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Impacts of climate change in European mountains — Alpine tundra habitat loss and treeline shifts under future global warming

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Contents

Abstract

The alpine tundra domain occurs in the high elevation zones of some of Europe's mountain ranges. It is an important reservoir of freshwater and provides habitat to unique species. Almost 20% of the domain falls within Natura 2000 sites. The treeline, which is below the domain, represents the forest limit.

Despite the importance of high mountains little is known concerning the potential impacts of climate change in high altitude ecosystems. This study assess 1) changes in the spatial range of the alpine tundra domain, and 2) changes in the elevational shift of treelines in Europe, in three warming levels, i.e. 1.5 °C, 2 °C and 3 °C.

Our results indicate that 98% of Europe's alpine tundra domain is in the Pyrenees, the Alps and the Scandes. The domain is projected to shrink by over 75% in all these regions in a 3°C warming scenario. Likewise, the treeline is projected to move vertically upwards by up to 8 m every year in a 3°C warming scenario. There are large differences in the losses projected for the three main regions that make up the domain. The most severe impact is projected for the Pyrenees, where the current domain virtually disappears at 3°C, compared to the Scandes and Alps which shrink by around 87% and 75% respectively. Of the 210 Natura 2000 sites that contain alpine tundra, almost all of them are projected to see a shrinking of the domain: 207 and 208 in the 2°C and 3°C warming scenarios respectively.

The projected changes have implications for vital ecosystem services, such as the provision and regulation of freshwater from melting snow, habitat for biodiversity and recreational services such as skiing. Adaptation options in high mountain systems face constraints arising from the unique topographic, edaphic and climatic characteristics of these systems. Additionally, the challenges and limitations for adaptation increase in parallel with warming.

Acknowledgements

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Authors

José I. Barredo, Achille Mauri, Giovanni Caudullo.

Executive summary

The alpine zone or alpine tundra is the highest elevation belt in mountains. The alpine tundra is an important reservoir of fresh water resources and plays a key role in water provision for agriculture and human consumption, additionally it provides key ecosystem services besides habitat to endemic species and alpine communities. For instance, only in the Alpine biogeographical region, 105 habitat types, 97 plants and 134 animal species listed in the EU Habitats Directive are found. The alpine tundra is present across Europe in several high-mountain zones. The most extended are in the high-mountain ranges of the Pyrenees on the border between France and Spain; the Alps which stretch over France, Italy, Germany, Austria, Slovenia, Switzerland and Monaco; the Scandes located between Sweden, Norway and Finland; and some less prominent zones such as the Scottish Highlands and Carpathians. More than 98% of the alpine tundra is located within the Alps, Scandes and Pyrenees.

Below the alpine tundra, the treeline forms a high elevation vegetation boundary, i.e. the forest limit. The treeline is a highly responsive bioindicator, it is a temperature sensitive transition zone that is expected to respond to climate warming by advancing upwards beyond its current position. Treelines are very sensitive to temperature increases, therefore they provide early signals of the response of mountain forest ecosystems.

Despite the importance of high mountains, little is known concerning the potential impacts of climate change in high altitude ecosystems. Therefore, the aim of this study is to assess changes 1) in the spatial range of the alpine tundra domain (ATD), and 2) in elevational shifts of the treeline ecotone[1] in Europe under scenarios of climate change. We used 11 regional climate model (RCM) simulations from EURO CORDEX [https://www.euro-cordex.net], disaggregated at the 1 km grid size, representing two RCP scenarios, i.e. RCP4.5 and RCP8.5, in three warming levels, i.e. 1.5 °C, 2 °C and 3 °C and the 2050s (2036-2065).

Findings of this study indicate a pronounced contraction of the ATD across regions, scenarios and warming levels. First, in the Alps, it is projected that with a 1.5 °C warming the alpine tundra will lose an extent of around 31-36% with respect to the reference period (1981-2010). In the 2 °C and 3 °C warming levels the projected contractions are larger, exhibiting a loss of 50% and 75% of the extent, respectively. Second, in the Scandes, a contraction of the alpine tundra of around 50% is projected in the 1.5 °C warming level. Then, in the 2 °C and 3 °C warming levels a contraction of above 59% and 87%, respectively, is projected. Lastly, in the Pyrenees the projected contraction is larger than in the Alps and Scandes. The contraction of the alpine tundra is already projected above 74% in the 1.5 °C warming. Then, in the 2 °C the loss is projected at above 90%, and the alpine tundra is projected to virtually disappear with a 3 °C warming in the Pyrenees.

A large proportion of ATD is covered by Natura 2000 sites, i.e. 53% of ATD falling in EU countries. Of the 210 Natura 2000 sites that contain ATD, almost all of them are projected to see a shrinking of the domain. The contraction increases gradually with warming, and in the 3 °C warming level the current domain inside Natura 2000 sites shrinks by over 74% in all three mountain regions where most of the ATD is currently found.

Furthermore, our results indicate that the natural climatic treeline is projected to shift upward in the entirety of the most prominent 16 European mountain regions. The shift is projected across scenarios, simulations and warming levels. Altitudinal shifts differ from

[1] Ecotone is a transition zone between two different and homogeneous plant communities.

one region to another and the magnitude of the shifts seems to follow a latitudinal gradient. For instance, in the Alps, a mean shift of 192 m, 277 m and 526 m was projected respectively in the three warming levels, with respect to the reference period. In the Pyrenees the projected mean shift was 206 m, 322 m and 642 m, and in the South Scandes 128 m, 185 m and 336 m, respectively in the three warming levels.

Impacts and adaptation

Treeline advance and ATD contraction can have an important impact in high mountain ecosystem functions and services. For example, regarding water regulation and quality, winter snowpack accumulation and snow retention in summer occurs in the ATD above the treeline. The retention of snow is critical because it releases water from the mountains during the summer months. Therefore, contraction of the ATD and changes in snowpack accumulation, both driven by changes in climate, affect low elevation biota and change mountain hydrology. Regarding plant assemblages, our results suggest cold-adapted species decline and increase of the more warm-adapted species. This process, referred to as thermophilization, suggests a progressive decline of cold mountain habitats and their associated biota, leading to decline and/or extirpation (local extinction) of alpine plant species. Finally, retreat of the nival zone[2], associated with contraction of the ATD on higher mountains, will likely restrict winter sports. A summary of current knowledge on impacts is shown in this report.

Adaptation options in high mountain systems face constraints arising from the unique topographic, edaphic and climatic characteristics of these systems. For instance, migration of species could be constrained by lack of sufficient altitude to migrate vertically or due to limiting soil conditions for plant growth. In alpine systems physical constraints could reduce the range of adaptation options for conservation. Additionally, regarding ecosystem-based adaptation options, e.g. ecological restoration, increasing biological diversity, assisted migration or managed translocation, ecological corridors, ex-situ conservation and seed banks, local level traits (e.g. altitude, slope, biota, soil depth) should be considered for proper implementation. Furthermore, limits to adaptation in high mountains and long-term sustainability of the options should be assessed taking into consideration the magnitude of the projected changes and the feasibility of the options. Lastly, potential trade-offs between adaptation for nature conservation and adaptation for winter tourism should be considered.

In high mountains the challenges and limitations for adaptation increase in parallel with warming. The impacts in the 3 °C warming level would require higher adaptation efforts than in the 1.5 or 2 °C level. Similarly, adaptation needs in the 2 °C warming are higher than in 1.5 °C warming.

[2] Nival or snow zone is the higher thermal belt of high mountains located above the alpine zone.

1. Introduction

Several important mountain chains are present in Europe covering around 29% of the EU's land area and stretching across the majority of the countries. Within the EU, five of the longest and highest ranges are the Alps, Apennines, Pyrenees, Scandes and Carpathians. Mountains provide vital ecosystem services to society, such as freshwater from melting snow, and water regulation and release during the drier summer months, habitat for biodiversity, and recreational services among others.

Better knowledge is needed for appropriate adaptation to climate change regarding processes and dynamics in mountain habitats, in particular the alpine tundra and the treeline. Mountain regions are characterised by a relative cold and harsh climate, high altitudes and complex topography. Forest and grasslands often cover the lower slopes, but at higher elevations trees become scarcer giving place to alpine grasslands and scrub heath communities. Due to their steep gradients, mountains comprise latitudinal life zones in a relatively small extent, therefore habitats and species change rapidly with altitude (EEA 2010; European Commission 2005). These characteristics explain the rich biodiversity and variety of habitats present in mountain regions. For instance, two thirds of the plants of the European continent are present in mountains. Only in the Alpine biogeographical region[3], 105 habitat types, 97 plants and 134 animal species listed in the Habitats Directive (Council of the European Communities 1992) are found.

Anthropogenic climate change presents a major threat for mountain systems. Due to the tight ecological-climatic bands in mountains, small changes could have major effects in these systems. There is consensus that alpine habitats are showing a high sensitivity to climate change and will be highly vulnerable to future changes (Hock et al. 2019; Settele et al. 2014). Evidence indicates that in mountain regions the current and future effects of global warming are likely to be amplified (Bjorkman et al. 2018; Bradley et al. 2004; Diaz and Eischeid 2007; Diaz et al. 2003; Diaz and Graham 1996; Gottfried et al. 2012; Hock et al. 2019; Lenoir et al. 2008; Liu and Chen 2000). This results in that projected climate-driven impacts are greater at higher elevations (Dullinger et al. 2012; Engler et al. 2011).

