Nature-based Solutions for climate change adaptation are not located where they are most needed across the Alps

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Abstract

Climate change impacts mountains socio-ecosystems by increasing certain natural disasters and changing Nature's Contributions to People (NCP). Nature-based Solutions (NbS) are increasingly implemented to help local communities adapt to climatic hazards. However, the relevance of their location in relation to those hazards and local NCP has hardly been addressed. In the PORTAL project (Pathways of Transformation in the Alps), we identified and mapped a portfolio of 97 NbS for climate change adaptation in the European Alps. Most NbS addressed drought or soil instability, and aimed to provide multiple NCP simultaneously such as wood production and protective function against landslides. We analysed whether NbS are located where they are the most needed, according to both current and future intensity of the hazards they aim to address and to supply-flow-demand indicators of the NCP they aim to provide. We found that the location of NbS is overall not related to current supply-flow-demand indicators of most NCP, nor to intensity of hazards. Nevertheless, NbS addressing droughts and floods are located in areas where these hazards are more intense, but do not match higher values for NCP indicators. Conversely, NbS aiming to produce wood and to provide protective function against landslides are located in areas with greater levels of these NCP, regardless of the intensity of hazards. These results suggest that hazards and NCP indicators are not the main drivers of NbS implementation. We argue that integrating local climate conditions and current NCP flows is needed to underpin a macro-regional strategy for planning NbS implementation.

Keywords

Nature-based Solutions, Climate Change Adaptation, Nature's Contributions to People, European Alps, Spatial analysis.

1. Introduction

Considered as one of the greatest challenges humanity faces, climate change threatens human good quality of life and ecosystems, especially in high-elevation areas, where temperature has been rising faster than in lowlands (Pepin et al. 2022). With this accelerating change, mountain communities already experience more frequent and intense natural hazard events, and these are expected to increase in the future whatever the carbon emission scenario (Gobiet and Kotlarski 2020). In the European Alps, climate scenarios suggest that the frequency and the intensity of extreme climatic hazards and climate-induced disasters – such as heatwaves, erratic rainfall, floods, wildfires, landslides, rockfalls and avalanches – will increase significantly during the 21st century (Gobiet et al. 2014; Einhorn et al. 2015; Beniston and Stoffel 2016; Gariano and Guzzetti 2016; Huss et al. 2017). The magnitude of these hazards will be elevation-dependent, with higher altitudes expected to experience a greater relative increase in temperature, and a lower relative decrease in snow cover duration (Gobiet and Kotlarski 2020). Precipitation projections are more uncertain especially in terms of potential changes in their geographic distribution; overall precipitation is likely to increase in winter, and decrease in summer, with significant geographic variation along a north-south axis (Gobiet and Kotlarski 2020). This, together with glacier retreat, will lead to more intense and frequent droughts, especially in summer (Gobiet et al. 2014; Laurent et al. 2020). Snow cover decrease will continue, in terms of quantity and duration (Gobiet and Kotlarski 2020; Morin et al. 2021).

This climate change threatens mountain biodiversity. Increasing temperatures in all seasons drive the upward shift of plant species, resulting in ecosystem composition change (Lamprecht et al. 2018), extinction risk for cold-adapted plant and animal species isolated to summits that may have nowhere to go (Pauli and Halloy 2019) and new suitable climatic conditions for invasive species (Carboni et al. 2018). This suggests the future loss of major parts of the habitat for up to half of endemic alpine plants (Engler et al. 2011; Dullinger et al. 2012), and the high extinction risk of animal populations such as some alpine ungulates (Lovari et al. 2020) and birds (Dirnböck et al. 2011; Ferrarini et al. 2017; Brambilla et al. 2018) in the absence of adapted conservation planning (Chamberlain et al. 2016). These effects on biodiversity and ecosystems, added to the increasing natural hazards and declining cryosphere, affect ecosystem functioning and consequently the diverse Nature's Contributions to People (NCP) in mountain regions, including freshwater supply, wood and fodder production, forest protective function against landslides, pest control, outdoor recreation activities and global climate regulation among others, which benefit local communities, tourists and people living in lowlands (Palomo 2017; Schirpke et al. 2019a, b; Grêt-Regamey and Weibel 2020). For example, freshwater supply is highly sensitive to climate change in mountains, and millions of users upstream and downstream will be put at risk (Immerzeel et al. 2020; Mastrotheodoros et al. 2020). Heatwaves and drought hazards resulting from increasing temperature and the reduction of freshwater supply will have large social and economic consequences (Zappa and Kan 2007), with human health impacts in urban areas (Villanueva et al. 2015), perturbations of grassland and forest carbon sequestration ability (Mina et al. 2017; Ingrisch et al. 2018), pest expansion (Huss et al., 201), reduction of forest protective function against landslides due to increasing tree mortality (Allen et al. 2010; Sass 2014), and economic losses of farms with dairy cows submitted to more severe heat stress (Boni et al. 2014).

In the face of these unprecedented changes, adaptation options are being put in place in alpine socio-ecological systems (Terzi et al. 2019; Vij et al. 2021). Among them, Nature-based Solutions (NbS) have recently gained attention in global research and practice as climate adaptation strategies (Seddon et al. 2020). NbS are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al. 2016). Some examples are grassland conservation methods within ski resorts to reduce soil erosion (Casagrande Bacchiocchi et al. 2019); forest management practices and mixed tree species options to increase forest resilience (Elkin et al. 2015; Irauschek et al. 2017); adapted grassland management practices for mountain livestock production (Lamarque et al. 2013; Nettier et al. 2017); and green infrastructure to reduce heatwave intensity in urban areas (Kabisch et al. 2017).

NbS for climate change adaptation are claimed to have the potential to maintain or enhance multiple NCP that help society adapt to climate change (Jones et al. 2012; Colloff et al. 2020). These NbS can apply on the ground measures to conserve or improve NCP that protect people from climate change (e.g., reforesting a landslide-prone area to improve NCP such as soil conservation or landslide reduction). They can also act on NCP drivers, such as land-use policies or incentives for good management (e.g., forest harvesting regulations or payments for ecosystem services), and address the vulnerability of NCP to climate change (e.g., by reforesting with species that will be adapted to future climate).

To our knowledge no study has evaluated the location of NbS regarding NCP or the hazards they aim to address. We assume that the need for NbS is higher where society is more likely to be affected, i.e. where climatic hazards are more intense or frequent; NCP are less supplied; and/or NCP are more used or demanded by society. We hence explicitly consider for the first time for assessing NbS the three NCP dimensions: supply, the amount of NCP coproduced by ecosystems and people (Schröter et al. 2012); flow, the part of the supply benefiting society; and demand, the amount of NCP society needs (Burkhard and Maes 2017). Our analysis considered those socio-economic factors included in NCP indicators (such as population density, presence of infrastructure or livestock) but not other factors often used in risk assessments, such as education levels, wealth, or governance (e.g. Gerlitz et al. 2017; Birkmann et al. 2022). We restricted our analysis to hazards and NCP indicators because of the subjectivity of selecting and combining socio-economic factors that may not be relevant to local society needs (Beccari 2016; Il Choi 2019). Following the IPCC framework (Field and Barros 2014), we define a hazard as "the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources".

Here, we define needs for NbS in terms of climatic hazards combined with NCP, for example erratic rainfall (hazard) with forest protective function against landslides (NCP). We assume that the need for NbS is high where the NCP surplus is low, i.e. where the amount of NCP supplied is closer to the amount of NCP used or demanded by society. In our example, this would regard areas with limited protective function from current forest against landslides. Similarly, we also assume that the needs for NbS are high where the NCP demand-supply is high, i.e. where any decrease in NCP supply risks to leave demand unmet. This would regard the same areas with currently low protective function of forest against landslides but also high demand from population and infrastructure for protective function against landslides. Similarly, we also assume that the need for NbS is high where the NCP demand-supply is high, i.e. where any decrease in NCP supply risks to leave demand unmet. This would regard the same areas with currently low protective function against landslides but also important protective function demand from the population and infrastructures against landslides. This consideration also applies to locations with a low demand-supply ratio in cases where currently low demand is expected to increase due to increasing hazards and current NCP supply may not sufficiently cover future demand. However, we note that this approach does not address cases of mismatch between supply and demand locations (Schirpke et al. 2019b).

To understand how NbS are distributed, we explore the spatial distribution of NbS in the Alps in relation to current and future climate change hazards and to NCP indicators separately, and in relation to their combinations. We first identified and mapped the location of implemented NbS in the Alps into a novel database. Secondly, we computed a spatial analysis to compare NbS locations to i) a series of current and future climate change hazards; ii) the NCP indicators including NCP supply, flow, demand as well as flow-supply and demand-supply ratios; iii) common combinations of hazards and NCP indicators.

2. Materials & Methods

2.1. Nature-based Solutions grey literature review

We identified NbS for climate change adaptation within the Alpine Convention space area, referred to as the Alps henceforth, which covers 190 717 km² within Austria, Italy, France, Switzerland, Germany, Slovenia, Liechtenstein and Monaco. We searched existing NbS and adaptation initiative databases, including ClimateADAPT, Oppla and PHUSICOS. Then, we explored the websites of environmental public agencies related to the forest, agriculture, freshwater provision, biodiversity conservation and protected area sectors, for all countries of the Alps. We complemented this search with data from websites of partner organisations involved in the implementation of these NbS. Our main inclusion criteria targeted NbS aiming to address at least one climate change impact or at least one impact that is known to be enhanced by climate change. These initiatives had to address also the loss of habitat for biodiversity to be included.

