Schloss AL. Global climate
1002 change and terrestrial net primary production. *Nature* 1993; 363: 234-240.

1003 Milner AM, Khamis K, Battin TJ, Brittain JE, Barrand NE, Füreder L, et al. Glacier shrinkage
1004 driving global changes in downstream systems. *Proceedings of the National Academy of*
1005 *Sciences* 2017; 114: 9770-9778.

1006 Miró A, Ventura M. Evidence of exotic trout mediated minnow invasion in Pyrenean high
1007 mountain lakes. *Biological Invasions* 2015; 17: 791-803.

1008 Miró A, Ventura M. Introduced fish in Pyrenean high mountain lakes: impact on amphibians and
1009 other organisms, and conservation implications. *Limnetica* 2020; 39: 283-297.

1010 Mölg T, Hardy DR, Cullen NJ, Kaser G. Tropical glaciers, climate change, and society.
1011 *Darkening peaks: Glacier retreat, science, and society* 2008: 168-182.

1012 Moser KA, Baron JS, Brahney J, Oleksy IA, Saros JE, Hundey EJ, et al. Mountain lakes: Eyes
1013 on global environmental change. *Global and Planetary Change* 2019; 178: 77-95.

1014 Moulin C, Chiapello I. Impact of human-induced desertification on the intensification of Sahel
1015 dust emission and export over the last decades. *Geophysical Research Letters* 2006; 33:
1016 L18808.

- 1017 Myhre G, Alterskjær K, Stjern CW, Hodnebrog Ø, Marelle L, Samset BH, et al. Frequency of
1018 extreme precipitation increases extensively with event rareness under global warming.
1019 *Scientific Reports* 2019; 9: 16063.
- 1020 Negi VS, Tiwari DC, Singh L, Thakur S, Bhatt ID. Review and synthesis of climate change
1021 studies in the Himalayan region. *Environment, Development and Sustainability* 2021.
- 1022 Niedertscheider M, Tasser E, Patek M, Rüdiger J, Tappeiner U, Erb K-H. Influence of Land-Use
1023 Intensification on Vegetation C-Stocks in an Alpine Valley from 1865 to 2003.
1024 *Ecosystems* 2017; 20: 1391-1406.
- 1025 Niedrist G, Psenner R, Sommaruga R. Climate warming increases vertical and seasonal water
1026 temperature differences and inter-annual variability in a mountain lake. *Climatic Change*
1027 2018; 151: 473-490.
- 1028 Niedrist GH, Füreder L. Real-time warming of alpine streams:(Re) defining invertebrates'
1029 temperature preferences. *River Research and Applications* 2021; 37: 283-293.
- 1030 Nielsen DL, Smith D, Petrie R. Resting egg banks can facilitate recovery of zooplankton
1031 communities after extended exposure to saline conditions. *Freshwater Biology* 2012; 57:
1032 1306-1314.
- 1033 Niu L, Cheng Z. Impact of tourism disturbance on forest vegetation in Wutai Mountain, China.
1034 *Environmental Monitoring and Assessment* 2019; 191: 81.
- 1035 Nodvin S, Van Miegroet H, Lindberg S, Nicholas N, Johnson D. Acidic deposition, ecosystem
1036 processes, and nitrogen saturation in a high elevation southern Appalachian watershed.
1037 *Water, Air, and Soil Pollution* 1995; 85: 1647-1652.
- 1038 Nogues-Bravo D, Araújo MB, M.P. E, Martínez-Rica JP. Exposure of global mountain systems to
1039 climate warming during the 21st Century. *Global Environmental Change* 2007; 17: 420-
1040 428.
- 1041 Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, et al. The toxicology
1042 of climate change: environmental contaminants in a warming world. *Environ Int* 2009; 35:
1043 971-86.
- 1044 Obertegger U, Flaim G. A 40-year perspective of an alpine lake: Is everything the same?
1045 *Limnologia* 2021; 91: 125929.
- 1046 Palomo I. Climate change impacts on ecosystem services in high mountain areas: a literature
1047 review. *Mountain Research and Development* 2017; 37: 179-187.
- 1048 Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural
1049 systems. *Nature* 2003; 421: 37-42.
- 1050 Pauchard A, Kueffer C, Dietz H, Daehler CC, Alexander J, Edwards PJ, et al. Ain't no mountain
1051 high enough: plant invasions reaching new elevations. *Frontiers in Ecology and the*
1052 *Environment* 2009; 7: 479-486.
- 1053 Payne D, Spehn EM, Prescott GW, Geschke J, Sneathlage MA, Fischer M. Mountain Biodiversity
1054 Is Central to Sustainable Development in Mountains and Beyond. *One earth* 2020; 3:
1055 530-533.
- 1056 Pecl GT, Araújo MB, Bell JD, Blanchard J, Bonebrake TC, Chen I-C, et al. Biodiversity
1057 redistribution under climate change: Impacts on ecosystems and human well-being.
1058 *Science* 2017; 355: eaai9214.
- 1059 Pepin N, Bradley RS, Diaz H, Baraër M, Caceres E, Forsythe N, et al. Elevation-dependent
1060 warming in mountain regions of the world. *Nature climate change* 2015; 5: 424-430.
- 1061 Pepin N, Lundquist J. Temperature trends at high elevations: patterns across the globe.
1062 *Geophysical Research Letters* 2008; 35.
- 1063 Pimm SL. Biodiversity: Climate change or habitat loss - Which will kill more species? *Current*
1064 *Biology* 2008; 18: R117-R119.
- 1065 Pozo K, Urrutia R, Barra R, Mariottini M, Treutler H-C, Araneda A, et al. Records of
1066 polychlorinated biphenyls (PCBs) in sediments of four remote Chilean Andean Lakes.
1067 *Chemosphere* 2007; 66: 1911-1921.