Alpine tundra is present across Europe in several high elevation zones. The most extended zones are the high mountain ranges of the Pyrenees on the border between France and Spain; the Alps which stretch over France, Italy, Germany, Austria, Slovenia, Switzerland and Monaco; the Scandes located between Sweden, Norway and Finland; and some less prominent zones such as the Scottish Highlands and Carpathians.

In Europe alpine tundra occurs at the top of high mountains (Figure 1). Here, alpine grasslands and scrub heath communities dominate vegetation. The mean temperature of the warmest month is less than 10 °C, these conditions does not support tree growth. The Alpine tundra is an important reservoir of fresh water resources and play a key role in water release. Mountain ecosystems intercept water and store it as snow, glaciers and reservoirs before supplying mostly in spring and summer. These ecosystems play a key role in water provision for agriculture and human consumption and provide key ecosystem services such as habitat to endemic species and alpine communities.

Below the alpine tundra, the treeline forms a high elevation vegetation boundary, i.e. the forest limit (Figure 1). Nevertheless, the treeline is frequently a diffuse limit, therefore it is often addressed as the treeline ecotone, which is an area of transition in high mountains where closed canopy forests from lower elevations give way to the open alpine tundra and rocky expanses above (Butler et al. 2009; Körner 2012; Körner and Paulsen 2004). Treeline is a highly responsive bioindicator (Hagedorn et al. 2014), it is a temperature sensitive transition zone that is expected to respond to climate warming by advancing beyond their current position (Harsch et al. 2009). Treelines are very sensitive

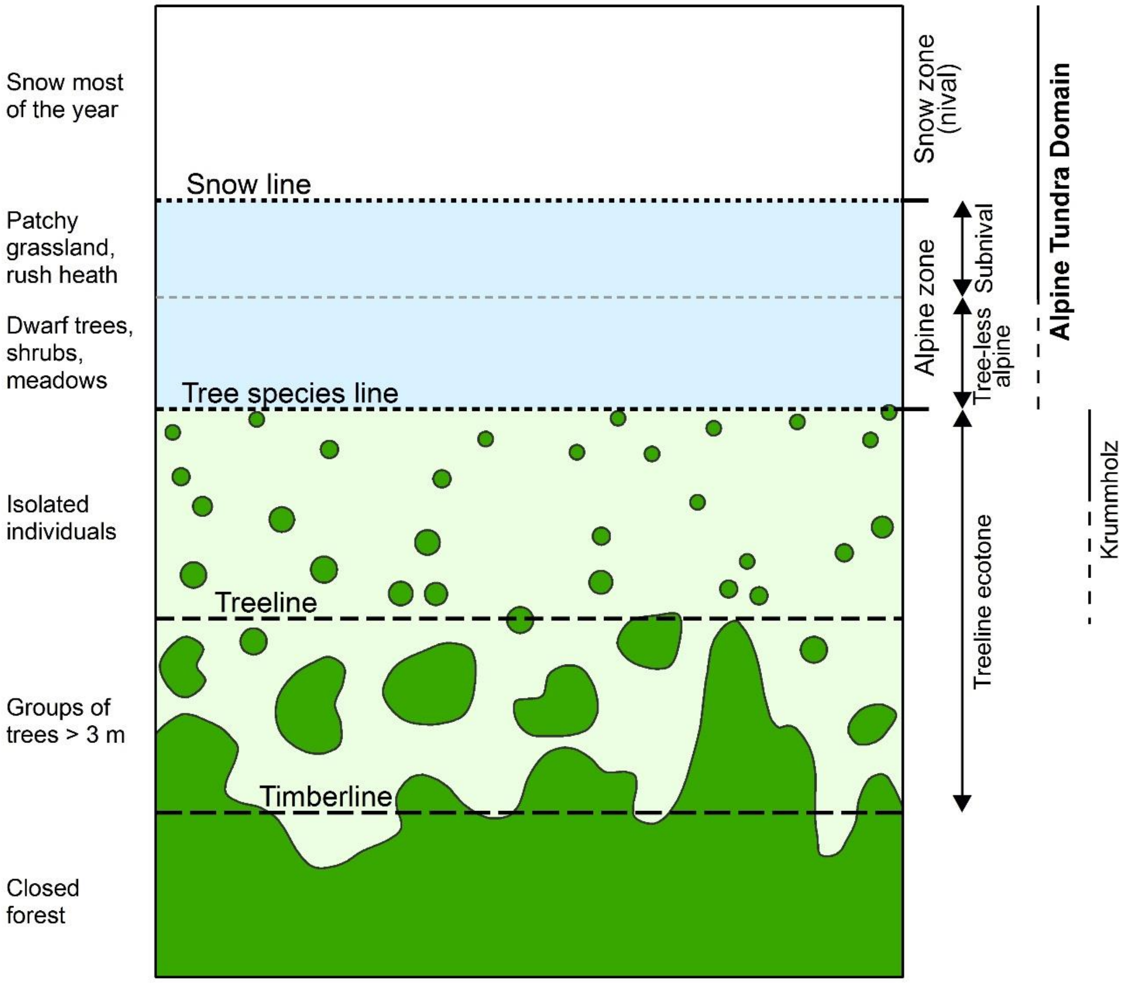
[3] The Alpine biogeographical region includes the Alps, the Apennines, the Pyrenees, the Scandes and the Carpathians (European Commission 2005).

to temperature increases, therefore they provide early signals of the response to climate change to be expected in mountain forest ecosystems (Greenwood and Jump 2014).

Despite the importance of high mountain systems little is known concerning the potential impacts of climate change in high altitude ecosystems (Greenwood and Jump 2014). The aim of this study is to assess changes in the spatial range of the alpine tundra and shifts of the treeline ecotone in Europe under scenarios of climate change.

We discuss potential impacts on biodiversity and ecosystem services, hydrology and slope stabilisation from available evidence. Additionally, this study assesses Natura 2000 sites projected to be affected by contraction of the alpine tundra. Natura 2000 is a network of nature protection sites for animal and plant species, and for natural habitat types in the EU. This network is the cornerstone of the EU nature and biodiversity policies. The terrestrial part of the network covers around 26,000 sites representing about 18% of the EU territory and 15% of the mountain area (EEA 2010; European Commission 2018b). Finally, the study assesses adaptation options for mountain habitats and Natura 2000 sites. Results of this study are useful for mapping critical conservation areas and support decision-making on potential interventions such as Green Infrastructure (European Commission 2018a) and other adaptation options in high mountains ecosystems.

Figure 1. Schematic representation of the alpine tundra domain and treeline ecotone. Source: modified from Körner and Paulsen (2004) and Gottfried et al. (2012). Krummholz is the uppermost belt of the treeline ecotone where trees develop forming shrub-like structures.



2. Methodology

This section is a summary of the methodology used in this study. The complete description of the methods is in annex 1. The objective of the first part of the method is to map the European alpine tundra and the treeline under historical climate, i.e. the reference period (1981—2010), and two different Representative Concentration Pathways (RCPs) adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment report, namely RCP4.5 and RCP8.5 (Moss et al. 2010; van Vuuren et al. 2011). The first scenario, RCP4.5, corresponds to a projected change in global mean surface air temperature of + 1.8 °C (likely range 1.1–2.6 °C) relative to the reference period of 1986–2005 (Collins et al. 2013). The second, RCP8.5, describes a business as usual (high emission) scenario (Moss et al. 2010; van Vuuren et al. 2011), corresponding to a + 3.7 °C (likely range 2.6–4.8 °C) world by the end of the century relative to 1986–2005 (Collins et al. 2013). Following the guidance of the PESETA IV project, we used 11 Regional Climate Model (RCM) simulations for three warming levels i.e. 1.5 °C, 2 °C and 3 °C, the latter available only for RCP8.5, and one additional period centred on the 2050s (2036-2065). Maps accounting for changes in the alpine tundra and the treeline were created for the 11 simulations, the two scenarios and four periods. The second part of the method aims at identifying Natura 2000 sites that are projected to be affected by changes of the alpine tundra. For this purpose, maps of projected alpine tundra change were overlaid with the map of Natura 2000 sites, then the area and number of sites affected by the changes were computed.

High-resolution climate model simulations were sourced from the Coordinated Regional Downscaling Experiment (CORDEX) (http://www.cordex.org) of the World Climate Research Programme (WCRP). As part of the CORDEX project, the EURO-CORDEX (Jacob et al. 2014) initiative provides regional climate projections for Europe at ~12.5 km horizontal resolution. In this study, we used simulations of air temperature for 11 RCMs, two RCP scenarios and four periods (2050s, 1.5 °C, 2 °C and 3 °C warming levels). The spatial domain of this study covers the EU-28, Switzerland, Norway and the five European microstates (Andorra, Liechtenstein, Monaco, San Marino and Vatican City). Then, we used the change factor approach (Baker et al. 2010; Barredo et al. 2016; Ekström et al. 2015; Klausmeyer and Shaw 2009; Tabor and Williams 2010) for reduce model bias and spatially disaggregate temperature fields from RCMs to a higher horizontal resolution of 1 km, compatible with high mountain (Rubel et al. 2017) and biodiversity (Ekström et al. 2015) studies. For the change factor approach we used CHELSA ver. 1.2 (Karger et al. 2017) at 1 km spatial resolution as baseline data.