We grouped NbS into three categories following the classification from Donatti et al. (2020): i) On the ground NbS, including the restoration, protection, creation of ecosystems and ecosystem sustainable management ; ii) Enabling NbS, which focus on the creation of new knowledge, awareness-raising activities and the implementation of new policies or plans in relation to nature-based adaptation; iii) Mixed NbS, which implement both on the ground and enabling activities.

We coded the climatic hazards addressed by each NbS as well as the NCP they address. For NCP we used the classification from Diaz et al. (2018) and adapted it to specific NCP addressed by NbS in mountain regions. We created subcategories resulting into 22 NCP listed in Supplementary file 1. For example, the extreme events regulation NCP from IPBES classification has been divided in eight sub-categories such as flood regulation or heatwave regulation. We then computed a Sankey diagram to illustrate the links between hazards addressed by NbS and the NCP they aim to provide. Finally, we mapped the boundaries of each NbS (QGIS software version 3.16.5) based on the initiative's description online or by contacting the person in charge.

2.2. Climatic hazards and Nature's Contributions to People

To assess current and future climatic hazards, we used data from the Climate Data Store, hosted on the Copernicus platform, between 1970 and 2000 for the reference period, and between 2050 and 2060 for the future. We selected the following variables: temperature, precipitation, snow cover, heatwaves intensity, flood hazard and wildfire hazard. Because we aimed to compare relative rather than absolute values between locations we selected the climatic scenario that had been used for each climate model (RCP 8.5 for most variables, and RCP 4.5 when RCP 8.5 was not available). For all variables, we computed the relative change from current to future values for each pixel. Details on each specific variable are in the Supplementary Files 2 and 3.

We used the indicators of NCP supply, flow and demand for seven NCP assessed and mapped at the municipality level by the AlpES project (*Alpine Ecosystem Services - mapping, maintenance, management*) based on biophysical and socio-economic variables (Schirpke et al. 2019a): freshwater; fodder; fuel wood; forest protective function against landslides; CO_2 sequestration; outdoor recreation; and symbolic biodiversity (for details, see Supplementary File 4). As the flood and heatwave regulation NCP were not mapped by the AlpES project, we did not include them in our analysis.

Adapted from the surplus-balance-deficit indicator developed by (Li et al. 2016), we computed the demand-supply ratio and the flow-supply ratio for each NCP, except for symbolic biodiversity for which we computed only the flow-supply ratio given demand for this NCP can be considered as global and was therefore not mapped by AlpES. As most NbS identified have been implemented after the data acquisition to map NCP indicators (e.g. 2012 for land use and land cover maps), we assumed that the NbS identified have not influenced NCP values (Schirpke et al. 2019a; Meisch et al. 2019; Jäger et al. 2020). Moreover, because most on-the-ground NbS cover a small surface relatively to the municipality's surface, we considered that they have a low influence on NCP supply at the municipality scale.

2.3. Data analysis

To deal with the different sets of units across studied climatic and NCP variables, we rescaled their values using a min-max normalisation (Peng et al. 2016), both for positive and negative values, calculated as (1):

$$X_s = \frac{X_i - X_{min+}}{X_{max+} - X_{min+}} \; if\, X_i > 0 \; ; \; X_s = \frac{X_i - X_{max-}}{X_{min-} - X_{max-}} \; if\, X_i < 0 \qquad (1)$$

Where X_s is the rescaled value, X_i is the initial value, X_{min+} the lowest value of the subset of positive value, X_{max+} the highest value of the subset of positive value, X_{min-} the lowest value of the subset of negative value, X_{max-} the highest value of the subset of negative value.

We assigned the values of hazards and NCP layers spatially overlapping each NbS, and we performed Wilcoxon tests in order to detect whether values of hazards and NCP within NbS addressing them are significantly higher or lower than across the entire Alps (for details, see Supplementary File 2).

To detect whether the presence of NbS in the Alps reflects the combination of the intensity of the targeted climatic hazard and of the NCP known to help adapt to, or impacted by this hazard, we first created subsets of NbS targeting a specific combination of hazards and NCP known to address the impact. Given available data these were: drought hazards addressed by NbS aiming to provide freshwater; drought hazards addressed by NbS aiming to provide grassland fodder; drought hazards addressed by NbS aiming to produce wood; heatwave hazards addressed by NbS aiming to produce wood. For each of them, we then computed two heatmaps of value distributions across the gradients of climatic hazard and NCP values, one for NbS locations and one for the entire Alps. We then subtracted the heatmaps of the Alps from the NbS heatmaps and used a Khi2 test to detect whether the NbS distribution is different from the distribution across the Alps.

3. Results

3.1. The multifunctionality of Nature-based Solutions in the Alps

We identified 97 NbS in the Alps (Fig. 1, for details in Supplementary File 5), addressing in total 22 different hazards in relation to climate change, and aiming to provide 22 different NCP. A quarter of NbS implement activities on the ground only (n=23), a quarter of NbS are enabling activities (n=23), and around half of the NbS are mixed (n=51), implementing simultaneously enabling activities and activities on the ground.

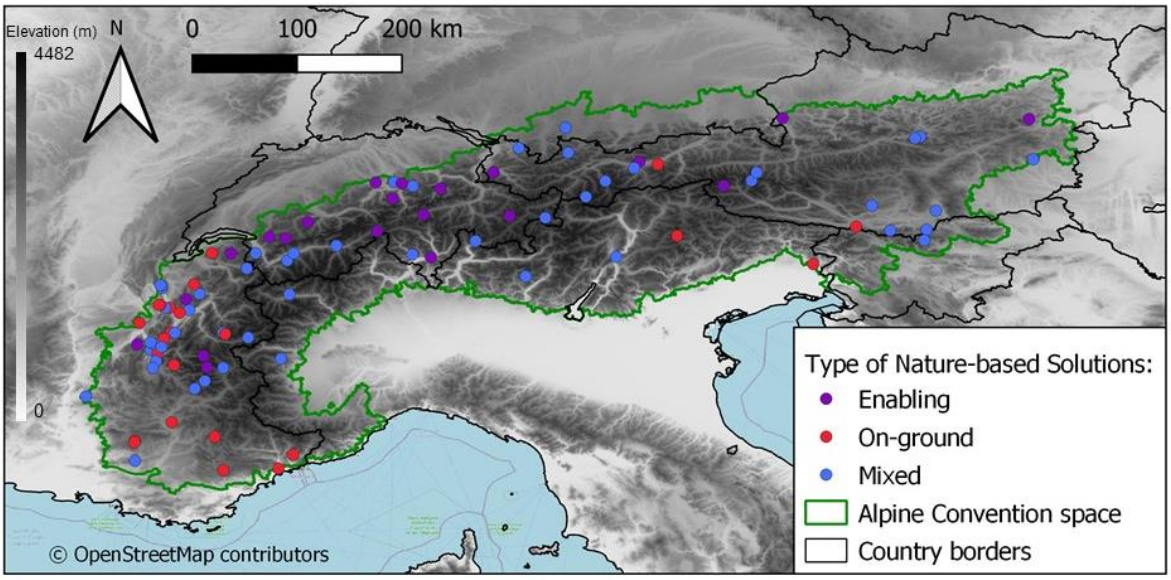

Fig. 1: Map of the 97 Nature-based Solutions identified within the Alps.

Overall, NbS across the Alps address a diversity of hazards. Half of NbS documented in our database aim to address at least two hazards simultaneously (51%). NbS addressing three (9%) or four hazards simultaneously (5%) are enabling activities that aim to counteract several hazards or target several sectors, such as research projects or local adaptation plans designed with stakeholders from multiple sectors (Supplementary File 5). Each NbS often aims to provide more than one NCP, which highlights the multifunctionality potential of NbS in terms of NCP they aim to deliver (Fig. 2). Hazards related to temperature changes are those most commonly addressed by NbS, including drought (32% of NbS), heatwaves (11%) and increasing temperature (6%). Among these, drought is associated with the highest diversity of NCP. Overall, NbS targeting drought aim to address 19 different NCP, including material NCP (mainly food), regulating NCP (mainly freshwater supply and soil quality) and non-material NCP (providing outdoor recreation activities) (Fig. 2). NbS also commonly address hazards related to soil stability, specifically landslides (11%), rock falls (7%), soil erosion

(10%), avalanches (7%), and mudslides events (2%). Among these, NbS addressing landslides and rockfalls co-occur with 14 different NCP in total, mainly those related to the protective function against landslides. NbS addressing vector and water-borne diseases (32% of NbS – related to pests) co-occur with 14 different NCP in total, mainly the material NCP of wood production and the pest control regulating NCP (Fig. 2).

When considering NCP, NbS mainly aim to provide materials, mainly wood production (31%), and address a total of at least 17 different hazards (mainly landslides and vector and water-borne diseases) (Fig. 2). A large number of NbS (29%) aim to provide food production NCP, and they address mostly food insecurity and drought hazards. A significant number of NbS aims to provide regulating NCP particularly the regulation of floods (15%), the protective function against landslides (14%) and the regulation of heatwaves (12%). Importantly, we reported many cases of NCP co-occurrence. For example, among initiatives aiming to provide protective function against landslides, some reforestation initiatives simultaneously target avalanche prevention. This explains why most NbS (50/97) aim to provide at least two NCP simultaneously, and seven NbS aim to provide more than five NCP simultaneously.

