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Climate Change Adaptation in European Mountain Systems: A Systematic Mapping of Academic Research

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European mountain regions have already been impacted by climate change, and this is projected to increase in the future. These mountain regions experience rapid changes, which influence social-ecological systems in the lower-mountain and floodplain regions of Europe. There is scattered evidence across different strands of academic literature on the ways in which the impacts of changing climate in mountain regions are addressed and adaptive capacity is enhanced. Using a systematic mapping review, we mapped English-language scientific journal articles that analyzed the climate change adaptation options that are planned or implemented in European mountain regions. Our understanding of how academic literature has investigated climate change adaptation is critical to identifying key knowledge gaps and research foci. Following the Reporting Standards for Systematic Evidence Syntheses in environmental research protocol, 72 scientific articles published between January 2011 and August 2019 were identified from a total of 702 scientific articles. Our findings show that existing academic literature has a strong focus on the western and southern European mountains: the European Alps (n = 24), Pyrenees (n = 11), and Sierra Nevada (n = 4). Key climate impacts reported for the biophysical systems include reduction in forest carbon, soil erosion, changes in vegetation patterns, and changes in plant population and tree heights; in human systems, these include water availability, agricultural production, changes in viticulture, and impacts on tourism. Key adaptation options reported in this article are wetland conservation options, changing cropping and cultivation cycles, tree species management strategies, and snow-making technology. We found very few articles analyzing governance responses to planning and implementing adaptation; these had a strong bias toward techno-managerial responses. We conclude that, while climate impacts are substantial in European mountain regions, there are knowledge gaps in academic literature that need to be addressed.

Keywords: *climate change; mountains; adaptation options; systematic literature review; Europe.*

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Introduction

Climate change in European mountain regions is a reality (EEA 2017; IPCC 2018). It is projected that, by the end of the current century, European mountains will have changed physically, and large glaciers will have experienced significant mass loss (Beniston et al 2018). Changes in these regions also impact the lower, mid-hills, and floodplain environments, thereby impacting water availability, agricultural production, tourism, and health sectors (BAFU 2012: 44–64; Beniston et al 2013; IPCC 2018; Hock et al 2019). Mountain systems have a complex topography that changes considerably over short distances, resulting in diversified climate impacts at different elevations. For instance, with increasing air temperature and higher precipitation, seasonal snow lines will be found at higher elevations, and snow seasons will become shorter (EEA 2009). In high mountain countries, such as Switzerland, climate change will impact the water balance, which will have repercussions on hydropower, urban drainage, navigation, and an increase in the intensity of water-induced natural hazards (BAFU 2019).

Considering such impacts, certain human and biophysical systems are already autonomously adapting to climatic changes. For instance, Habel et al (2011) observed that, between 1991 and 2005/2006, lycaenid butterflies (*Lycaena helle*) moved from the middle mountain to higher mountain areas as a result of climatic changes. Similarly, Marchi et al (2016) observed a shift of black pine species (*Pinus nigra* subsp *nigra* var *italica*) to higher elevations in the Italian Alps. For human systems, Kundzewicz and Matczak (2012) argued that mountain areas in Poland are currently relying on soft and autonomous (private) adaptation options (eg adjusting agronomic practices) rather than hard planned adaptation options, such as building dams and large water storage structures. However, with rapid climatic changes, both human and biophysical systems will require additional interventions through planned adaptation to address future climate risks. Here, we refer to climate change adaptation as the process of adjustment to actual or expected climate and its effects, where in human systems, adaptation seeks to

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moderate or avoid harm and exploit beneficial opportunities (IPCC 2014: 5, 118; IPCC 2018).