1068 Purcell AM, Hayer M, Koch BJ, Mau RL, Blazewicz SJ, Dijkstra P, et al. Decreased growth of
1069 wild soil microbes after 15 years of transplant-induced warming in a montane meadow.
1070 *Global Change Biology* 2022; 28: 128-139.

1071 Ragettli S, Tong X, Zhang G, Wang H, Zhang P, Stähli M. Climate change impacts on summer
1072 flood frequencies in two mountainous catchments in China and Switzerland. *Hydrology*
1073 *Research* 2021; 52: 4-25.

1074 Rahbek C, Borregaard MK, Antonelli A, Colwell RK, Holt BG, Nogues-Bravo D, et al. Building
1075 mountain biodiversity: Geological and evolutionary processes. *Science* 2019a; 365:
1076 1114-1119.

1077 Rahbek C, Borregaard MK, Colwell RK, Dalsgaard B, Holt BG, Morueta-Holme N, et al.
1078 Humboldt's enigma: What causes global patterns of mountain biodiversity? *Science*
1079 2019b; 365: 1108-1113.

1080 Rajczak J, Schär C. Projections of future precipitation extremes over Europe: A multimodel
1081 assessment of climate simulations. *Journal of Geophysical Research: Atmospheres*
1082 2017; 122: 10,773-10,800.

1083 Rangwala I, Miller JR. Climate change in mountains: a review of elevation-dependent warming
1084 and its possible causes. *Climatic change* 2012; 114: 527-547.

1085 Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, et al. Emerging threats and
1086 persistent conservation challenges for freshwater biodiversity. *Biological Reviews* 2019;
1087 94: 849-873.

1088 Ripple W, J., Estes J, A., Beschta R, L., Wilmers C, C., Ritchie E, G., Hebblewhite M, et al.
1089 Status and Ecological Effects of the World's Largest Carnivores. *Science* 2014; 343:
1090 1241484.

1091 Ripple WJ, Newsome TM, Wolf C, Dirzo R, Everatt KT, Galetti M, et al. Collapse of the world's
1092 largest herbivores. *Science advances* 2015; 1: e1400103.

1093 Ripple WJ, Wolf C, Newsome TM, Galetti M, Alamgir M, Crist E, et al. World Scientists' Warning
1094 to Humanity: A Second Notice. *BioScience* 2017: bix125-bix125.

1095 Ripple WJ, Wolf C, Newsome TM, Gregg JW, Lenton TM, Palomo I, et al. World Scientists'
1096 Warning of a Climate Emergency 2021. *BioScience* 2021.

1097 Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, et al. A safe operating
1098 space for humanity. *Nature* 2009; 461: 472-475.

1099 Rodway-Dyer S, Ellis N. Combining remote sensing and on-site monitoring methods to
1100 investigate footpath erosion within a popular recreational heathland environment. *Journal*
1101 *of Environmental Management* 2018; 215: 68-78.

1102 Roe GH. Orographic precipitation. *Annu. Rev. Earth Planet. Sci.* 2005; 33: 645-671.

1103 Rose KC, Williamson CE, Saros JE, Sommaruga R, Fischer JM. Differences in UV transparency
1104 and thermal structure between alpine and subalpine lakes: implications for organisms.
1105 *Photochemical & Photobiological Sciences* 2009; 8: 1244-1256.