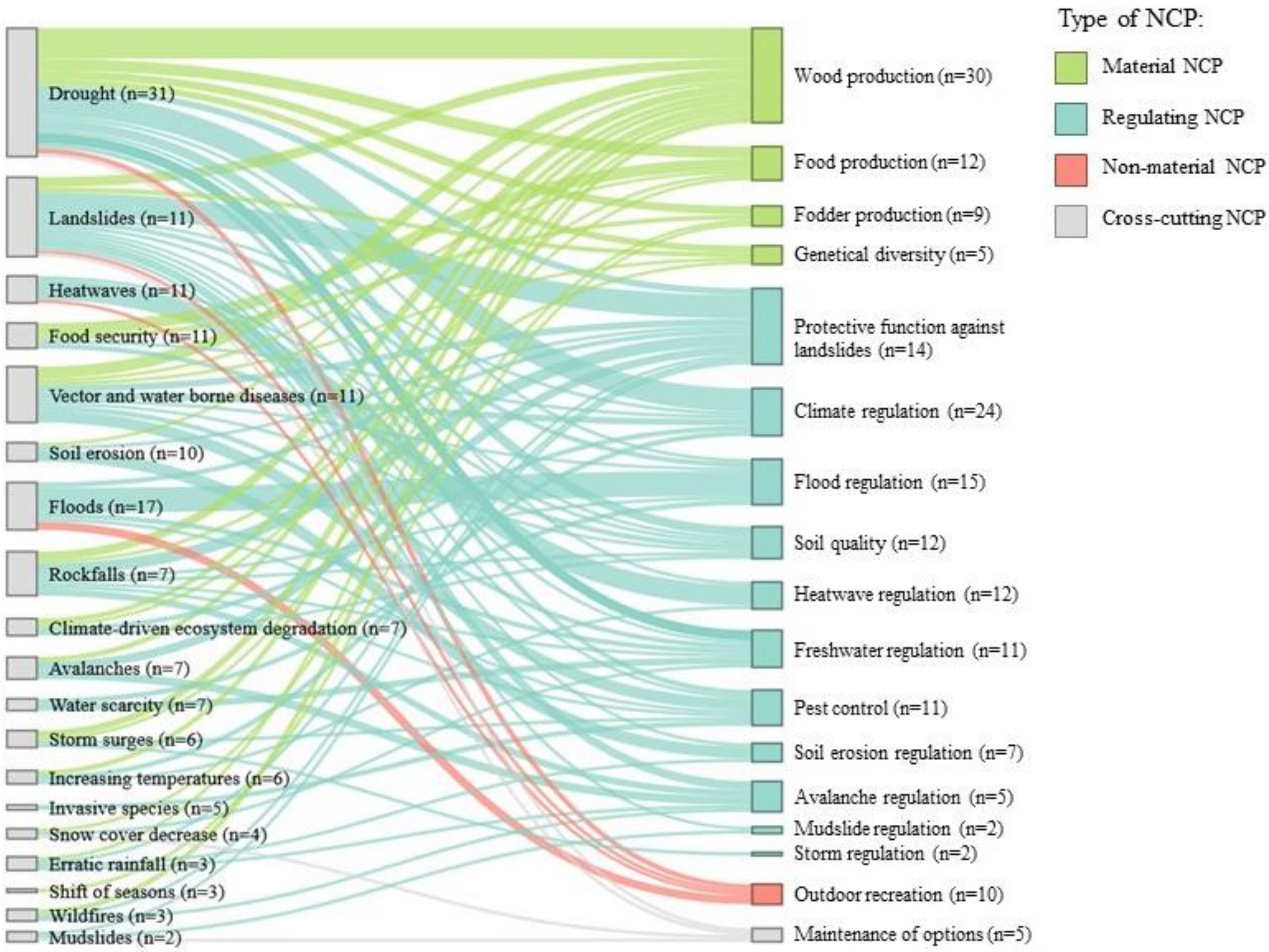

Fig. 2: Systematic map of the climatic hazards addressed by Nature-based Solutions (NbS) – on the left – and the Nature's Contributions to People (NCP) targeted by NbS – on the right. The links involving only one NbS are not represented. The number in each row indicates the number of NbS in each category.

3.2. Location of Nature-based Solutions according to climatic hazards

For most hazards, NbS are not located in areas of highest hazards within the Alps, for the historical period, the future, or for the relative change of this hazard between the two periods, except for a few exceptions (Tab. 1). NbS addressing drought are located in areas that are not currently submitted to higher hazards than across the Alps. However, they do target areas that are projected to experience more intense drought, with greater changes in the drought index. On the contrary, NbS addressing heatwaves are located in areas that have experienced lower occurrence in the historical period than the Alps overall and that are likely to experience lower heatwaves in the future. Similarly, NbS addressing snow cover reduction are located where the snow cover will be less reduced during summer than across the Alps, with a lower reduction in summer snow cover from the historical to the future period. NbS addressing floods are located where the flood index is higher in the historical period than across the Alps. However, we found future flood hazards to be lower within NbS than across the Alps. Distributions of hazard values for each NbS are illustrated in the Supplementary File 6.

Tab. 1 : Wilcoxon tests results comparing climatic variable values within Nature-based Solutions (NbS) and across the Alps. Significance level: (*): p-value <0.1 ; (**): p-value <0.05 ; (***): p-value <0.01; NS: not-significant. n: number of NbS.

Addressed-hazard	Seasonality	Historical	Future	Relative change
Temperature change (n=6)	Annual	NS	NS	NS
Heatwaves (n=11)	Annual	NbS < Alps (***)	NbS < Alps (*)	NbS < Alps (*)
Drought (n=38)	Annual	NS	NbS > Alps (***)	NbS > Alps (***)
Wildfires (n=3)	Annual	NS	NS	NS
Floods (n=17)	Annual	NbS > Alps (***)	NbS < Alps (***)	NbS > Alps (***)
Precipitation change (n=9)	Annual	NS	NS	NS
	Winter	NS	NS	NS
	Spring	NS	NS	NS
	Summer	NS	NS	NS
	Autumn	NS	NS	NS
Snow cover reduction (n=4)	Winter	NS	NS	NS
	Spring	NS	NS	NS
	Summer	NS	NbS < Alps (***)	NbS < Alps (***)
	Autumn	NS	NS	NS

3.3. Location of Nature-based Solutions according to Nature's Contributions to People

NbS follow different spatial patterns in relation to the distribution of NCP supply, flow, demand and their ratios. NbS targeting fodder production and outdoor recreation NCP are generally not located where their supply or demand differ from the Alps (Tab. 2). In contrast, NbS targeting freshwater supply are located where its flow value, namely water use, is higher than across the Alps. Similarly, NbS targeting protective function against landslides are located in hotspots of its flow-supply ratio, mostly reflecting the higher value of the flow. This indicates that these NbS are implemented where the NCP is highly used, independently of the supply and demand. NbS targeting wood production are located in areas where they are least needed as they are located where fuel wood demand is lower and supply is higher compared to the Alps. NbS targeting CO_2 sequestration are located in areas where supply is higher than across the Alps, yet where demand is also higher. Finally, regarding symbolic biodiversity all NbS are located in areas with lower values of both supply and flow than across the Alps. Distributions of NCP values for each NbS are illustrated in the Supplementary File 7.

Tab. 2 : Wilcoxon tests results comparing Nature's Contributions to People (NCP) values within Nature-based Solutions (NbS) and across the Alps. D-S ratio means NCP demand-supply ratio. F-S ratio means NCP flow-supply ratio. D-S/F ratio is used when the supply and the flow are equivalent. Significance level: (*): p-value <0.1 ; (**): p-value <0.05 ; (***): p-value <0.01; NS: Not-significant. The number on each row indicates the number of NbS targeting the specific NCP

NCP	Demand	D-S ratio	Supply	F-S ratio	Flow
Freshwater (n=11)	NS	NS	NS	NS	NbS > Alps (***)
Fodder (n=9)	NS	NS	NS	NS	NS
Fuel wood (n=30)	NbS < Alps (**)	NS	NbS > Alps (*)	NS	NS
Protective function against landslides (n=14)	NS	NS	NS	NbS > Alps (*)	NbS > Alps (*)
Outdoor recreation (n=10)	NS	NS	NS	NS	NS
Symbolic biodiversity (n=97)	*NA*	*NA*	NbS < Alps (**)	NS	NbS < Alps (*)
NCP	**Demand**	**D-S/F ratio**	**Supply/Flow**		
CO2 sequestration (n=24)	NbS > Alps (**)	NS	NbS > Alps (***)		

3.4. Location of Nature-based Solutions according to the combination of climatic hazards and Nature's Contributions to People

Consistent with our findings for climatic hazards and NCP supply, flow and demand, overall NbS are not located in combined hotspots of relative change in hazards and NCP flow-supply ratio, nor in combination with the NCP demand-supply ratio. In the following we focus in particular on the distribution of values within the most numerous NbS addressing drought hazards in combination with NCP of freshwater, fodder or wood production, and NbS addressing heatwaves in combination with wood production (Fig. 3). Our analyses show that values within NbS are similar to those across the Alps regarding the future relative change in drought index and NCP flow-supply and demand-supply ratios. However, NbS addressing drought appear to be concentrated in the upper values of relative change in the drought index, whatever the targeted NCP, in comparison with Alps values (Fig. 3). Nevertheless, the distributions of values within NbS addressing drought differ across targeted NCP. NbS targeting fodder and wood production match upper values of their flow-supply ratio, while the NbS addressing the freshwater NCP are uniformly distributed along the drought change gradient.

We also assessed the combination of relative change in fire hazard and wood production NCP. While the distribution of values within NbS is not statistically different to those across the Alps, our analyses show an absolute greater occurrence of NbS at the higher end of the hazard gradient in conjunction with the medium-to-high range of the wood production flow-supply ratio (Supplementary File 8), suggesting further analysis of this potential correlation.