Despite the proliferation of general adaptation literature (Ford et al 2011), there is a limited understanding of specific research on climate change adaptation in high European mountain regions. The knowledge that exists is scattered across different scientific domains, including natural and social sciences. For instance, Beniston et al (2018) argued for developing appropriate adaptation strategies to respond to the changes in cryosphere with the changing climate. Muccione et al (2016) showed that the knowledge gained from natural science disciplines is not always useful to address complex vulnerabilities of human and natural systems. To be able to answer critical questions that are relevant to policy actions and to enable timely adaptation, it is essential to collect and systematically map the knowledge base for adaptation options. Research on the types of adaptation actions used (incremental and transformative), efficiency and effectiveness of adaptation options, and ways in which adaptation is managed and governed can advance adaptation policy efforts in the mountain regions of Europe.

Here, we mapped and characterized the English-language academic literature on climate change adaptation in high European mountain regions and identified critical knowledge gaps. Findings from this mapping can inform future research and policy actions on climate change adaptation in European mountain regions. In the next section (Methodology), we explain the methodology and systematic review protocol used. In the Results, we present the key findings, mapping the various mountain ranges, climate change impacts, types of adaptation options, and actors covered in the academic literature. Finally, in the Discussion, we reflect upon the key findings of the mapping, highlighting the gaps and future climate change adaptation research needs.

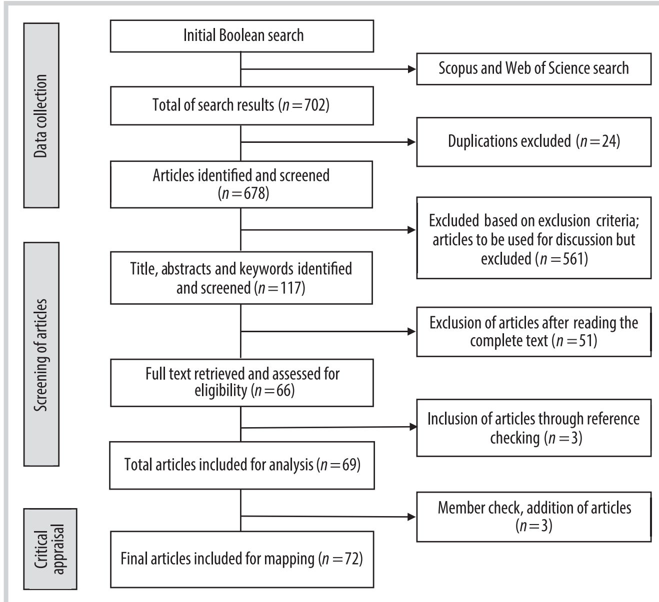
Methodology

There is no single agreed-upon definition of what constitutes a mountain (range) (Fairbridge 1968; Körner et al 2011; Sayre et al 2018). Each definition contains a set of criteria that fulfill different purposes or framings for mountain delineation. For this study, we defined a mountain as an elevated platform of high local relief (1000 feet, ∼304 m) with distinct habitat delineation from its base to the summit (Mountain Agenda 2000; Meybeck et al 2001). We distinguished between low mountains (elevation of 304–914 m) and high mountains (above 914 m). Here, we only considered high mountains. We followed the boundaries of Europe from the Intergovernmental Panel on Climate Change (IPCC) Working Group II Fifth Assessment Report, which includes 44 countries. Based on the definition above, Appendix S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1.S1) identifies 35 mountain regions in Europe.

Systematic mapping and ROSES protocol

The systematic mapping methodology allowed us to conduct a formal, transparent, and standardized mapping of English-language scientific journal articles (Gough et al 2012). Systematic mapping aims to provide descriptive information about the "state of the art" of a topic and to identify gaps in the research base (Clapton et al 2009). Unlike systematic literature reviews, systematic mapping attempts to collate, describe, and catalogue available scientific evidence on a selected topic. Studies can include policy-relevant questions or questions to direct future primary research (James et al 2016). In some cases, systematic mapping is conducted before an elaborate systematic review on a specific topic.

FIGURE 1 Steps involved in systematic review for data collection.