2.1. Mapping alpine tundra domain

Alpine tundra was mapped using the Köppen-Geiger climate classification (Hantel 1989; Kottek et al. 2006). The alpine tundra domain (ATD) domain is equivalent to the polar climates classified in Köppen-Geiger as E-type (Diaz and Eischeid 2007). Polar climates are defined as occurring if the mean temperature of the warmest month is less than 10 °C. No precipitation differentiation is included in the Köppen-Geiger classification for Polar climates. We defined the ATD as equivalent of polar climates (E-type) according to Diaz and Eischeid (2007). Maps of ATD were produced for the reference period and for each scenario, warming level and simulation. Summary maps describing changes of ATD containing three potential categories (stable, contraction and expansion) were then computed between the reference period and the future. As a result, we obtained one map of projected changes for each scenario/warming level. The category expansion is absent in the summary maps and was therefore excluded from the assessment.

2.2. Mapping treeline

Treeline position is strongly dependent on temperature, although other factors such as precipitation, nutrient availability, orographic and anthropogenic influences (e.g. grazing, deforestation, fire) may also play a role in tree position at local level (Greenwood and

Jump 2014; Holtmeier and Broll 2005). The focus of this assessment is the natural climatic treeline in mountains, disregarding situations where moisture shortages prevent tree growth because this is not a cause specific to high elevations (Körner and Paulsen 2004). A point to which we will return later in the results section.

A method derived from Körner and Paulsen (2004) was used to map the treeline position in the reference period and future scenarios. Using a global sample of root temperature measures at natural climatic treelines obtained between 1996 and 2003, they found that treelines are associated with a growing season mean root temperature of 6.7 °C (±0.8 SD). Thus concluding that there seems to be a common thermal threshold for forest and tree growth at high elevations. According to Körner and Paulsen (2004) the mean temperature during the growing season showed minor variations across the global sample, therefore a common 7 °C threshold of root zone temperature (7.6 °C canopy temperature) seems like a very reasonable approximation of the treeline for high latitudes (30° to 70° N). Therefore, for the delineation of the treeline we selected the 7.6 °C canopy (air) temperature for our study zone that falls within the range of high latitudes.

We delineated the treeline in the reference period and the combination of scenarios/warming levels using the growing season 7.6 °C canopy temperature threshold. Then, an assessment of treeline shifts was done in 16 mountain regions in Europe, from Mediterranean islands to boreal and from the Iberian Peninsula to the Carpathians, including the more prominent treeline ecotones of Europe (EEA 2010; Virtanen et al. 2016).

2.3. Validation

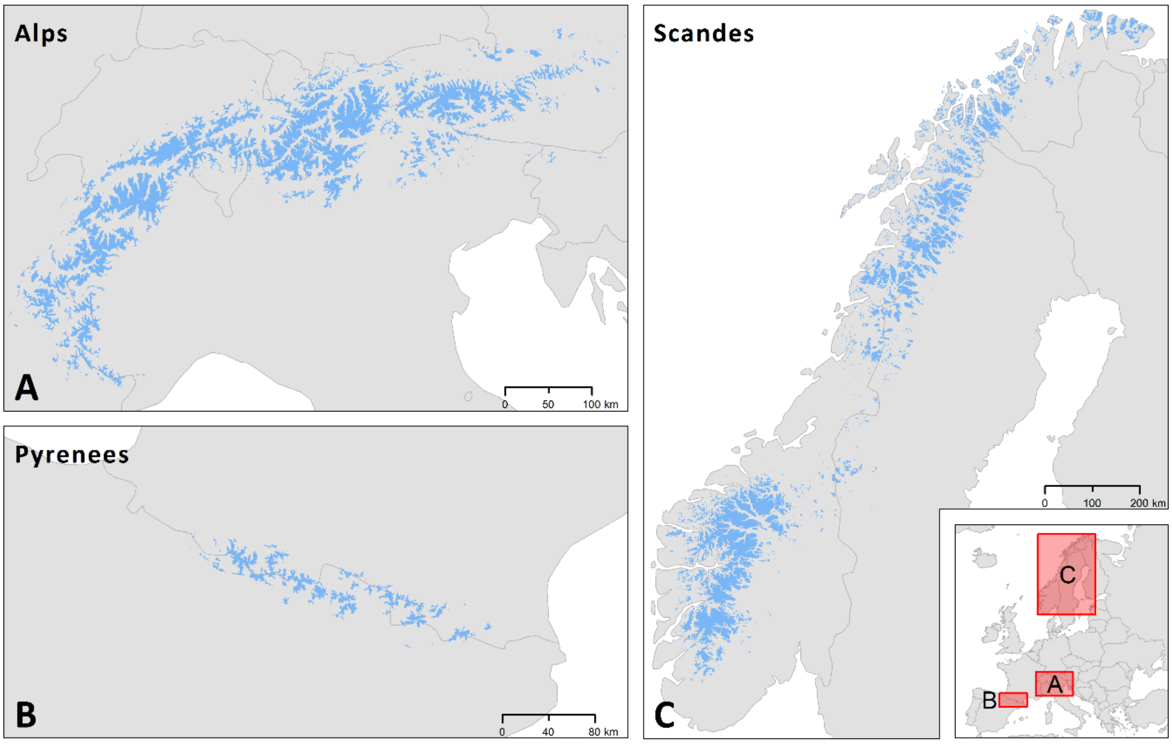
To determine the ability of our methodology to reproduce a faithful delineation of the ATD and the treeline two validation procedures were implemented. Results of the validation indicate a reasonable level of agreement between the maps of ATD, and treeline, and the independent data used for comparison. Technical details of the validation are shown in Annex 2.

3. Results

3.1. Alpine tundra domain

In Europe (excluding Iceland) the extent of the ATD in the reference period is around 87,000 km^2. Of this extent, 98% is found in the Alps, Scandes and Pyrenees, which are the focus of this study (Figure 2). A few isolated areas are present in the Scottish Highlands, Tatra Mountains, Carpathians and Apennines in central Italy.

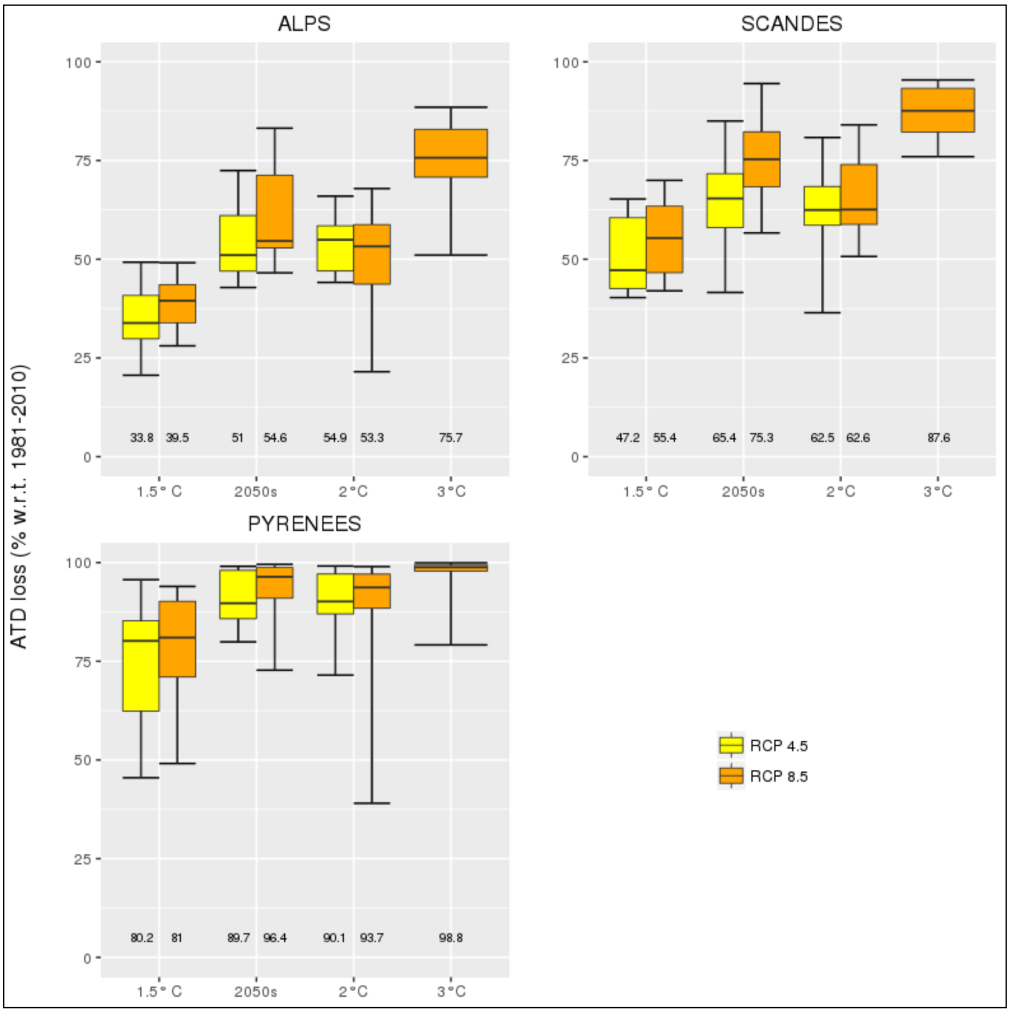
Figure 2. Extent of the alpine tundra domain (ATD) according to the Köppen-Geiger definition using CHELSA data (Karger et al. 2017) in the reference period (1981-2010) in the Alps, Scandes and Pyrenees. Note the different scale in the boxes.



We computed projected changes of the ATD relative to the reference period in two categories. First, stable areas, where the ATD is projected to persist in the future. And second, contraction areas, where the ATD is projected to disappear. Expansion areas were not included because none of the models projected new ATD zones.