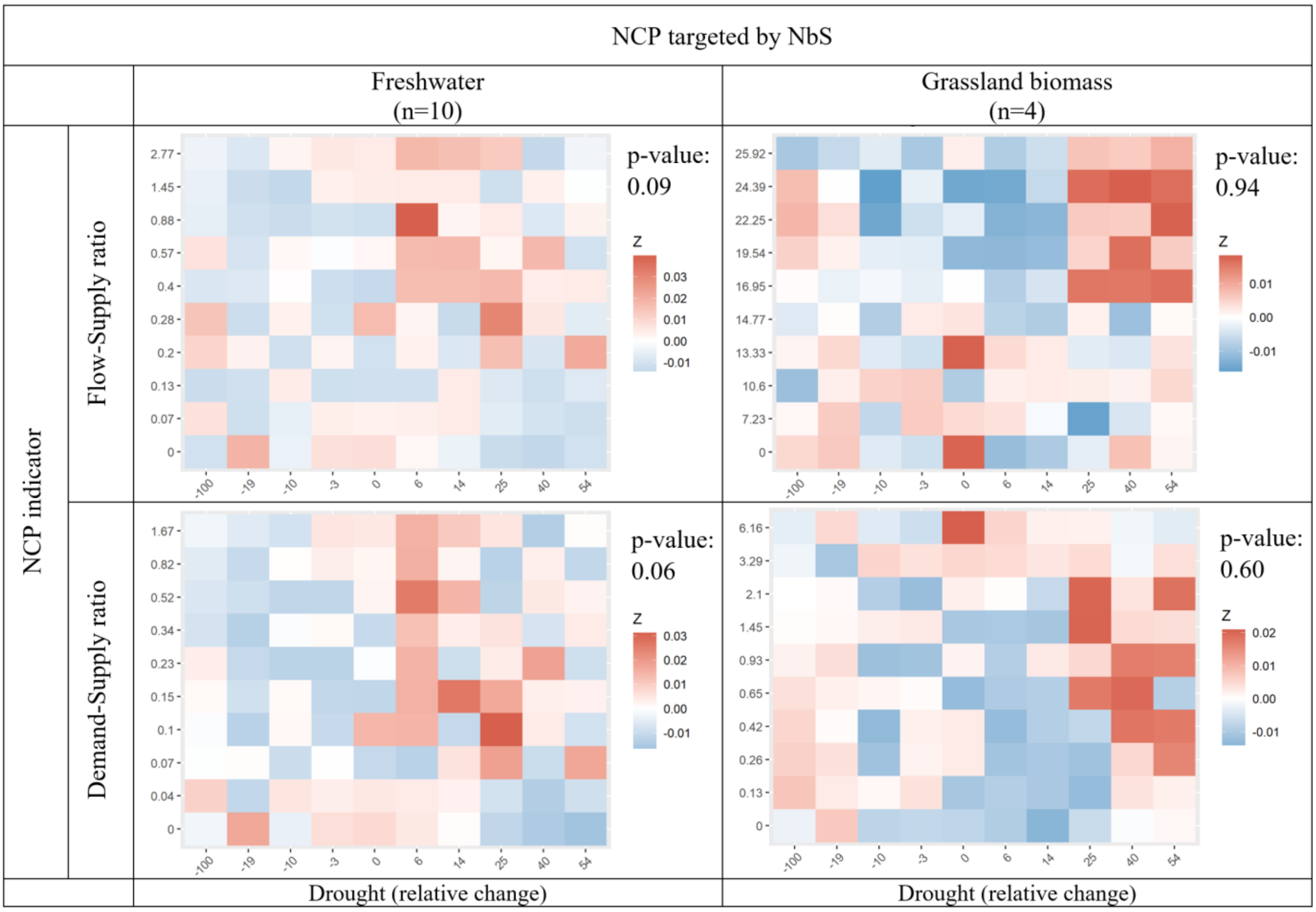

Fig. 3: Heatmaps displaying the associations between one climate-related hazard (horizontal axis) and one Nature's Contributions to People (NCP) indicator (vertical axis). The values correspond to the difference between the number of values within Nature-based Solutions (NbS) addressing the hazard as well as the NCP and the values within the entire Alps distributed along the gradient of the hazard and the NCP. The number (n) associated to each NCP corresponds to the number of NbS addressing both hazard and NCP for each heatmap.

4. Discussion

This study explores climate change adaptation within a large region, and questions the spatial location of NbS in relation to societal needs, by focusing on hazards and NCP. We identified 97 NbS in the Alps illustrating the diverse potential actions in various type of habitat. This portfolio confirms NbS practical implementation including the creation of knowledge for nature-based climate change adaptation on the ground (Debele et al. 2019; Vij et al. 2021) as well as enabling initiatives (Donatti et al. 2020). However, we found that in general NbS are not located in areas of higher current and future climatic hazards, nor of greater NCP supply-flow-demand indicators. We discuss in the following sections what drives implementation of adaptation initiatives such as NbS, and first explore the barriers of implementation that can explain why NbS did not match the greatest climatic hazards and NCP levels. Secondly, we explore the further consideration of socio-ecological and climatic conditions for optimal NbS location. Lastly, we address recommendations to overcome the limited knowledge on NbS effectiveness for climate change adaptation (Seddon et al. 2019; Donatti et al. 2020), through a macro-regional programme supporting adaptation of areas experiencing the most intense hazards and higher impacts on NCP.

4.1. Diversity and multifunctionality of Nature-based Solutions for climate change adaptation

Consistent with previous syntheses, we found that NbS in the Alps have the potential to address multiple hazards (Chausson et al. 2020; Palomo et al. 2021). Some hazards are addressed jointly because of their similar nature and biophysical mechanisms, for example NbS addressing several natural hazards such as landslides and avalanches through forest protection, management and restoration. But co-occurring hazards of different natures are also addressed jointly by NbS, such as wildfires and natural pests through sustainable forest management (Felipe-Lucia et al. 2018; Stritih et al. 2021). Drought and floods are also addressed jointly by wetland restoration, which is known to be effective when well designed (Erwin 2009).

As highlighted in previous reviews, most of the NbS we identified aim to maintain a NCP threatened by climate change hazards, and to provide multiple NCP co-benefits (Brink et al. 2016; Osaka et al. 2021). While a large proportion of NbS target material NCP, such as wood, fodder and food production, the NbS which we documented across the Alps involved a large diversity of ecosystems, such as forests, pastures, wetlands, bare rock and urban areas. They are not predominantly located within a given ecosystem, such as previous study on European NbS (Vij et al. 2021), but in contrast with global review identifying NbS mostly in forests (Chausson et al. 2020).

4.2. Nature-based Solutions are distributed across a range of climate change hazard levels

Although NbS in the Alps are overall not located in hotspots of the current and future hazards they target, we found a few significant trends for NbS addressing specific hazards. For example, NbS addressing drought are located in areas where drought will be more severe in the future than across the Alps. While NbS locations are not associated with current droughts, this result is consistent with a previous study illustrating that local adaptation initiatives in Mediterranean agriculture are implemented where farmers experience higher temperatures and more intense water scarcity (Harmanny and Malek 2019). NbS addressing floods are located within hotspots of current hazard, but not in areas of higher future hazard. This focus on current rather than future hazard can be explained by the future decrease of flood risk in lowlands due to change in precipitation patterns in future climate scenarios for the Alps (Beniston and Stoffel 2016; Wilhelm et al. 2022). For example, NbS addressing floods are mostly located to protect downstream cities such as Innsbruck (Austria) or Vizille (France) from current flood events. Although here we did not consider impacted populations and their adaptive capacity, a previous study reported a mismatch between nature-based adaptation initiatives for flood regulation and where they are the most needed (Houghton and Castillo-Salgado 2020).

A large part of the NbS from our database addresses droughts and floods. It can be explained by the fact that these two hazards impact NCP supply from various sectors, like agriculture (Tello-García et al. 2020), forestry (Elkin et al. 2013), and natural disaster risk reduction (Mina et al. 2017), with severe economic impacts (Fraser et al. 2013; Andres and Badoux 2019; Brèteau-Amores et al. 2019). Moreover, the assessment and adaptation of these two hazards are hot topics in the literature(Aguiar et al. 2018; Mubeen et al. 2021), especially in mountain areas(Deléglise et al. 2019; Zingraff-Hamed et al. 2021a) and this can contribute to the large number of adaptation actions (Cook et al. 2012; Street et al. 2019).

Contrary to drought and floods, NbS addressing heatwaves are located in areas with lower hazard occurrence than across the Alps. While we have not explored the fine-resolution land cover of areas where NbS are implemented, in our database NbS that address heatwaves are green infrastructure within urban areas, where vulnerability to heatwaves is higher (Jagarnath et al. 2020). However, the heatwave index used in this study is based on predicted temperatures, which increase most in higher-altitude areas, therefore not fully relevant to these NbS. Future analyses would need to include urban heat islands as a hazard that urban NbS are addressing by controlling temperature with trees (Schwaab et al. 2021).

The paucity of NbS addressing snow cover reduction and wildfires can explain the non-significant results regarding these, for which further studies are needed. Nevertheless, we found that NbS addressing snow cover reduction are located where changes will be lower in summer than across the Alps. This is because they refer to three enabling NbS that focus on ski resorts at higher altitudes that are less affected by snow cover change during winter but with higher change during summer (Beaumet et al. 2021). While our database is not exhaustive, the relatively small number of initiatives identified for ski resorts adaptation is consistent with previous syntheses showing limited nature-based interventions from the skiing sector, which still mainly invests in snowmaking solutions (Berard-Chenu et al. 2021). Concerning wildfires, although climate change is expected to increase their frequency in the Alps (Stritih et al. 2021), impacts are not severe or intense enough yet as a single threat to mountain forests (Kulakowski et al. 2017), especially outside of the southern Alps (Bebi et al. 2017). Our results are thus in line with this current low risk perception, with the three NbS addressing wildfires targeting multiple co-benefits of adaptation to landslides, storms or drought.