1106 Saunders DL, Kalff J. Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologia* 2001; 443:
1107 205-212.

1108 Scarano FR. Biodiversity Sector: Risks of Temperature Increase to Biodiversity and
1109 Ecosystems. In: Nobre CA, Marengo JA, Soares WR, editors. *Climate Change Risks in*
1110 *Brazil*. Springer International Publishing, Cham, 2019, pp. 131-141.

1111 Schabetsberger R, Kaiser R, Rott E, Lenzenweger R, Traunspurger W, Kotov AA, et al. On the
1112 brink – investigating biodiversity in endangered crater lakes of the Amber Mountains
1113 National Park (Madagascar). *Aquatic Conservation: Marine and Freshwater Ecosystems*
1114 2013; 23: 316-331.

1115 Schai-Braun SC, Jenny H, Ruf T, Hackländer K. Temperature increase and frost decrease
1116 driving upslope elevational range shifts in Alpine grouse and hares. *Global Change*
1117 *Biology* 2021; 27: 6602-6614.

- 1118 Schindler DE, Knapp RA, Leavitt PR. Alteration of Nutrient Cycles and Algal Production
1119 Resulting from Fish Introductions into Mountain Lakes. *Ecosystems* 2001; 4: 308-321.
- 1120 Schirpke U, Tappeiner U, Tasser E. A transnational perspective of global and regional
1121 ecosystem service flows from and to mountain regions. *Scientific reports* 2019; 9: 1-11.
- 1122 Schmeller DS, Bridgewater P. The eighth plenary of the Intergovernmental Science-Policy
1123 Platform for Biodiversity and Ecosystem Services (IPBES-8): online, nexus, and
1124 transformative change. *Biodiversity and Conservation* 2021; 33: 2857-2862.
- 1125 Schmeller DS, Courchamp F, Killeen G. Biodiversity loss, emerging pathogens and human
1126 health risks. *Biodiversity and Conservation* 2020: 3095–3102.
- 1127 Schmeller DS, Loyau A, Bao K, Brack W, Chatzinotas A, De Vleeschouwer F, et al. People,
1128 pollution and pathogens – Global change impacts in mountain freshwater ecosystems.
1129 *Science of The Total Environment* 2018; 622-623: 756-763.
- 1130 Schmeller DS, Niemelä J, Bridgewater P. The Intergovernmental Science-Policy Platform on
1131 Biodiversity and Ecosystem Services (IPBES): getting involved. *Biodiversity and
1132 Conservation* 2017; 26: 2271-2275.
- 1133 Scientists UoC. World scientists' Warning to Humanity. Union of Concerned Scientists,
1134 <http://www.ucsusa.org/sites/default/files/attach/2017/11/World%20Scientists%27%20Warning%20to%20Humanity%201992>, 1992.
- 1135
- 1136 Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, et al. Projecting the
1137 continental accumulation of alien species through to 2050. *Global Change Biology* 2021;
1138 27: 970-982.
- 1139 Sentenac H, Loyau A, Leflaive J, Schmeller DS. The significance of biofilms to human, animal,
1140 plant and ecosystem health. *Functional Ecology* 2022; 33: 294 - 313.
- 1141 Shijin W, Dahe Q. Mountain inhabitants' perspectives on climate change, and its impacts and
1142 adaptation based on temporal and spatial characteristics analysis: a case study of Mt.
1143 Yulong Snow, Southeastern Tibetan Plateau. *Environmental Hazards* 2015; 14: 122-136.
- 1144 Shunthirasingham C, Oyiliagu CE, Cao X, Gouin T, Wania F, Lee S-C, et al. Spatial and
1145 temporal pattern of pesticides in the global atmosphere. *Journal of Environmental
1146 Monitoring* 2010; 12: 1650-1657.
- 1147 Silva V, Montanarella L, Jones A, Fernández-Ugalde O, Mol HG, Ritsema CJ, et al. Distribution
1148 of glyphosate and aminomethylphosphonic acid (AMPA) in agricultural topsoils of the
1149 European Union. *Science of the Total Environment* 2018; 621: 1352-1359.
- 1150 Siraj A, Santos-Vega M, Bouma M, Yadeta D, Carrascal DR, Pascual M. Altitudinal changes in
1151 malaria incidence in highlands of Ethiopia and Colombia. *Science* 2014; 343: 1154-1158.
- 1152 Small ST, Labbé F, Coulibaly YI, Nutman TB, King CL, Serre D, et al. Human migration and the
1153 spread of the nematode parasite *Wuchereria bancrofti*. *Molecular biology and evolution*
1154 2019; 36: 1931-1941.
- 1155 Sommaruga R. The role of solar UV radiation in the ecology of alpine lakes. *Journal of
1156 Photochemistry and Photobiology B: Biology* 2001; 62: 35-42.
- 1157 Sommaruga R. When glaciers and ice sheets melt: consequences for planktonic organisms.
1158 *Journal of plankton research* 2015; 37: 509-518.
- 1159 Sommaruga R, Sattler B, Oberleiter A, Wille A, Wögrath-Sommaruga S, Psenner R, et al. An in
1160 situ enclosure experiment to test the solar UVB impact on plankton in a high-altitude
1161 mountain lake. II. Effects on the microbial food web. *Journal of Plankton Research* 1999;
1162 21.
- 1163 Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary
1164 boundaries: Guiding human development on a changing planet. *Science* 2015; 347.
- 1165 Steinbauer MJ, Grytnes J-A, Jurasinski G, Kulonen A, Lenoir J, Pauli H, et al. Accelerated
1166 increase in plant species richness on mountain summits is linked to warming. *Nature*
1167 2018; 556: 231-234.