For this mapping study, we created a protocol based on ROSES (Reporting standards for Systematic Evidence Syntheses in environmental research) (Haddaway et al 2018). To identify the relevant articles, we used Scopus and Web of Science, the 2 largest databases for scientific literature. The following steps were taken to implement the approach; see Figure 1.

As a first step, we used several search queries to identify synonyms and explore the scope of the relevant literature. Search queries ($n = 47$) included: *TITLE-ABS-KEY (*mounta* OR *alp*) AND TITLE-ABS-KEY (*europ*) AND TITLE-ABS-KEY (climate AND change OR global AND warming OR climatic AND change OR anthropogenic AND warming) AND TITLE-ABS-KEY (*adapt* OR *resilien*) AND LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") AND LIMIT-TO (LANGUAGE, "English")*. The databases were searched for the title, abstract, and/or keywords of published articles for different Boolean configurations of a *mountain* (and related terms, such as "ranges," name of the mountain) and *climate change adaptation* (and other related terms, such global and anthropogenic warming). Our search was limited to peer-reviewed journal articles with a full text written in English, published and/or accepted between January 2011 and August 2019 to inform the IPCC Sixth Assessment cycle. Moreover, we limited our search to studies explicitly referring to "climate change adaptation" to capture those studies where adaptation was the key focus, an approach used in most systematic reviews on this topic (Ford et al 2011; Berrang-Ford et al 2015). The main focus was on empirical climate change adaptation cases in European mountain regions to capture the breadth of topics discussed (see Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1.S1).

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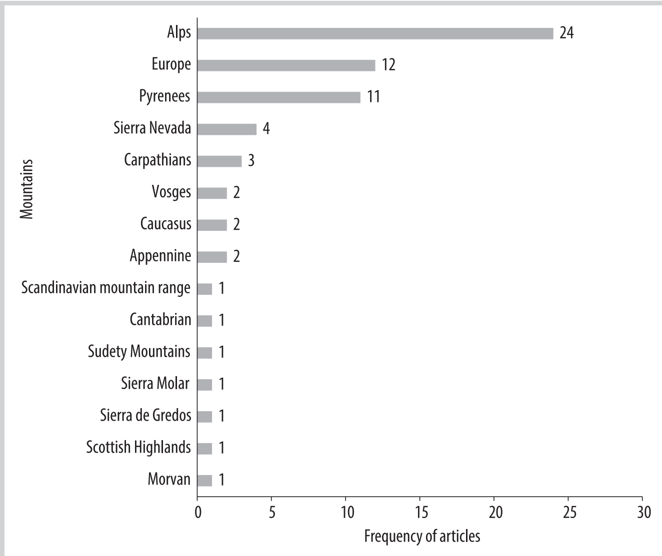
FIGURE 2 Frequency of articles discussing top 15 mountain ranges.



The search was implemented in September 2019 (Scopus $n = 423$, Web of Science $n = 279$), and after removing duplicates, the resulting 678 articles were used in the second step.

In the second step, all articles were screened based on the abstract, title, and keywords. This resulted in 117 articles for which we screened the full text. After reading, 51 articles did not meet our criteria and were removed from the final set of articles. These articles had, for example, unclear or missing methodological sections, or they did not discuss any adaptation options but simply referred to adaptation in the abstract. This critical appraisal resulted in a final list of 66 articles. Next, we cross-checked our list with references from Chapter 5 "Changing Ocean, Marine Ecosystems, and Dependent Communities" of the *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC) (Hock et al 2019) and did an author (member) check to ensure our assessment was comprehensive. From this, we included 6 new articles. The final database contained 72 articles.

In the third step, we recorded metadata such as author(s) name, year of publication, journal title, name of the mountain range, and the geographical area. Next, we used our codebook to inductively code the articles (see Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1.S1) on the following themes: scenario and climate model used, temperature target, climate change impacts and adaptation, sector impacted, type of adaptation (autonomous and planned, and incremental and transformative), and type of actors involved in the adaptation process (IPCC 2014: 118). Incremental adaptation actions maintain the essence and integrity of the existing technological, institutional, governance, and value systems, while transformative adaptation actions refer to change in the fundamental attributes of systems in response to actual or expected climate and its effects (IPCC 2014).