The location of NbS addressing increasing temperature or precipitation appeared independent of the geographic distribution of these two climatic variables. Although they are leading indicators of climate change in the literature (Field and Barros 2014), we identified relatively few NbS addressing these drivers directly. This may be because, except for their direct impacts on shifts in species niches or changes in plant phenology, their socio-ecological impacts are indirect through increased intensity of hazards like floods or avalanches (Gobiet and Kotlarski 2020).

4.3. Nature-based Solutions location according to NCP demand, supply and flow

Overall, we found that NbS location was in general poorly related to hotspots of NCP demand, supply or flow. Nevertheless, our analyses showed that many NbS are located in areas needing protective function against landslides according to the flow of this NCP. A visual analysis confirmed that they tend to be situated in probable release areas above settlements that need protection, such as railways, roads or infrastructure (see Supplementary File 5). This suggests accurate perceptions of risks and NCP by managers, in spite of contentions this may not be the case (Stritih et al. 2021). In contrast, NbS targeting the freshwater NCP are located where freshwater flow (indicating the water use by inhabitants) is highest across the Alps, but not in hotspots of freshwater supply (indicating water availability). In the Alps, as happens in many mountain massifs, hotspots of freshwater supply (upstream) and flow (in lowlands) are disjoint (Meisch et al. 2019). Thus, NbS appeared to focus on areas where freshwater is used rather than on supplying areas which are often located at high altitude areas which also have lower population density (Meisch et al. 2019).

Symbolic biodiversity and climate mitigation CO_2 sequestration are two NCP for which demand is global, but supply is local or regional. While biodiversity conservation is a priority goal of NbS (Cohen-Shacham et al. 2016), we found that locations of NbS for climate change adaptation are unrelated to symbolic biodiversity, which is mainly located within protected areas (Schirpke et al. 2018). In-depth analyses would need to investigate whether NbS implemented outside protected areas are located where the value of symbolic biodiversity is higher or lower than within non-protected alpine areas. Furthermore, only few NbS identified in the Alps mention a symbolic species; they rather target species with a key functional role like *Pinus heldreichii* to test new tree varieties or *Carex nigra* to characterise the wetland restoration success. The case of symbolic biodiversity contrasts with climate mitigation. Although not directly motivated by climate change mitigation, many NbS identified for climate change adaptation across the Alps are located within low- to mid-elevation forests with higher, even if not maximum values of both demand and supply for the CO_2 sequestration NCP (Schirpke et al. 2019a).

4.4. Combination of climatic hazards and NCP for Nature-based Solutions implementation

While climatic hazards and socio-ecological variables have been used to prioritise areas for implementing NbS for climate change adaptation (Bourne et al. 2016), the location of NbS in this study does not generally coincide with climatic hazards or NCP, neither with their combinations. Of all the combinations of hazards and NCP assessed, our results suggest that only NbS targeting the resilience of freshwater supply to drought are located where drought threatens this NCP's flow. Indeed agricultural practices and especially irrigation are emerging as responses to drought impacts in mountain areas (Grüneis et al. 2018; Bergeret and Lavorel 2022), as in other regions (Harmanny and Malek 2019). Although the results were not significant, NbS targeting the resilience of fodder production to drought appeared to be located in the areas most exposed to drought and with a higher fodder flow, namely high mountain pastures, whose forage production is known to be vulnerable to climate change (Schirpke et al. 2017; Deléglise et al. 2022) and where adaptation of practices is essential (Nettier et al. 2017). Nevertheless, hazards perceived by stakeholders, and therefore adaptation behaviours, are not always associated with the most sensitive conditions, as previously observed in the French Alps (Bruley et al. 2021b).

4.5. Limitations of the study

Our analyses had four main limitations. First, we acknowledge that the database of NbS we compiled is not exhaustive, and therefore, further studies that include a larger number of NbS are needed, particularly for targeted hazards for which the number of NbS we identified was lower, such as for temperature change, wildfires, snow cover or precipitation changes. Reviewing grey literature is a practical way to identify NbS and adaptation initiatives (Zingraff-Hamed et al. 2021b). Although we identified almost one hundred initiatives, our database is limited as identifying and georeferencing all NbS implemented in the Alps is impossible. As our analysis is mainly based on project documentation, we were limited in understanding reports published in other languages than English and French. This also explains why we identified more initiatives in France, but when analysing NbS addressing a specific hazard or NCP, the limited number of NbS for each alpine country reduced this bias *de facto*.

Secondly, our analyses were further constrained by the coarse spatial resolution for climatic hazards (5 km² for the flood index) that might also be a source of mismatch, where some pixels covering up to a 1000 m elevation range may not provide an accurate flood hazard value for NbS implemented in valleys, nor capture change in future hazards for small catchments (Wilhelm et al. 2022). As the on-the-ground NbS usually had a small extent, a more precise estimation of the hazard value could yield different results for some specific NbS. Moreover, other socio-economic factors may better capture societal needs for NbS through aspects of exposure or vulnerability to hazards (Pörtner et al. 2022). However, these were included in several NCP indicators. For example, demand for freshwater and outdoor recreation activities were assessed through population density and tourism statistics. As another example, the quantification of the demand for the protective function of forest against landslides is based on the presence of infrastructure at risk (Schirpke et al. 2019a; Meisch et al. 2019). Thirdly, the overall mismatch between NbS and NCP needs to be considered cautiously given we used NCP values mapped at municipality level (Schirpke et al. 2019a), while some NbS are smaller than the municipality in which they are implemented. This may conceal local social needs or biophysical details, especially land use at finer resolution. For example, the protective forest against landslides implemented in Engadin (Switzerland) covers 45 ha, while the municipality in which it implemented is 20 000 ha, with 20% covered by forest. As a result, the municipal data indicates a low level of wood supply, while the NbS is well located to protect downstream settlements. Likewise, our approach did not allow us to assess the spatial location of NbS in relation to certain vulnerable social groups, as for example for heatwaves impacting elderly people and children in urban areas (Kabisch et al. 2017).

Fourthly, our spatial analysis explored the combination between current or future climatic conditions and NCP supply-flow-demand representing socio-ecological conditions. However, as we focused solely on initiatives that aim to adapt to climate change, we did not consider multiple other anthropogenic pressures on ecosystems that must be examined in future analyses of NbS optimal locations (Egarter Vigl et al. 2021). Furthermore, we only analysed climatic hazards rather than their potential impacts on future NCP supply, which is likely to be reshaped due to combined climate and land-use changes (Dunford et al. 2015; Mouchet et al. 2017; Schirpke et al. 2017). We did not consider climate-driven ecosystem transformation, which with the exception of glacier retreat is unlikely at higher altitudes in the short term (Schirpke et al. 2020).

4.6. Recommendations for outscaling Nature-based Solutions

To implement NbS for climate change adaptation, integrating current and future climate conditions and NCP indicators into spatial planning tools is essential for avoiding maladaptation (Lavorel et al. 2015; Pártl et al. 2017; Hurlimann et al. 2021). Moreover, they need to be combined with local decision contexts to offer effective solutions (Kruse and Pütz 2014). Spatial planning is still poorly addressed for NbS (Bourne et al. 2016), especially in Europe (Geneletti and Zardo 2016), and the establishment of appropriate processes is critical (Albert et al. 2021). Spatial planning of NbS has mostly been limited to urban areas (Brink et al. 2016; Kooy et al. 2020; Simperler et al. 2020), coastal ecosystems (Jones et al. 2020; Sutrisno et al. 2021), or locally tailored initiatives (Turconi et al. 2020; Zaimes et al. 2020). To support the future scaling of NbS and their spatial planning, future research needs to determine the personal, institutional and economic drivers of NbS implementation, such as previous experiences of climate change impacts (Demski et al. 2017; Harmanny and Malek 2019), stakeholder visions for adaptation (Lupp et al. 2021; Bergeret and Lavorel 2022), governance processes (Zingraff-Hamed et al. 2021a) and funding (Jones et al. 2017; Bruley et al. 2021a). Improving knowledge on NbS effectiveness and their cost-benefit balance compared to other types of solutions is also essential to support decision-maker choices and avoid maladaptation (Seddon et al. 2020; Seddon 2022).

Broad scale planning and active adaptation can also provide positive outcomes for climate change adaptation. Macro-regional strategies have shown their positive outcomes at national level for NbS implementation for climate change mitigation (Bradfer- Lawrence et al. 2021), at the European scale for climate change adaptation (Wende et al. 2012; Lung et al. 2013) and ecosystem restoration (Egoh et al. 2014; Schulp et al. 2016), and at the Alps to conserve biodiversity through ecological networks (Plassmann et al. 2016). Macro-regional strategies need to be strengthened for future NbS outscaling (Bennett et al. 2016; Juschten et al. 2021), so that NbS better target climatic hazards and NCP.

Conclusion

Climate change is already threatening mountain ecosystems and the NCP they provide to local and distant communities. We found that NbS are implemented in the Alps to tackle the diverse impacts of climate change and to increase or maintain the supply of several NCP. While few NbS are located within hotspots of climate change hazards, such as for droughts and current floods, NbS are generally not located within the hotspots of the current or future hazards they claim to address, neither within NCP hotspots, nor where they coincide. This reveals the need to explore the NbS decision-making context with an interdisciplinary approach including in particular institutional and economic aspects, personal values and knowledge. Our findings also suggest the need to integrate local climatic projections and NCP quantification into future planning of NbS. A macro-regional strategy in combination with local stakeholder engagement has the potential to meet this challenge.