1168 Stephan R, Erfurt M, Terzi S, Žun M, Kristan B, Haslinger K, et al. An inventory of Alpine drought
1169 impact reports to explore past droughts in a mountain region. *Nat. Hazards Earth Syst.*
1170 *Sci.* 2021; 21: 2485-2501.

1171 Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, et al. Drought, Tree
1172 Mortality, and Wildfire in Forests Adapted to Frequent Fire. *BioScience* 2018; 68: 77-88.

1173 Sultan B, Labadi K, Guégan J-F, Janicot S. Climate drives the meningitis epidemics onset in
1174 West Africa. *PLoS medicine* 2005; 2: e6.

1175 Swanson F, Kratz T, Caine N, Woodmansee R. Landform effects on ecosystem patterns and
1176 processes. *BioScience* 1988; 38: 92-98.

1177 Tasser E, Tappeiner U. Impact of land use changes on mountain vegetation. *Applied Vegetation*
1178 *Science* 2002; 5: 173-184.

1179 Tegen I, Werner M, Harrison S, Kohfeld K. Relative importance of climate and land use in
1180 determining present and future global soil dust emission. *Geophysical Research Letters*
1181 2004; 31: L05105.

1182 Temme AJ. Using climber's guidebooks to assess rock fall patterns over large spatial and
1183 decadal temporal scales: an example from the swiss alps. *Geografiska Annaler: Series*
1184 *A, Physical Geography* 2015; 97: 793-807.

1185 Tiberti R, Bogliani G, Brighenti S, Iacobuzio R, Liautaud K, Rolla M, et al. Recovery of high
1186 mountain Alpine lakes after the eradication of introduced brook trout *Salvelinus fontinalis*
1187 using non-chemical methods. *Biological invasions* 2019; 21: 875-894.

1188 Tiberti R, von Hardenberg A, Bogliani G. Ecological impact of introduced fish in high altitude
1189 lakes: a case of study from the European Alps. *Hydrobiologia* 2014; 724: 1-19.

1190 Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, et al. Bending the curve
1191 of global freshwater biodiversity loss: an emergency recovery plan. *BioScience* 2020; 70:
1192 330-342.

1193 Trisos CH, Merow C, Pigot AL. The projected timing of abrupt ecological disruption from climate
1194 change. *Nature* 2020; 580: 496-501.

1195 Turner B, Clark W, Kates R, Richards J, Mathews J. The earth as transformed by human action:
1196 global and regional changes in the biosphere over the past 300 years. 1990.

1197 United Nations Environment Programme A Scientific Assessment of the Third Pole Environment,
1198 Nairobi, 2022.

1199 Urrutia R, Vuille M. Climate change projections for the tropical Andes using a regional climate
1200 model: Temperature and precipitation simulations for the end of the 21st century. *Journal*
1201 *of Geophysical Research: Atmospheres* 2009; 114.

1202 Vadeboncoeur Y, Peterson G, Vander Zanden MJ, Kalff J. Benthic algal production across lake
1203 size gradients: interactions among morphometry, nutrients, and light. *Ecology* 2008; 89:
1204 2542-2552.