All the RCM simulations projected a pronounced reduction of the ATD under both RCP4.5 and RCP8.5 (Figure 3). However, projected contractions of the ATD vary considerably depending on the region considered. For instance, in the 1.5 °C warming level the projected median loss of ATD is around 80% in the Pyrenees and greater than 47% in the Scandes. While the projected mean contraction in the Alps is less pronounced, though still representing 34—40% of the extent in the reference period. By the 2050s, the projected median loss in the Alps, 51—55%, is less marked than in the Pyrenees and the Scandes with 90—96% and 65—75%, respectively. Then, in the 2 °C warming level the contraction process is projected to continue in the range of around 54%, 63% and more than 90% of median loss in the Alps, Scandes and Pyrenees, respectively. Finally, in the 3 °C warming level the projected mean contraction affects 76% and 88% of the Alps and Scandes, respectively. While the ATD is projected to virtually disappear in the Pyrenees.

Figure 3. Projected relative area loss of the alpine tundra domain (ATD) under scenario RCP4.5 and RCP8.5 in future periods (1.5 °C, 2 °C and 3°C warming, and 2050s) in relation to the reference period (1981—2010). Results are presented for the Alps, Scandes and Pyrenees. Box-and-whisker plots show minimum, maximum, median (number), lower quartile (25%) and upper quartile (75%) of the 11 RCM simulations. Note that 2050s refers to the period 2036-2065.



3.2. Mapping projected changes of the alpine tundra domain

Using the projected maps of ATD across scenarios and warming levels, we mapped all of the grid cells where the ATD is projected to contract or to remain stable using different levels of confidence (see Table 5 in annex 1). Summary maps of projected changes of ATD in the two scenarios and three warming levels are shown for the Alps (Figure 4), Scandes (Figure 5) and Pyrenees (Figure 6). Figure 7 summarises the information from the maps. In the Alps with a 1.5 °C warming it is projected that the ATD will lose an extent of around 31—36% (in this section we report contraction including both the likely and confident categories of Table 5), exhibiting both scenarios similar results. The projected loss is more pronounced in areas just above the treeline, particularly in the eastern Alps and southern-western Alps where the mountain range rarely goes beyond 2600 m a.s.l.[4] By 2050s under RCP4.5, a projected loss of 49% extends to the southern and northern Alps exhibiting results virtually identical to the 2 °C warming level (Figure 7). In contrast, by the 2050s under RCP8.5 a greater contraction of 57% is projected. In this case the ATD is projected to occur only above ~2800 m a.s.l. In the 3 °C warming level it is projected that the extent of the ATD will be only 19% of the present extent, in

[4] a.s.l.: above sea level.

consequence almost the entirety of ATD areas below 3000 m a.s.l. are projected to disappear. Our results indicate that both scenarios, RCP4.5 and RCP8.5, project comparable results across regions regarding the 1.5 °C and 2 °C warming levels.

In the Scandes a contraction of the ATD of around 50% is projected in the 1.5 °C warming level in both scenarios. By 2050s the situation is projected to worsen in the two scenarios, but particularly in the RCP8.5, which indicates a contraction of 74%. While under RCP4.5 the loss is 60%. The contraction is particularly pronounced in northern Fennoscandia, with ATD persisting only in the highest mountain ranges (Figure 5). In southern Fennoscandia the situation is slightly better due to the presence of higher mountain ranges above 1800 m a.s.l., which may act as refugia for alpine tundra biota. In the 2 °C warming level, a comparable contraction of around 60% is projected in either scenario. Then, in the 3 °C warming level most of the ATD is projected to disappear, 87%, and only 8% is projected to persist. The remaining 5% falls within the uncertain category.

In the Pyrenees, the projected contractions are larger than in the Alps and Scandes. The contraction of ATD is already above 74% in the 1.5 °C warming level in both scenarios. In the 2 °C warming level only around 4% of ATD is projected to persist, whereas in the 3 °C warming level the area of ATD projected to persist is less than 1% (Figure 6).

Figure 4. Projected changes of the alpine tundra domain (ATD) in the Alps under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065) with respect to the reference period (1981-2010).

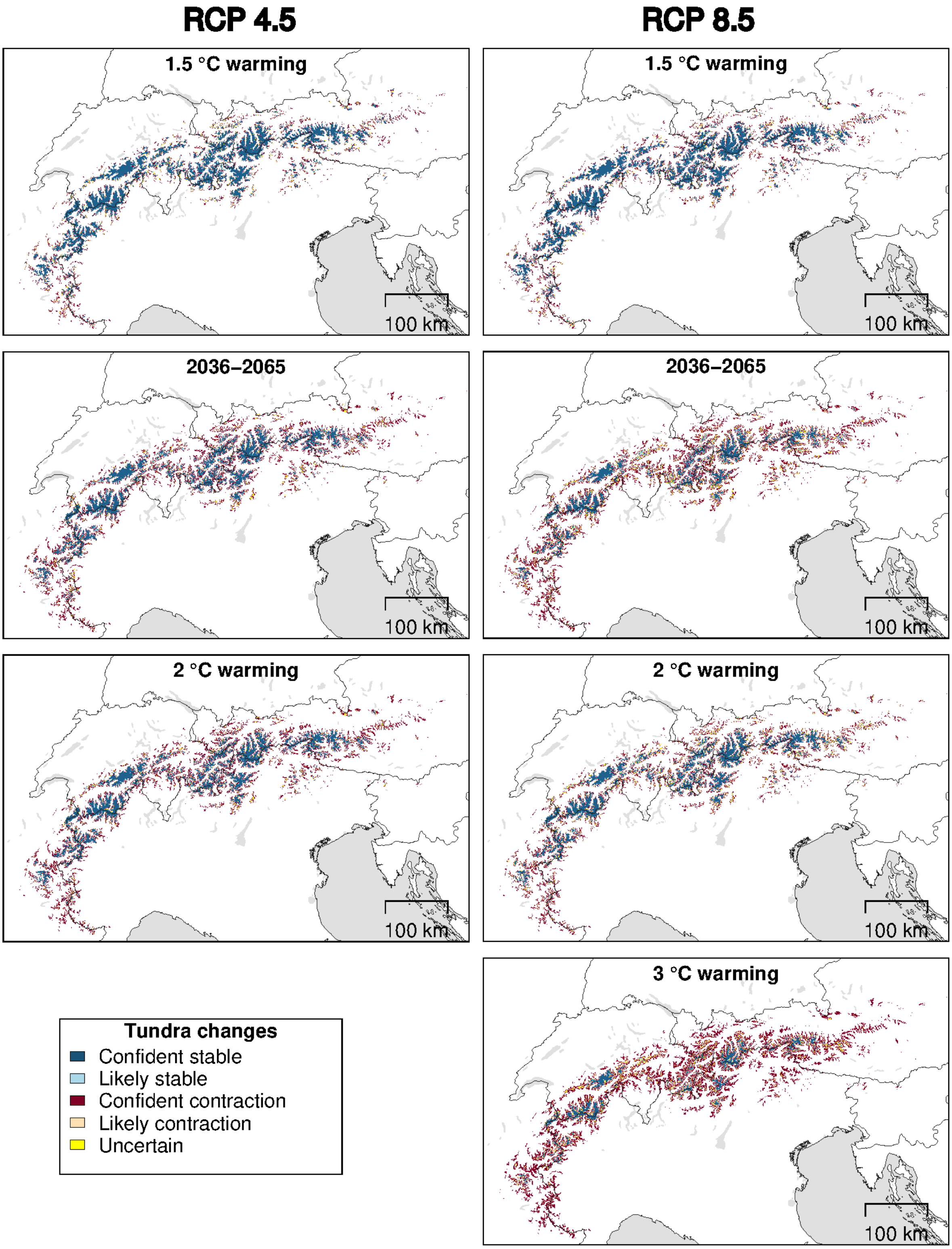


Figure 5. Projected changes of the alpine tundra domain (ATD) in the Scandes under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065) with respect to the reference period (1981-2010).