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References

Aguiar FC, Bentz J, Silva JMN, Fonseca AN, Swart R, et al (2018) Adaptation to climate change at local level in Europe: An overview. Environ Sci Policy 86:38–63. https://doi.org/10.1016/j.envsci.2018.04.010

Albert C, Brillinger M, Guerrero P, Gottwald S, Henze J, et al (2021) Planning nature-based solutions: Principles, steps, and insights. Ambio 50:1446–1461. https://doi.org/10.1007/s13280-020-01365-1

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Andres N, Badoux A (2019) The Swiss flood and landslide damage database: Normalisation and trends. J Flood Risk Manag 12:. https://doi.org/10.1111/jfr3.12510

Beaumet J, Ménégoz M, Morin S, Gallée H, Fettweis X, et al (2021) Twentieth century temperature and snow cover changes in the French Alps. Reg Environ Change 21:114. https://doi.org/10.1007/s10113-021-01830-x

Bebi P, Seidl R, Motta R, Fuhr M, Firm D, et al (2017) Changes of forest cover and disturbance regimes in the mountain forests of the Alps. For Ecol Manag 388:43–56. https://doi.org/10.1016/j.foreco.2016.10.028

Beccari B (2016) A Comparative Analysis of Disaster Risk, Vulnerability and Resilience Composite Indicators. PLoS Curr 8:ecurrents.dis.453df025e34b682e9737f95070f9b970. https://doi.org/10.1371/currents.dis.453df025e34b682e9737f95070f9b970

Beniston M, Stoffel M (2016) Rain-on-snow events, floods and climate change in the Alps: Events may increase with warming up to 4 °C and decrease thereafter. Sci Total Environ 571:228–236. https://doi.org/10.1016/j.scitotenv.2016.07.146

Bennett EM, Solan M, Biggs R, McPhearson T, Norström AV, et al (2016) Bright spots: seeds of a good Anthropocene. Front Ecol Environ 14:441–448. https://doi.org/10.1002/fee.1309

Berard-Chenu L, Cognard J, François H, Morin S, George E (2021) Do changes in snow conditions have an impact on snowmaking investments in French Alps ski resorts? Int J Biometeorol 65:659–675. https://doi.org/10.1007/s00484-020-01933-w

Bergeret A, Lavorel S (2022) Stakeholder visions for trajectories of adaptation to climate change in the Drôme catchment (French Alps). Reg Environ Change 22:33. https://doi.org/10.1007/s10113-022-01876-5

Birkmann J, Jamshed A, McMillan JM, Feldmeyer D, Totin E, et al (2022) Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. Sci Total Environ 803:150065. https://doi.org/10.1016/j.scitotenv.2021.150065

Boni R, Perrone LL, Cecchini S (2014) Heat stress affects reproductive performance of high producing dairy cows bred in an area of southern Apennines. Livest Sci 160:172–177. https://doi.org/10.1016/j.livsci.2013.11.016

Bourne A, Holness S, Holden P, Scorgie S, Donatti CI, et al (2016) A Socio-Ecological Approach for Identifying and Contextualising Spatial Ecosystem-Based Adaptation Priorities at the Sub-National Level. PLOS ONE 11:e0155235. https://doi.org/10.1371/journal.pone.0155235

Bradfer-Lawrence T, Finch T, Bradbury RB, Buchanan GM, Midgley A, et al (2021) The potential contribution of terrestrial nature-based solutions to a national 'net zero' climate target. J Appl Ecol 1365-2664.14003. https://doi.org/10.1111/1365-2664.14003

Brambilla M, Resano-Mayor J, Scridel D, Anderle M, Bogliani G, et al (2018) Past and future impact of climate change on foraging habitat suitability in a high-alpine bird species: Management options to buffer against global warming effects. Biol Conserv 221:209–218. https://doi.org/10.1016/j.biocon.2018.03.008

Brèteau-Amores S, Brunette M, Davi H (2019) An Economic Comparison of Adaptation Strategies Towards a Drought-induced Risk of Forest Decline. Ecol Econ 164:106294. https://doi.org/10.1016/j.ecolecon.2019.04.006

Brink E, Aalders T, Ádám D, Feller R, Henselek Y, et al (2016) Cascades of green: A review of ecosystem-based adaptation in urban areas. Glob Environ Change 36:111–123. https://doi.org/10.1016/j.gloenvcha.2015.11.003

Bruley E, Locatelli B, Colloff MJ, Salliou N, Métris T, et al (2021a) Actions and leverage points for ecosystem-based adaptation pathways in the Alps. Environ Sci Policy 124:567–579. https://doi.org/10.1016/j.envsci.2021.07.023

Bruley E, Locatelli B, Vendel F, Bergeret A, Elleaume N, et al (2021b) Historical reconfigurations of a social–ecological system adapting to economic, policy and climate changes in the French Alps. Reg Environ Change 21:34. https://doi.org/10.1007/s10113-021-01760-8

Burkhard B, Maes J (eds) (2017) Mapping ecosystem services. Pensoft Publishers, Sofia, Bulgaria

Carboni M, Guéguen M, Barros C, Georges D, Boulangeat I, et al (2018) Simulating plant invasion dynamics in mountain ecosystems under global change scenarios. Glob Change Biol 24:e289–e302. https://doi.org/10.1111/gcb.13879

Casagrande Bacchiocchi S, Zerbe S, Cavieres LA, Wellstein C (2019) Impact of ski piste management on mountain grassland ecosystems in the Southern Alps. Sci Total Environ 665:959–967. https://doi.org/10.1016/j.scitotenv.2019.02.086

Chamberlain D, Brambilla M, Caprio E, Wellstein C (2016) Alpine bird distributions along elevation gradients: the consistency of climate and habitat effects across geographic regions. Oecologia 181:1139–1150. https://doi.org/10.1007/s00442-016-3637-y

Chausson A, Turner B, Seddon D, Chabaneix N, Girardin CAJ et al (2020) Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob Change Biol 26:6134–6155. https://doi.org/10.1111/gcb.15310

Cohen-Shacham E, Walters G, Janzen C, Maginnis S (eds) (2016) Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature, Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2016.13.en

Colloff MJ, Wise RM, Palomo I, Lavorel S, Pascual U (2020) Nature's contribution to adaptation: insights from examples of the transformation of social-ecological systems. Ecosyst People 16:137–150. https://doi.org/10.1080/26395916.2020.1754919

Cook CN, Carter RW (Bill), Fuller RA, Hockings M (2012) Managers consider multiple lines of evidence important for biodiversity management decisions. J Environ Manage 113:341–346. https://doi.org/10.1016/j.jenvman.2012.09.002

Debele SE, Kumar P, Sahani J, Marti-Cardona B, Mickovski SB, et al (2019) Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. Environ Res 179:108799. https://doi.org/10.1016/j.envres.2019.108799

Deléglise C, Dodier H, Garde L, François H, Arpin I, et al (2019) A Method for Diagnosing Summer Mountain Pastures' Vulnerability to Climate Change, Developed in the French Alps. Mt Res Dev 39:. https://doi.org/10.1659/MRD-JOURNAL-D-18-00077.1

Deléglise C, François H, Dodier H, Crouzat E, Samacoïts R, et al (2022) Agro-climatic profiles of summer mountain pastures in the French Alps: towards a monitoring tool to contribute to climate risk assessment. Agron Sustain Dev 42:40. https://doi.org/10.1007/s13593-022-00776-6

Demski C, Capstick S, Pidgeon N, Sposato RG, Spence A (2017) Experience of extreme weather affects climate change mitigation and adaptation responses. Clim Change 140:149–164. https://doi.org/10.1007/s10584-016-1837-4

Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, et al (2018) Assessing nature's contributions to people. Science 359:270–272. https://doi.org/10.1126/science.aap8826

Dirnböck T, Essl F, Rabitsch W (2011) Disproportional risk for habitat loss of high-altitude endemic species under climate change. Glob Change Biol 17:990–996. https://doi.org/10.1111/j.1365-2486.2010.02266.x

Donatti CI, Harvey CA, Hole D, Panfil SN, Schurman H (2020) Indicators to measure the climate change adaptation outcomes of ecosystem-based adaptation. Clim Change 158:413–433. https://doi.org/10.1007/s10584-019-02565-9

Dullinger S, Gattringer A, Thuiller W, Moser D, Zimmermann NE, et al (2012) Extinction debt of high-mountain plants under twenty-first-century climate change. Nat Clim Change 2:619–622. https://doi.org/10.1038/nclimate1514

Dunford RW, Smith AC, Harrison PA, Hanganu D (2015) Ecosystem service provision in a changing Europe: adapting to the impacts of combined climate and socio-economic change. Landsc Ecol 30:443–461. https://doi.org/10.1007/s10980-014-0148-2

Egarter Vigl L, Marsoner T, Schirpke U, Tscholl S, Candiago S, et al (2021) A multi-pressure analysis of ecosystem services for conservation planning in the Alps. Ecosyst Serv 47:101230. https://doi.org/10.1016/j.ecoser.2020.101230

Egoh BN, Paracchini ML, Zulian G, Schägner JP, Bidoglio G, et al (2014) Exploring restoration options for habitats, species and ecosystem services in the European Union. J Appl Ecol 51:899–908. https://doi.org/10.1111/1365-2664.12251

Einhorn B, Eckert N, Chaix C, Ravanel L, Deline P, et al (2015) Changements climatiques et risques naturels dans les Alpes. J Alp Res Rev Géographie Alp. https://doi.org/10.4000/rga.2829

Elkin C, Giuggiola A, Rigling A, Bugmann H (2015) Short- and long-term efficacy of forest thinning to mitigate drought impacts in mountain forests in the European Alps. Ecol Appl 25:1083–1098. https://doi.org/10.1890/14-0690.1

Elkin C, Gutiérrez AG, Leuzinger S, Manusch C, Temperli C, et al (2013) A 2 °C warmer world is not safe for ecosystem services in the European Alps. Glob Change Biol 19:1827–1840. https://doi.org/10.1111/gcb.12156