Results

The articles in our database were published in a range of social and natural science journals and covered both disciplinary and interdisciplinary studies. The journals in which most articles were published were: *Forest Ecology and Management* ($n = 5$), *Global Change Biology* ($n = 5$), *Regional Environmental Change* ($n = 4$), *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* ($n = 2$), *PLoS One* ($n = 2$), and *Climatic Change* ($n = 2$). Between 2012 and 2018, the number of articles steadily increased. We found that most of the studies followed a single or small-sample-size comparative research design, whereby the focus was on exploring a single mountain case in great detail ($n = 61$). We found very few studies that compared cases within the same mountain range ($n = 8$) or between different mountain regions ($n = 3$).

Most studies focused on 4 mountain ranges: the European Alps ($n = 24$) and Pyrenees ($n = 11$), the Sierra Nevada ($n = 4$), and the Carpathians ($n = 3$); see Figure 2. Of the 35 mountain regions from which we started our search, we only found scientific articles for 13 (see Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1.S1). Most of these 13 mountain ranges are located in eastern and southeastern Europe. Considering the mountain ranges studied, it is unsurprising that climate change impacts and adaptation options were discussed for the following countries: Spain ($n = 15$), France ($n = 12$), Switzerland ($n = 8$), Italy ($n = 8$), and Austria ($n = 4$). Moreover, some articles focused on the mountains of Europe as a whole ($n = 12$), discussing various mountain ranges but largely focusing on the Alps, Pyrenees, Sierra Nevada, Carpathians, and Voges.

Climate change scenarios, temperature targets, and impacts

Our database shows that 18 out of 72 articles discussed or used climate scenarios such as Representative Concentration Pathways (RCPs), most frequently RCP8.5 ($n = 11$), RCP4.5 ($n = 10$), and RCP2.6 ($n = 6$), followed by A1B ($n = 3$) and A1FI ($n = 2$). None of the articles referred to shared socioeconomic pathways. Only 5 articles explicitly discussed temperature targets, focusing mostly on 1.5°C ($n = 3$) and 2–2.5°C ($n = 2$). High-end temperature targets were not found.

Most articles discussed various climate change impacts. They particularly focused on sectors such as ecosystems and biodiversity ($n = 19$), forestry ($n = 19$), water resources ($n = 11$), tourism ($n = 11$), and agriculture ($n = 7$). Some of the key impacts discussed included: upward/downward shift and growth of alpine species due to changes in temperature and rainfall; impacts on viticulture and other mountain crops; glacial retreats; warming of rivers; changes in frequency of droughts and floods in the floodplains; and shorter snow seasons affecting tourism (Abeli et al 2012; Beniston and Stoffel 2014; Delay et al 2015; Campos Rodrigues et al 2018; Kruhlov et al 2018; Rumpf et al 2018).

Sectors, type of adaptation, and governance

Our database shows that 46 out of 72 articles made an explicit reference to autonomous and planned adaptation options. Of the 46 articles, 10 articles discussed autonomous adaptation options in biophysical systems only, for instance, where tree and animal species have moved to higher elevations in the mountain, based on the changes in temperature, rainfall patterns, snow cover, and humidity. Ortega et al (2016) suggested that alpine lizards (*Iberolacerta cyreni*) buffer the potential impact of an increase in their environmental temperatures through behavioral responses.

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FIGURE 3 Sector-wise adaptation options discussed in top 5 mountain ranges.

Sectors	Mountains														
	Alps			Pyrenees			Sierra Nevada			Carpathians			Europe a)		
Agriculture				1	1										1
Biodiversity	3			2			1	2					2		
Forestry	2			2			1				1		3	1	1
Tourism	1	1			1										
Water	3												1	1	1

Incremental Transformative Both

a) Articles discussing multiple mountain systems or presenting findings from European context. This category excludes the other mentioned mountain systems.