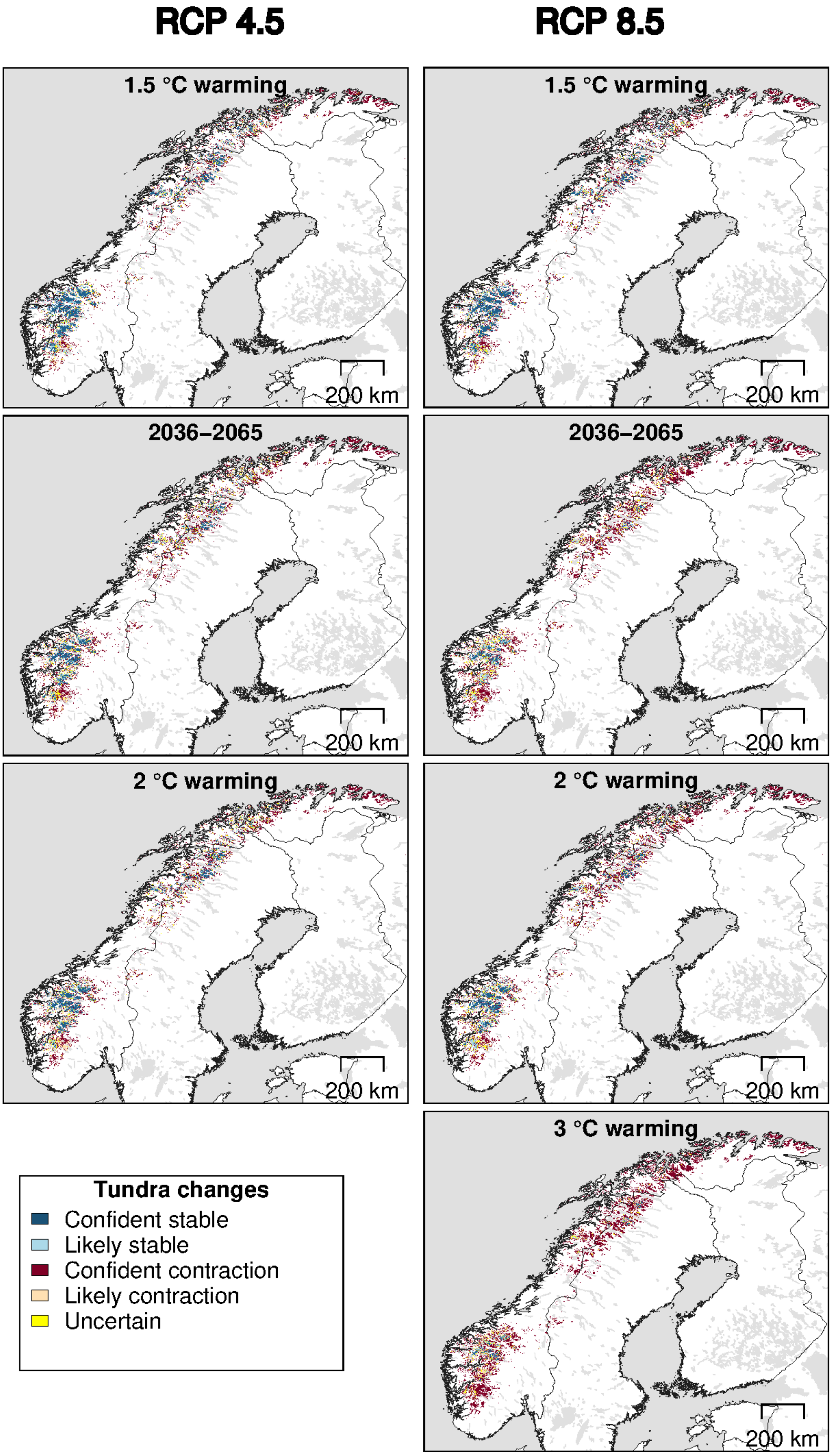


Figure 6. Projected changes of the alpine tundra domain (ATD) in the Pyrenees under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065) with respect to the reference period (1981-2010).

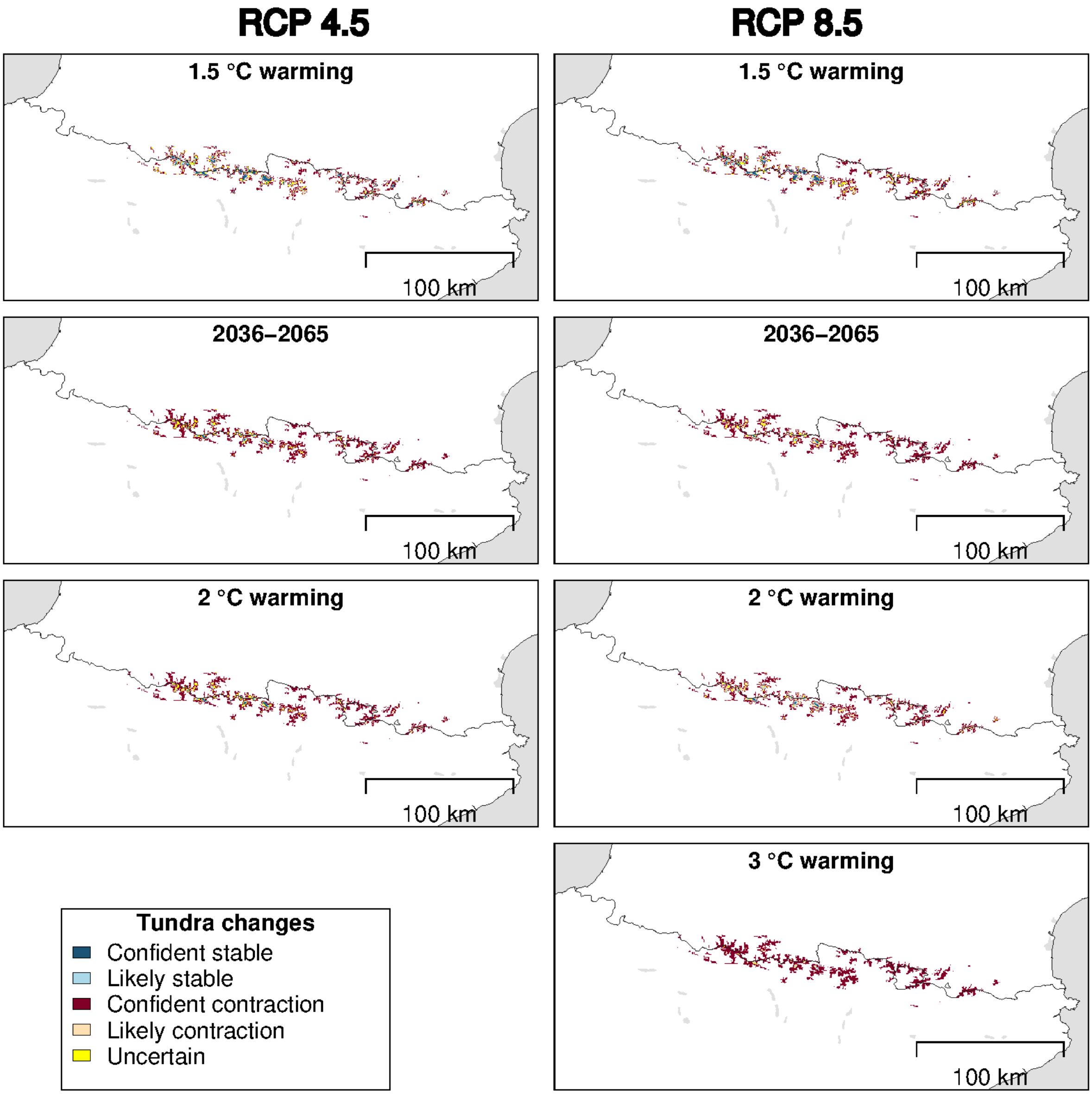
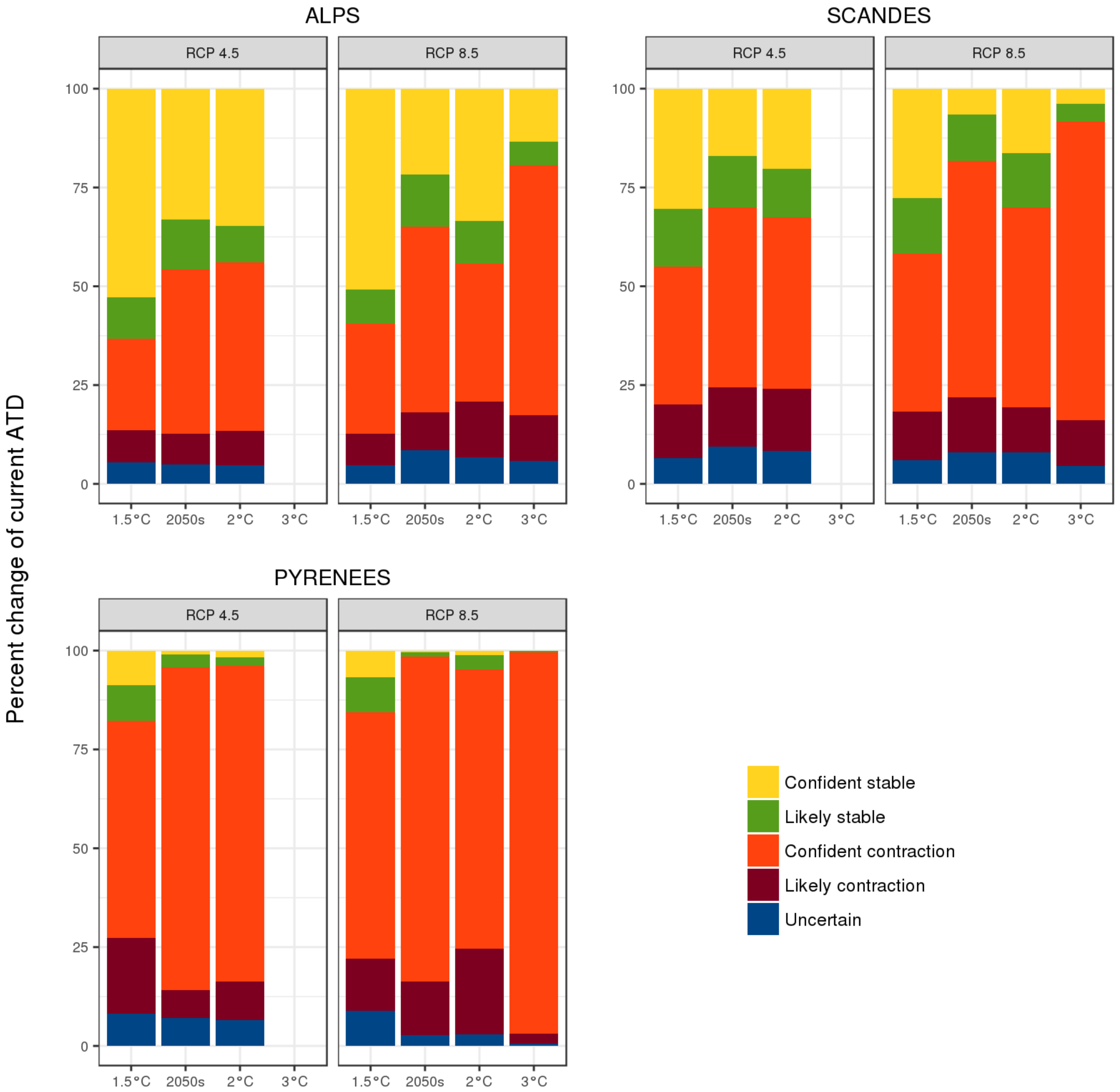