1205 Valbuena-Ureña E, Oromi N, Soler-Membrives A, Carranza S, Amat F, Camarasa S, et al. Jailed
1206 in the mountains: Genetic diversity and structure of an endemic newt species across the
1207 Pyrenees. *PLOS ONE* 2018; 13: e0200214.

1208 Valdivia C, Thibeault J, Gilles JL, García M, Seth A. Climate trends and projections for the
1209 Andean Altiplano and strategies for adaptation. *Adv. Geosci.* 2013; 33: 69-77.

1210 van Wilgen BW. Evidence, Perceptions, and Trade-offs Associated with Invasive Alien Plant
1211 Control in the Table Mountain National Park, South Africa. *Ecology and Society* 2012; 17.

1212 van Wilgen BW, Richardson DM. Three centuries of managing introduced conifers in South
1213 Africa: Benefits, impacts, changing perceptions and conflict resolution. *Journal of*
1214 *Environmental Management* 2012; 106: 56-68.

1215 Ventura M, Tiberti R, Buchaca T, Buñay D, Sabás I, Miró A. Why should we preserve fishless
1216 high mountain lakes? In: Catalan J, Ninot JM, Aniz M, editors. *High mountain*
1217 *conservation in a changing world.* Springer, Cham, 2017, pp. 181-205.

- 1218 Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R. Mountains of the world, water
 1219 towers for humanity: Typology, mapping, and global significance. *Water Resources*
 1220 *Research* 2007; 43.
- 1221 Viviroli D, Kummu M, Meybeck M, Kallio M, Wada Y. Increasing dependence of lowland
 1222 populations on mountain water resources. *Nature Sustainability* 2020; 3: 917-928.
- 1223 Vuille M, Carey M, Huggel C, Buytaert W, Rabatel A, Jacobsen D, et al. Rapid decline of snow
 1224 and ice in the tropical Andes—Impacts, uncertainties and challenges ahead. *Earth-*
 1225 *Science Reviews* 2018; 176: 195-213.
- 1226 Wania F, Mackay D. Global fractionation and cold condensation of low volatility organochlorine
 1227 compounds in polar regions. *Ambio* 1993; 22: 10-18.
- 1228 Watermann LY, Hock M, Blake C, Erfmeier A. Plant invasion into high elevations implies
 1229 adaptation to high UV-B environments: a multi-species experiment. *Biological Invasions*
 1230 2020; 22: 1203-1218.
- 1231 Werner CM, Harrison SP, Safford HD, Bohlman GN, Serata R. Extreme pre-fire drought
 1232 decreases shrub regeneration on fertile soils. *Ecological Applications* 2022; 32: e02464.
- 1233 Wester P, Mishra A, Mukherji A, Shrestha AB. *The Hindu Kush Himalaya assessment:*
 1234 *mountains, climate change, sustainability and people: Springer Nature, 2019.*
- 1235 Yan D, Zhang T, Su J, Zhao L-L, Wang H, Fang X-M, et al. Diversity and composition of airborne
 1236 fungal community associated with particulate matters in Beijing during haze and non-
 1237 haze days. *Frontiers in microbiology* 2016; 7: 487.
- 1238 Yang H, Engstrom DR, Rose NL. Recent changes in atmospheric mercury deposition recorded
 1239 in the sediments of remote equatorial lakes in the Rwenzori Mountains, Uganda.
 1240 *Environmental science & technology* 2010; 44: 6570-6575.
- 1241 Zanchett G, Oliveira-Filho EC. Cyanobacteria and cyanotoxins: from impacts on aquatic
 1242 ecosystems and human health to anticarcinogenic effects. *Toxins* 2013; 5: 1896-1917.
- 1243 Zemp M, Frey H, Gärtner-Roer I, Nussbaumer SU, Hoelzle M, Paul F, et al. Historically
 1244 unprecedented global glacier decline in the early 21st century. *Journal of glaciology*
 1245 2015; 61: 745-762.
- 1246 Zhang J-T, Xiang C, Li M. Effects of Tourism and Topography on Vegetation Diversity in the
 1247 Subalpine Meadows of the Dongling Mountains of Beijing, China. *Environmental*
 1248 *Management* 2012; 49: 403-411.
- 1249 Zuecco G, Penna D, Borga M. Runoff generation in mountain catchments: long-term
 1250 hydrological monitoring in the Rio Vauz Catchment, Italy. *Cuadernos de investigación*
 1251 *geográfica/Geographical Research Letters* 2018: 397-428.
- 1252
- 1253
- 1254
- 1255
- 1256