Similarly, Frei et al (2014) reported that grassland species such as *Ranunculus bulbosus*, *Trifolium montanum*, and *Briza media* in the Swiss Alps have the potential to respond to environmental variation. Moreover, the authors concluded that species might not have to migrate to higher elevations due to increasing temperature.

Our analysis shows that the studies that reported on planned adaptation ($n = 36$) predominantly focused on incremental adaptation options (62%), with more than a third of the articles referring to transformational adaptation options (36%). Examining the 5 most frequently reported sectors, studies on biodiversity only reported on incremental changes; there were no studies on transformative changes. For the remaining 4 sectors, we observed a mix of incremental, transformative, and combined adaptation options (see Appendix S1, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00033.1.S1). Considering the various mountain regions across Europe, our evidence suggests that of the 5 most researched mountain regions, most are covered by research on both incremental and transformative adaptation options; see Figure 3.

Various adaptation options were reported in the studies. For example, incremental adaptation options included wetland conservation, management strategies to protect certain tree species, conservation of the snow coverage area, diversification of recreation activities, and snow-making technology for tourism purposes (Delay et al 2015; Campos Rodrigues et al 2018). For instance, Spandre et al (2019) showed that under RCP8.5 projections, there would no longer be any snow-reliable ski resorts in the French Alps and Pyrenees (France and Spain) by the end of the century (2080–2100). Similarly, transformative adaptation options reported included changing cropping systems and cultivation cycles, developing artificial snow parks, and shifting vineyards to suitable climatic locations (Pérez 2016). Peltonen-Sainio et al (2016) suggested that new irrigation systems will have to be developed to realize future yields at higher elevations in northern European regions.

Implementing these adaptation options requires some form of governance, that is, the (inter)action of actors to make decisions about what adaptation options to select and how to implement the options. Our results show that 29 out of 72 articles made explicit reference to governmental actors only ($n = 3\%$), nongovernmental actors only ($n = 19\%$), and mixed government and nongovernmental actors (78%) for implementing adaptation options. We only found a few articles, such as those by Lamarque et al (2013) and Ruiz-Labourdette et al (2013), that discussed aspects of governance and planning of adaptation options in detail. In most cases, articles focused on the technical aspects of selecting and designing adaptation options. These included the use of land-use cover change maps for future climate disruptions and land-use changes, and devising appropriate technology for snow-making in ski resorts in the Alps and Pyrenees mountain ranges (Houet et al 2015; Spandre et al 2019).

Discussion

This study mapped scientific journal articles on climate change adaptation options in European mountain regions. Here, we discuss the key findings and their implications for future research on climate change adaptation in these regions.

Key knowledge gaps

First, we found that most studies in our database were focused on a few mountain regions located in western, southern, and northern Europe, specifically the Alps, Pyrenees, Sierra Nevada, and Carpathians. We found very few scientific articles about the adaptation options and governance of the mountain ranges of eastern and southeastern Europe, with some exceptions: Kundzewicz and Matczak (2012) and Panayotov et al (2019), for example, discussed adaptation governance in Poland and Bulgaria, but these studies did not exclusively focus on the mountain systems. The geographical distribution of research on adaptation mirrors the historical disparity between western and eastern Europe in environmental research more generally, which is often driven by lack of access to environment- and sustainability-related research funding (Ćetković and Buzogány 2019).

As we know from previous studies, climate vulnerability is generally high in eastern and southeastern Europe, which are also regions with limited adaptive capacity (Hu et al 2016; Koutroulis et al 2018; Mackenbach et al 2018). Further investments in research on climate change impacts and adaptation options in these poorly reported mountain regions of Europe are therefore of critical importance in gaining a Europe-wide understanding of adaptation (Vanschoenwinkel et al 2016). Such studies could be highly contextualized to better understand the governance of adaptation, as little is currently reported in the English literature. Such insights will be critical to inform Europe-wide and global assessments on the state of climate science, such as the IPCC Sixth Assessment Report and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services assessment.