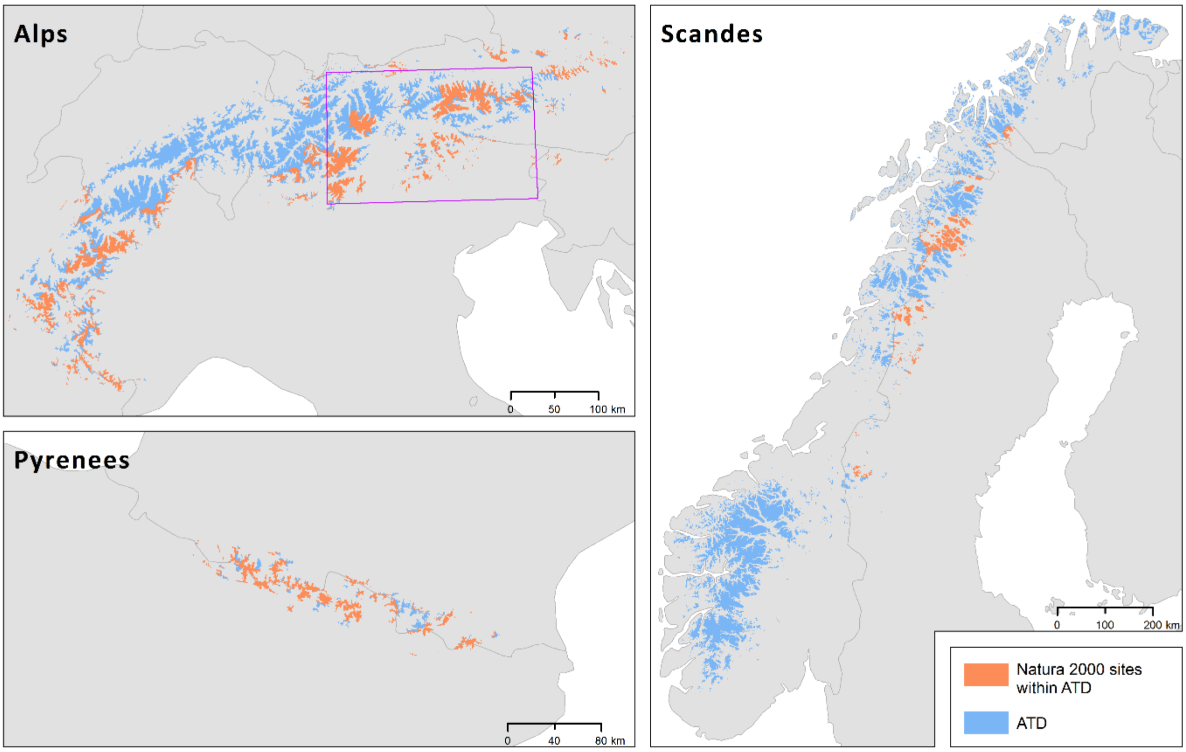
Figure 7. Projected relative area change of the alpine tundra domain (ATD) under scenario RCP4.5 and RCP8.5 in in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065). Changes with respect to the reference period (1981-2010) extent of the ATD in three regions: Alps, Scandes and Pyrenees.



3.3. Mapping projected changes of the alpine tundra domain in the Natura 2000 protected area network

In this section we show projected changes of the ATD occurring within sites of the Natura 2000 network (EEA 2018). The ATD includes 210 Natura 2000 sites across Europe, totalling 16,180 km^2, which represent 19% of the extent of the ATD. Taking into consideration the ATD occurring in EU countries only, the area covered by Natura 2000 sites rises to 53%. Natura 2000 sites are distributed in the ATD as shown in Figure 8. The Pyrenees, with 90%, shows the highest proportion of ATD area covered by Natura 2000 sites. Changes of ATD within Natura 2000 sites indicates a range of impacts (e.g. reduction in alpine habitats and shifts in plant community composition and structure), a point to which we shall return later in section 4.

Figure 8. Natura 2000 sites in relation to the alpine tundra domain (ATD) in the reference period (1981-2010). The purple box in the Alps represents a sample area used latter to represent changes of the ATD within Natura 2000 sites. Note the different scale in the boxes



Maps of projected changes of the ATD (Figure 4, Figure 5 and Figure 6) were used for computing changes in Natura 2000 sites. Figure 9 shows, for illustrative purposes, a zoom over the Eastern Alps where changes of the ATD within Natura 2000 sites are represented. In these sites, the ATD is mostly projected to persist in the 1.5 °C warming level under both scenarios. Nevertheless, projected contraction is evident in the 2050s, affecting the sites at lower elevations (central part of the maps). Projected changes in this period are comparable with those of the 2 °C warming level in both scenarios. In the 3 °C warming level, large contraction of the ATD is observed within Natura 2000 sites. In this case, the ATD is projected to persist only in Natura 2000 sites at higher elevations.

The proportion of projected area changes of the ATD inside Natura 2000 sites is close to the proportion in the overall ATD (Figure 10). This is because the large share of ATD covered by Natura 2000 sites. It is at least likely (i.e. likely as well as confident) that the ATD inside Natura 2000 sites will contract by 45%-48% in the 1.5 °C warming level across Europe. The contraction increases gradually with warming levels, and in the 3 °C period, only 15% (likely and confident stable) of the ATD inside Natura 2000 sites is projected to persist. Projected changes vary across regions and the results are comparable to those obtained in the whole ATD. In fact, although substantial, projected contraction is lower in the Alps, higher in the Scandes, and extreme in the Pyrenees, where only 1% is projected to persist in the 3 °C period. Table 8 in annex 3 shows a detailed breakdown per region, category and period.

In the 1.5 °C warming level, 196 and 199 sites out of 210 in the EU are projected to face (total or partial) confident contraction in RCP4.5 and RCP8.5, respectively. The number increases to almost the totality, 199 and 207, in the 2 °C warming level in both scenarios, respectively (Table 9 in annex 3). Note that in Table 9 (annex 3) one site can be represented in more than one category of change. For instance, in the Alps, 112 out of 114 sites are classified in confident contraction in the 1.5 °C warming level under RCP4.5. However, in many of these sites the contraction is partial.

Figure 9. Projected changes of the alpine tundra domain (ATD) occurring within Natura 2000 sites in a sample area of the Alps (see Figure 8) under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065) with respect to the reference period (1981-2010). In grey: ATD in the reference period (1981-2010) outside Natura 2000 sites.