Engler R, Randin CF, Thuiller W, Dullinger S, Zimmermann NE, et al (2011) 21st century climate change threatens mountain flora unequally across Europe. Glob Change Biol 17:2330–2341. https://doi.org/10.1111/j.1365-2486.2010.02393.x

Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl Ecol Manag 17:71–84. https://doi.org/10.1007/s11273-008-9119-1

Felipe-Lucia MR, Soliveres S, Penone C, Manning P, van der Plas F, et al (2018) Multiple forest attributes underpin the supply of multiple ecosystem services. Nat Commun 9:4839. https://doi.org/10.1038/s41467-018-07082-4

Ferrarini A, Alatalo JM, Gustin M (2017) Climate change will seriously impact bird species dwelling above the treeline: A prospective study for the Italian Alps. Sci Total Environ 590–591:686–694. https://doi.org/10.1016/j.scitotenv.2017.03.027

Field CB, Barros VR (2014) Climate change 2014: impacts, adaptation, and vulnerability Working Group II contribution to the fifth assessment report of the Intergovernmental panel on climate change. Cambridge university press, New York

Fraser EDG, Simelton E, Termansen M, Gosling SM, South A (2013) “Vulnerability hotspots”: Integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. Agric For Meteorol 170:195–205. https://doi.org/10.1016/j.agrformet.2012.04.008

Gariano SL, Guzzetti F (2016) Landslides in a changing climate. Earth-Sci Rev 162:227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

Geneletti D, Zardo L (2016) Ecosystem-based adaptation in cities: An analysis of European urban climate adaptation plans. Land Use Policy 50:38–47. https://doi.org/10.1016/j.landusepol.2015.09.003

Gerlitz J-Y, Macchi M, Brooks N, Pandey R, Banerjee S, et al (2017) The Multidimensional Livelihood Vulnerability Index – an instrument to measure livelihood vulnerability to change in the Hindu Kush Himalayas. Clim Dev 9:124–140. https://doi.org/10.1080/17565529.2016.1145099

Gobiet A, Kotlarski S (2020) Future Climate Change in the European Alps. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.767

Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, et al (2014) 21st century climate change in the European Alps—A review. Sci Total Environ 493:1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050

Grêt-Regamey A, Weibel B (2020) Global assessment of mountain ecosystem services using earth observation data. Ecosyst Serv 46:101213. https://doi.org/10.1016/j.ecoser.2020.101213

Grüneis H, Penker M, Höferl K-M, Schermer M, Scherhaufer P(2018) Why do we not pick the low-hanging fruit? Governing adaptation to climate change and resilience in Tyrolean mountain agriculture. Land Use Policy 79:386–396. https://doi.org/10.1016/j.landusepol.2018.08.025

Harmanny KS, Malek Ž (2019) Adaptations in irrigated agriculture in the Mediterranean region: an overview and spatial analysis of implemented strategies. Reg Environ Change 19:1401–1416. https://doi.org/10.1007/s10113-019-01494-8

Houghton A, Castillo-Salgado C (2020) Analysis of correlations between neighborhood-level vulnerability to climate change and protective green building design strategies: A spatial and ecological analysis. Build Environ 168:106523. https://doi.org/10.1016/j.buildenv.2019.106523

Hurlimann A, Moosavi S, Browne GR (2021) Urban planning policy must do more to integrate climate change adaptation and mitigation actions. Land Use Policy 101:105188. https://doi.org/10.1016/j.landusepol.2020.105188

Huss M, Bookhagen B, Huggel C, Jacobsen D, Bradley RS, et al (2017) Toward mountains without permanent snow and ice. Earths Future 5:418–435. https://doi.org/10.1002/2016EF000514

Il Choi H (2019) Assessment of Aggregation Frameworks for Composite Indicators in Measuring Flood Vulnerability to Climate Change. Sci Rep 9:19371. https://doi.org/10.1038/s41598-019-55994-y

Immerzeel WW, Lutz AF, Andrade M, Bahl A, Biemans H, et al (2020) Importance and vulnerability of the world's water towers. Nature 577:364–369. https://doi.org/10.1038/s41586-019-1822-y

Ingrisch J, Karlowsky S, Anadon-Rosell A, Hasibeder R, König A, et al (2018) Land Use Alters the Drought Responses of Productivity and CO2 Fluxes in Mountain Grassland. Ecosystems 21:689–703. https://doi.org/10.1007/s10021-017-0178-0

Irauschek F, Rammer W, Lexer MJ (2017) Evaluating multifunctionality and adaptive capacity of mountain forest management alternatives under climate change in the Eastern Alps. Eur J For Res 136:1051–1069. https://doi.org/10.1007/s10342-017-1051-6

Jagarnath M, Thambiran T, Gebreslasie M (2020) Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa—identifying urban planning priorities for adaptation. Clim Change 163:807–829. https://doi.org/10.1007/s10584-020-02908-x

Jäger H, Peratoner G, Tappeiner U, Tasser E (2020) Grassland biomass balance in the European Alps: current and future ecosystem service perspectives. Ecosyst Serv 45:101163. https://doi.org/10.1016/j.ecoser.2020.101163

Jones AE, Turner J, Caminade C, Heath AE, Wardeh M, et al (2019) Bluetongue risk under future climates. Nat Clim Change 9:153–157. https://doi.org/10.1038/s41558-018-0376-6

Jones HP, Hole DG, Zavaleta ES (2012) Harnessing nature to help people adapt to climate change. Nat Clim Change 2:504–509. https://doi.org/10.1038/nclimate1463

Jones HP, Nickel B, Srebotnjak T, et al (2020) Global hotspots for coastal ecosystem-based adaptation. PLOS ONE 15:e0233005. https://doi.org/10.1371/journal.pone.0233005

Jones L, Champalle C, Chesterman S, Turner W, Gonzalez-Roglich M, et al (2017) Constraining and enabling factors to using long-term climate information in decision-making. Clim Policy 17:551–572. https://doi.org/10.1080/14693062.2016.1191008

Juschten M, Reinwald F, Weichselbaumer R, Jiricka-Pürrer A (2021) Developing an Integrative Theoretical Framework for Climate Proofing Spatial Planning across Sectors, Policy Levels, and Planning Areas. Land 10:772. https://doi.org/10.3390/land10080772

Kabisch N, Korn H, Stadler J, Bonn A (eds) (2017) Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-560

Kooy M, Furlong K, Lamb V (2020) Nature Based Solutions for urban water management in Asian cities: integrating vulnerability into sustainable design. Int Dev Plan Rev 42:381–390. https://doi.org/10.3828/idpr.2019.17

Kruse S, Pütz M (2014) Adaptive Capacities of Spatial Planning in the Context of Climate Change in the European Alps. Eur Plan Stud 22:2620–2638. https://doi.org/10.1080/09654313.2013.860516

Kulakowski D, Seidl R, Holeksa J, Kuuluvainen T, Nagel TA, et al (2017) A walk on the wild side: Disturbance dynamics and the conservation and management of European mountain forest ecosystems. For Ecol Manag 388:120–131. https://doi.org/10.1016/j.foreco.2016.07.037

Lamarque P, Artaux A, Barnaud C, Dobremez L, Nettier B, et al (2013) Taking into account farmers' decision making to map fine-scale land management adaptation to climate and socio-economic scenarios. Landsc Urban Plan 119:147–157. https://doi.org/10.1016/j.landurbplan.2013.07.012

Lamprecht A, Semenchuk PR, Steinbauer K, Winkler M, Pauli H (2018) Climate change leads to accelerated transformation of high-elevation vegetation in the central Alps. New Phytol 220:447–459. https://doi.org/10.1111/nph.15290

Laurent L, Buoncristiani J-F, Pohl B, Zekollari H, Farinotti D, et al (2020) The impact of climate change and glacier mass loss on the hydrology in the Mont-Blanc massif. Sci Rep 10:10420. https://doi.org/10.1038/s41598-020-67379-7

Lavorel S, Colloff MJ, Mcintyre S, Doherty MD, Murphy HT, et al (2015) Ecological mechanisms underpinning climate adaptation services. Glob Change Biol 21:12–31. https://doi.org/10.1111/gcb.12689

Li J, Jiang H, Bai Y, Alatalo JM, Li X, et al (2016) Indicators for spatial–temporal comparisons of ecosystem service status between regions: A case study of the Taihu River Basin, China. Ecol Indic 60:1008–1016. https://doi.org/10.1016/j.ecolind.2015.09.002

Lovari S, Franceschi S, Chiatante G, Fattorini L, Fattorini N, et al (2020) Climatic changes and the fate of mountain herbivores. Clim Change 162:2319–2337. https://doi.org/10.1007/s10584-020-02801-7

Lung T, Lavalle C, Hiederer R, Dosio A, Bouwer LM (2013) A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change. Glob Environ Change 23:522–536. https://doi.org/10.1016/j.gloenvcha.2012.11.009

Lupp G, Huang JJ, Zingraff-Hamed A, Oen A, Del Sepia N, et al (2021) Stakeholder Perceptions of Nature-Based Solutions and Their Collaborative Co-Design and Implementation Processes in Rural Mountain Areas—A Case Study From PHUSICOS. Front Environ Sci 9:678446. https://doi.org/10.3389/fenvs.2021.678446

Mastrotheodoros T, Pappas C, Molnar P, Burlando P, Manoli G, et al (2020) More green and less blue water in the Alps during warmer summers. Nat Clim Change 10:155–161. https://doi.org/10.1038/s41558-019-0676-5

Meisch C, Schirpke U, Huber L, Rüdisser J, Tappeiner, U (2019) Assessing Freshwater Provision and Consumption in the Alpine Space Applying the Ecosystem Service Concept. Sustainability 11:1131. https://doi.org/10.3390/su11041131