Second, the database reported the impacts of climate change in biodiversity, forests, agriculture, water, and tourism sectors. However, sectors such as infrastructure, energy, and health are not discussed extensively in the academic literature. Moreover, we found a limited number of studies that analyzed the linkages among sectoral climate impacts, adaptation options, and governance arrangements. The temporal dimension of the adaptation options in question was often lacking or not made explicit. These interlinkages are, however, of critical importance to understanding synergies and trade-offs among different sectors, adaptation options, and mitigation and adaptation efforts. A more comprehensive perspective across scales is necessary to build a better knowledge base to provide

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meaningful advice on the ways in which mountain systems in Europe can adapt.

Third, mountain regions are unique social-ecological systems that call for context-specific governance arrangements to protect and manage them successfully. However, we found very limited evidence on research being conducted on the governance of adaptation in European mountain regions. Most studies had a strong biophysical focus and were geared toward technical solutions to enable adaptation to occur. Very little literature asked critical questions about the human dimensions of adaptation to climate change in mountain regions that have been researched in other mountain regions in the world (see SROCC, Hock et al 2019). Such questions include the role of history, culture, and traditional and local knowledge in adaptation; the diverse groups involved in adaptation, ranging from state authorities to pastoralist communities and vulnerable mountain people; the role of power, politics, and decision-making in designing, selecting, and implementing adaptation options; the range of decision support tools to support actors in decision-making processes; and efforts to monitor and evaluate progress in adaptation (Chaudhary and Bawa 2011; Sarkki et al 2017; Vij 2019). Research on these topics is critically important if governing transitions of existing socioeconomic systems in mountain regions is a desired end goal or objective. It will help policy actors to understand, explain, and design new governance practices that allow implementation to take place and accelerate climate change adaptation (Haasnoot et al 2020). Clearly, the limited role of social sciences in climate impact and adaptation research is not unique to European mountain regions, and it has been observed for many other climate-related studies (Swart et al 2014).

The fact that we found few reports in the academic literature on various aspects of mountain adaptation in Europe does not mean mountain regions are not already adapting to climate change. Yet, documenting these practical examples and experiences through a scientific analytical lens is important to build a critical knowledge base, build and test theories on adaptation, and discover patterns and insights that may be lost if not analyzed more systematically. Moreover, the systematic review of gray literature can be complemented by reviewing specific adaptation options, such as natural hazard management, flood management, forest management, or agriculture, which were not included as adaptation options in this study. In addition to primary research on the topics discussed above, we argue that systematic reviews of gray literature, including key policy and project reports, would allow key questions to be asked concerning if and how European mountains and mountain communities are adapting.

Future research

Most studies mapped in this article were found to be single or small-sample-size studies. These offer great insights into detailed aspects of the case; however, they are generally more difficult to relate, compare, or transfer to other contexts. This is a key gap identified for adaptation scholarship in mountain regions generally (see Adler et al 2019; McDowell et al 2019). Similarly, observational and model studies have provided great insights into the range of biophysical mechanisms in place and describe whether adaptation occurs, but very limited explanatory research was found that answers "how" and "why" questions, which are critical for theory building. Moreover, there is value in gray literature, especially in answering the questions that are not discussed in academic work. The next logical step would be to conduct an extensive systematic literature review, including credible gray literature, to bridge science–policy gaps on adaptation of the mountain regions of Europe. Last, our plea is to expand the geographical scope, to involve the social sciences more actively, and to diversify the research designs, methods, and tools to answer new questions that are critical to timely and successful climate adaptation.

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OPEN PEER REVIEW

This article was reviewed by Marco Pütz and Daniela Hohenwallner-Ries. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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Supplemental material

APPENDIX S1 Protocol: 01-07-2019.

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