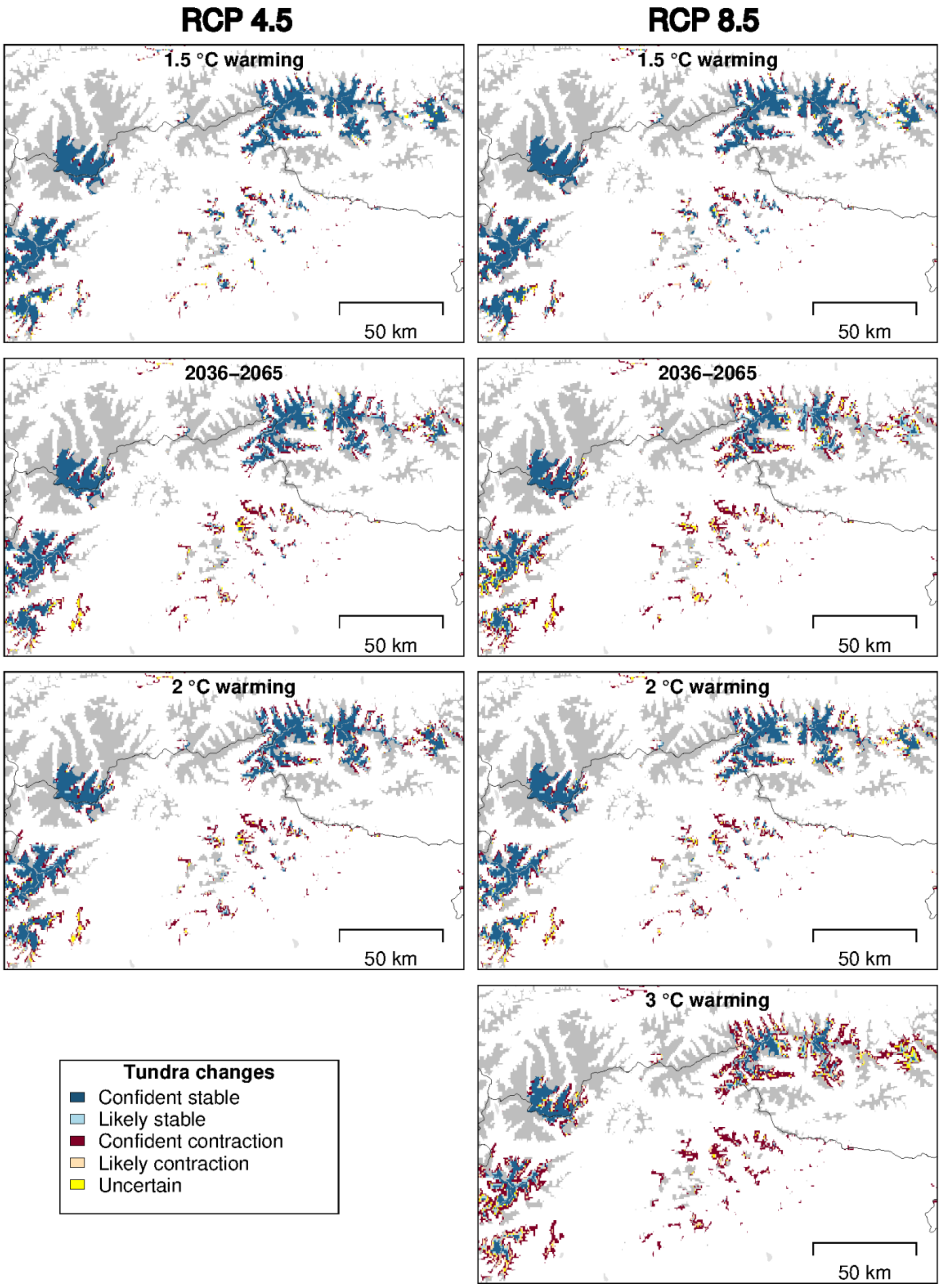
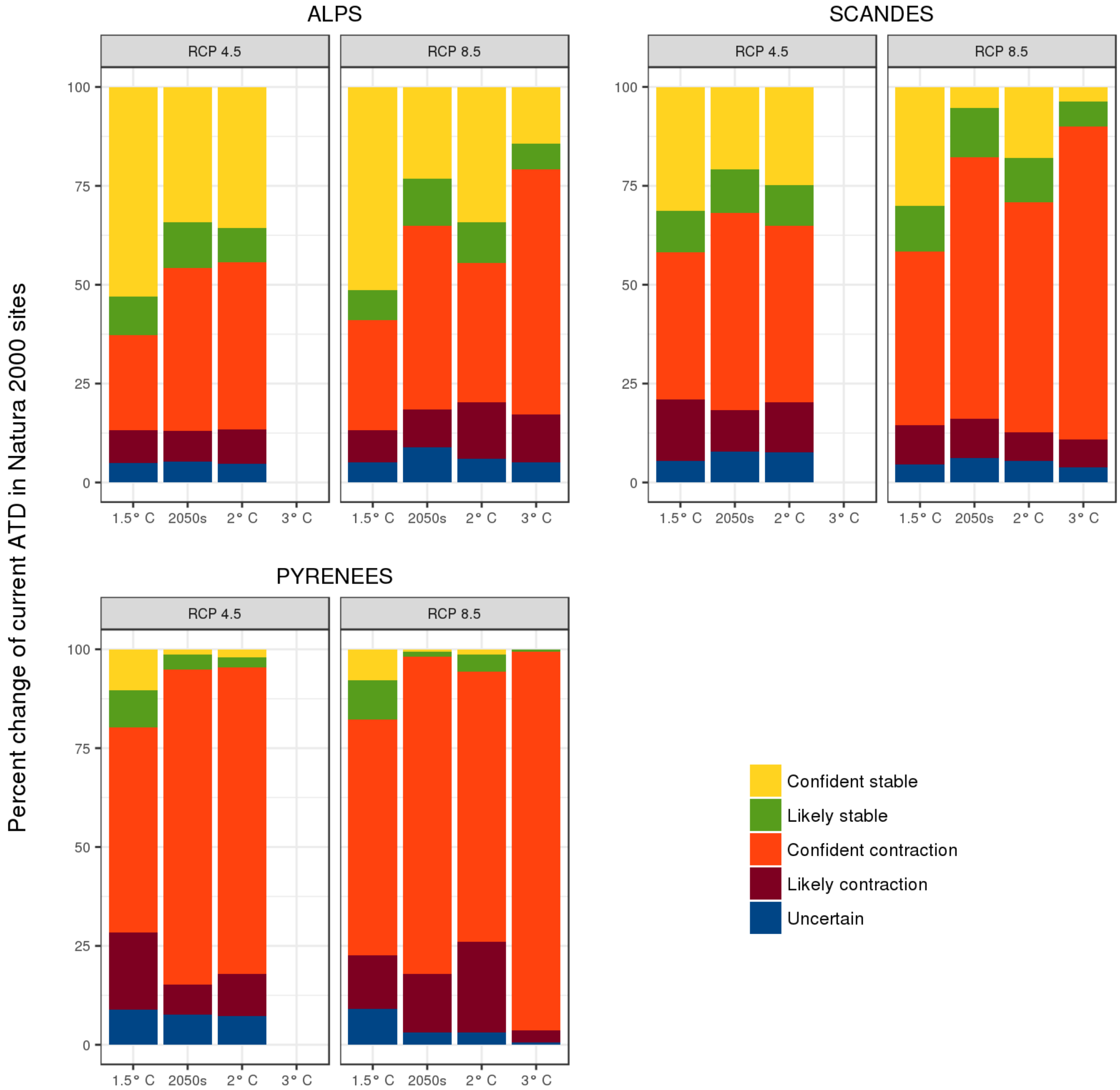


Figure 10. Projected relative area change of the alpine tundra domain (ATD) inside Natura 2000 sites under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065). Changes with respect to the reference period (1981-2010) extent of the ATD inside Natura 2000 sites in three regions: Alps, Scandes and Pyrenees.



3.4. Climatic parameters

Projected changes in climate parameters indicate that the area of the present ATD is projected to be warmer across regions, whereas projected changes in precipitation are less homogeneous, indicating a wetter climate in the Alps and Scandes, and drier in the Pyrenees. Projected changes are consistent between RCP4.5 and RCP8.5 regarding direction but not magnitude. Temperature is projected to increase in winter and summer across scenarios, warming levels and regions (Figure 11). In the Alps and Scandes, the increase is more pronounced in winter, in contrast to the Pyrenees where the increase is greater in summer. Thus, the mean annual temperature is projected to increase from the current -1.3, -1.8 and 0.6 °C in the Alps, Scandes and Pyrenees, respectively, to 0.2, 0 and 2.3 °C in the 2 °C warming level. Comparable results between RCP4.5 and RCP8.5 are projected in the 1.5 °C and 2 °C warming levels. In the 3 °C warming level the mean annual temperature is projected to almost double the increase projected in the 2 °C warming, thus projecting temperatures at 1.5, 1.2 and 3.6 °C in the three regions, respectively (Table 1).

Table 1. Projected mean annual temperature (°C) in the alpine tundra domain (ATD) across warming levels in three regions. Reference period (1981–2010) computed using CHELSA data (Karger et al. 2017). Warming levels show the mean of the 11 RCM simulations for RCP4.5 and RCP8.5.

Period/warming level	**Alps**	**Scandes**	**Pyrenees**
Reference (1981-2010)	-1.3	-1.8	0.6
1.5° C	-0.4	-0.6	1.7
2° C	0.2	0	2.3
3° C	1.5	1.2	3.6

The mean temperature of the warmest month (the parameter that defines alpine tundra) in the three ATD regions ranged between 7.9 °C and 9 °C in the referenced period. Projected changes indicate that this parameter will average between 9.8 °C and 11.4 °C in the 2 °C warming level under RCP4.5 (9.7 °C and 11.4 °C under RCP8.5), and 11.2 °C and 13.1 °C in the 3 °C warming. These figures are consistent with the projected contractions of ATD shown in section 3.2.

In the present area of ATD mean annual precipitation is projected to decrease in the Pyrenees across scenarios and warming levels between less of 1% and 8% in relation to the 1207 mm of the reference period (Figure 12). The projected decrease is more pronounced in the summer half of the year. For example, a decrease of 12% is projected in this season in the 3 °C warming in relation to the 618 mm of the reference period. In contrast, in the ATD of the Alps and Scandes, annual precipitation is projected to increase between 2% to 4% across warming levels in the first region, and between 4% and 11% in the former, in relation to the 1230 mm and 991 mm, respectively, of the reference period in both regions. In the Alps, the projected increase is more pronounced in winter, in contrast to the Scandes, where a larger increase is projected in summer.

Figure 11. Projected temperature change (°C) in the alpine tundra domain (ATD) across scenarios relative to the reference period (1981–2010) in three regions. Results are shown for the 11 RCM simulations for RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065). Summer (orange): temperature of the summer half of the year; annual (purple): annual temperature; winter (blue): temperature of the winter half of the year; tmax (red): temperature of the warmest month of the year. The median (horizontal line in boxes), mean (black circle in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario, period and season. Note that the 3 °C period was computed only in RCP8.5. w.r.t.: with respect to.