Mina M, Bugmann H, Cordonnier T, Irauschek F, Klopcic M, et al (2017) Future ecosystem services from European mountain forests under climate change. J Appl Ecol 54:389–401. https://doi.org/10.1111/1365-2664.12772

Morin S, Samacoïts R, François H, Carmagnola CM, Abegg B, et al (2021) Pan-European meteorological and snow indicators of climate change impact on ski tourism. Clim Serv 22:100215. https://doi.org/10.1016/j.cliser.2021.100215

Mouchet MA, Rega C, Lasseur R, Georges D, Paracchini ML, et al (2017) Ecosystem service supply by European landscapes under alternative land-use and environmental policies. Int J Biodivers Sci Ecosyst Serv Manag 13:342–354. https://doi.org/10.1080/21513732.2017.1381167

Mubeen A, Ruangpan L, Vojinovic Z, Sanchez Torrez A, Plavšić J (2021) Planning and Suitability Assessment of Large-scale Nature-based Solutions for Flood-risk Reduction. Water Resour Manag. https://doi.org/10.1007/s11269-021-02848-w

Nettier B, Dobremez L, Lavorel S, Brunschwig G (2017) Resilience as a framework for analyzing the adaptation of mountain summer pasture systems to climate change. Ecol Soc 22:art25. https://doi.org/10.5751/ES-09625-220425

Osaka S, Bellamy R, Castree N (2021) Framing “nature-based” solutions to climate change. WIREs Clim Change. https://doi.org/10.1002/wcc.729

Palomo I (2017) Climate Change Impacts on Ecosystem Services in High Mountain Areas: A Literature Review. Mt Res Dev 37:179–187. https://doi.org/10.1659/MRD-JOURNAL-D-16-00110.1

Palomo I, Locatelli B, Otero I, Colloff M, Crouzat E, et al (2021) Assessing nature-based solutions for transformative change. One Earth 4:730–741. https://doi.org/10.1016/j.oneear.2021.04.013

Pártl A, Vačkář D, Loučková B, Krkoška Lorencová E (2017) A spatial analysis of integrated risk: vulnerability of ecosystem services provisioning to different hazards in the Czech Republic. Nat Hazards 89:1185–1204. https://doi.org/10.1007/s11069-017-3015-z

Pauli H, Halloy SRP (2019) High Mountain Ecosystems Under Climate Change. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.764

Peng J, Chen X, Liu Y, Lü H, Hu X (2016) Spatial identification of multifunctional landscapes and associated influencing factors in the Beijing-Tianjin-Hebei region, China. Appl Geogr 74:170–181. https://doi.org/10.1016/j.apgeog.2016.07.007

Pepin NC, Arnone E, Gobiet A, Haslinger K, Kotlarski S, et al (2022) Climate Changes and Their Elevational Patterns in the Mountains of the World. Rev Geophys 60:e2020RG000730. https://doi.org/10.1029/2020RG000730

Plassmann G, Kohler Y, Badura M, Walzer C (eds) (2016) Alpine nature 2030: creating [ecological] connectivity for generations to come. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), Berlin

Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K et al (eds) (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 3–33. Cambridge University Press (2022), Cambridge, UK and New York. https://doi.org/10.1017/9781009325844.001

Sass O (2014) FIRIA – Fire risk and vulnerability of austrian forests under the impact of climate change (Endbericht), APRP 3rd Call 201. Institut für Geographie und Raumforschung, University of Graz, Graz, Austria. https://www.klimafonds.gv.at/report/acrp-3rd-call-2010

Schirpke U, Candiago S, Egarter Vigl L, Jäger H, Labadini A, et al (2019a) Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services. Sci Total Environ 651:928–941. https://doi.org/10.1016/j.scitotenv.2018.09.235

Schirpke U, Kohler M, Leitinger G, Fontana V, Tasser E, et al (2017) Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. Ecosyst Serv 26:79–94. https://doi.org/10.1016/j.ecoser.2017.06.008

Schirpke U, Meisch C, Tappeiner U (2018) Symbolic species as a cultural ecosystem service in the European Alps: insights and open issues. Landsc Ecol 33:711–730. https://doi.org/10.1007/s10980-018-0628-x

Schirpke U, Tappeiner U, Tasser E (2019b) A transnational perspective of global and regional ecosystem service flows from and to mountain regions. Sci Rep 9:6678. https://doi.org/10.1038/s41598-019-43229-z

Schirpke U, Tscholl S, Tasser E (2020) Spatio-temporal changes in ecosystem service values: Effects of land-use changes from past to future (1860–2100). J Environ Manage 272:111068. https://doi.org/10.1016/j.jenvman.2020.111068

Scholes RJ (2016) Climate change and ecosystem services. WIREs Clim Change 7:537–550. https://doi.org/10.1002/wcc.404

Schröter M, Remme RP, Hein L (2012) How and where to map supply and demand of ecosystem services for policy-relevant outcomes? Ecol Indic 23:220–221. https://doi.org/10.1016/j.ecolind.2012.03.025

Schulp CJE, Van Teeffelen AJA, Tucker G, Verburg PH (2016) A quantitative assessment of policy options for no net loss of biodiversity and ecosystem services in the European Union. Land Use Policy 57:151–163. https://doi.org/10.1016/j.landusepol.2016.05.018

Schwaab J, Meier R, Mussetti G, Seneviratne S, Bürgi C, et al (2021) The role of urban trees in reducing land surface temperatures in European cities. Nat Commun 12:6763. https://doi.org/10.1038/s41467-021-26768-w

Seddon N (2022) Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. Science 376:1410–1416. https://doi.org/10.1126/science.abn9668

Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, et al (2020) Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos Trans R Soc B Biol Sci 375:20190120. https://doi.org/10.1098/rstb.2019.0120

Seddon N, Turner B, Berry P, Chausson A, Girardin CAJ (2019) Grounding nature-based climate solutions in sound biodiversity science. Nat Clim Change 9:84–87. https://doi.org/10.1038/s41558-019-0405-0

Simperler L, Himmelbauer P, Ertl T, Stoeglehner G (2020) Prioritization of stormwater management sites in urban areas. J Environ Manage 265:110507. https://doi.org/10.1016/j.jenvman.2020.110507

Street RB, Buontempo C, Mysiak J, Karali E, Pulquério M, et al (2019) How could climate services support disaster risk reduction in the 21st century. Int J Disaster Risk Reduct 34:28–33. https://doi.org/10.1016/j.ijdrr.2018.12.001

Stritih A, Bebi P, Rossi C, Grêt-Regamey A (2021) Addressing disturbance risk to mountain forest ecosystem services. J Environ Manage 296:113188. https://doi.org/10.1016/j.jenvman.2021.113188

Sutrisno D, Darmawan M, Rahadiati A, Helmi M, Yusmur A, et al (2021) Spatial-Planning-Based Ecosystem Adaptation (SPBEA): A Concept and Modeling of Prone Shoreline Retreat Areas. ISPRS Int J Geo-Inf 10:176. https://doi.org/10.3390/ijgi10030176

Tello-García E, Huber L, Leitinger G, Peters A, Newesely C, et al (2020) Drought- and heat-induced shifts in vegetation composition impact biomass production and water use of alpine grasslands. Environ Exp Bot 169:103921. https://doi.org/10.1016/j.envexpbot.2019.103921

Terzi S, Torresan S, Schneiderbauer S, Critto A, Zebisch M, et al (2019) Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. J Environ Manage 232:759–771. https://doi.org/10.1016/j.jenvman.2018.11.100

Turconi L, Faccini F, Marchese A, Paliaga G, Casazza M, et al (2020) Implementation of Nature-Based Solutions for Hydro-Meteorological Risk Reduction in Small Mediterranean Catchments: The Case of Portofino Natural Regional Park, Italy. Sustainability 12:1240. https://doi.org/10.3390/su12031240

Vij S, Biesbroek R, Adler C, Muccione V (2021) Climate Change Adaptation in European Mountain Systems: A Systematic Mapping of Academic Research. Mt Res Dev 41:. https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1

Villanueva K, Badland H, Hooper P, Koohsari MJ, Mavoa S, et al (2015) Developing indicators of public open space to promote health and wellbeing in communities. Appl Geogr 57:112–119. https://doi.org/10.1016/j.apgeog.2014.12.003

Wende W, Bond A, Bobylev N, Stratmann L (2012) Climate change mitigation and adaptation in strategic environmental assessment. Environ Impact Assess Rev 32:88–93. https://doi.org/10.1016/j.eiar.2011.04.003

Wilhelm B, Rapuc W, Amann B, Anselmetti FS, Arnaud F, et al (2022) Impact of warmer climate periods on flood hazard in the European Alps. Nat Geosci 15:118–123. https://doi.org/10.1038/s41561-021-00878-y

Zaimes GN, Kasapidis I, Gkiatas G, Pagonis G, Savvopoulou A, et al (2020) Targeted placement of soil erosion prevention works after wildfires. IOP Conf Ser Earth Environ Sci 612:012050. https://doi.org/10.1088/1755-1315/612/1/012050

Zappa M, Kan C (2007) Extreme heat and runoff extremes in the Swiss Alps. Nat Hazards Earth Syst Sci 7:375–389. https://doi.org/10.5194/nhess-7-375-2007

Zingraff-Hamed A, Hüesker F, Albert C, et al (2021a) Governance models for nature-based solutions: Seventeen cases from Germany. Ambio 50:1610–1627. https://doi.org/10.1007/s13280-020-01412-x

Zingraff-Hamed A, Lupp G, Schedler J, Huang J, Pauleit S (2021b) 156 Nature-based solutions in the German Alps to mitigate hydro-meteorological risks. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-8522, https://doi.org/10.5194/egusphere-egu21-852