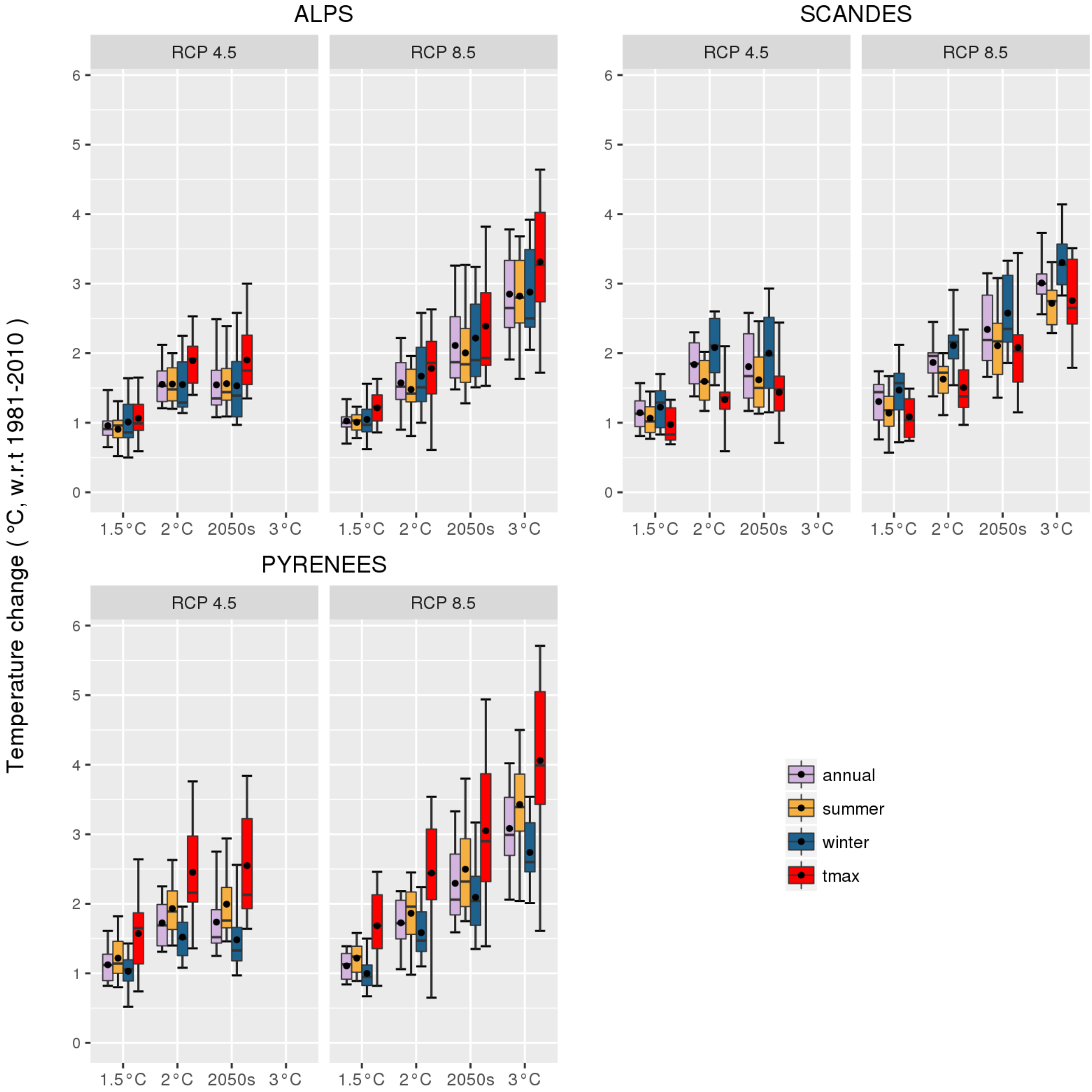
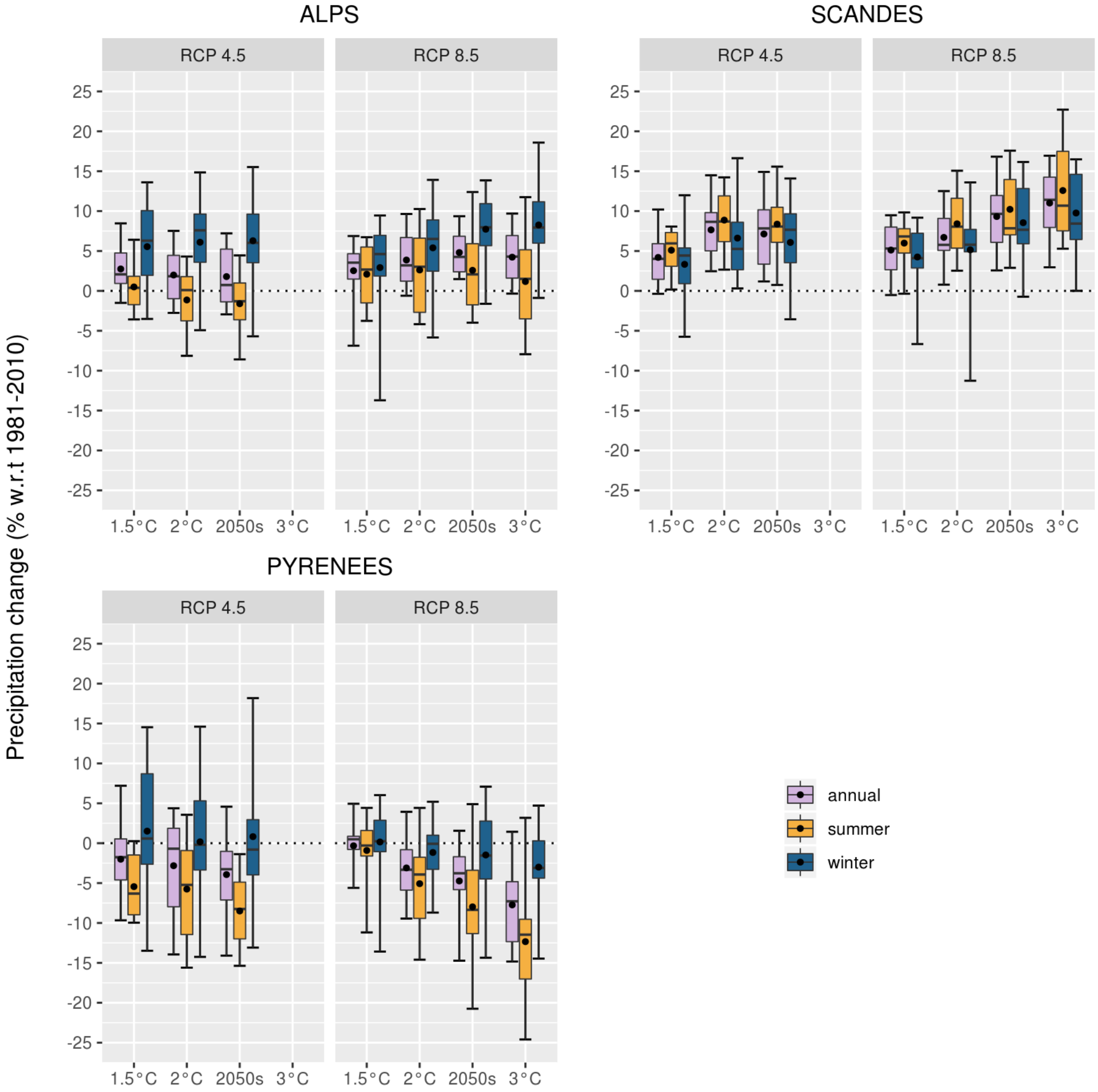


Figure 12. Projected precipitation change (%) in the alpine tundra domain (ATD) across scenarios relative to the reference period (1981–2010) in three regions. Results are shown for the 11 RCM simulations for RCP4.5 and RCP8.5 in in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-2065). Summer (orange): precipitation of the summer half of the year; annual (purple): annual precipitation; winter (blue): precipitation of the winter half of the year. The median (horizontal line in boxes), mean (black circle in boxes), 25–75% range (boxes), and minimum to maximum range (whiskers) across the 11 simulations are shown for each scenario, period and season. Note that the 3 °C period was computed only under RCP8.5. w.r.t.: with respect to.



3.5. Treeline

The natural climatic treeline is projected to shift upward across scenarios, simulations and warming levels in the entirety of the 16 mountain regions (Figure 17) assessed. Altitudinal shifts differ from one region to another. For instance, in the Alps, a mean shift of 211 and 325 m is projected in the 1.5 and 2 °C warming levels, respectively, under RCP4.5, from the 1762 m a.s.l. of the reference period. Likewise, a mean shift of 192, 277 and 526 m in the 1.5 °C, 2 °C and 3 °C warming levels, respectively, is projected under RCP 8.5 (Figure 13J), thus reaching the 2288 m a.s.l. in the 3 °C warming level. Larger changes were found in the Pyrenees, where shifts of 206, 322 and 642 m were projected in the 1.5 °C, 2 °C and 3 °C warming levels, respectively, under scenario RCP8.5. In this scenario in the 3 °C level the projected shift reaches a mean elevation of 2,317 m a.s.l. from the 1,675 m a.s.l. of the reference period (Figure 13K).

Figure 13A to P show the mean elevation of the climatic treeline in the reference period in each region. However, note that our results indicate that there is high variation in the treeline elevation within each region. For instance, in the Alps, the highest and lowest treeline elevations were found at ~1,200 and ~2,300 m a.s.l., respectively. Similarly, in the Pyrenees, the highest and lowest treeline elevations are 1,080 and 2,160 m a.s.l., respectively.

Elevational changes of the climatic treeline in a zone of the western Alps are shown in Figure 14 using as example one of the 11 simulations under scenario RCP8.5. The figure exhibits a steady elevational shift of the climatic treeline with increasing warming. A comparable pattern of shifts was found in the other regions across the 11 RCM simulations in both RCP4.5 and RCP8.5.

At higher latitudes, where the climatic treeline occurs at lower elevations, the shifts are less pronounced than at lower latitudes. In contrast with the projected shifts in the Alps or Pyrenees at ~42-47° N latitude mentioned above, in the south Scandes, at ~58-63° N latitude, shifts were projected at 128, 185 and 336 m in the 1.5 °C, 2 °C and 3 °C warming levels, respectively, under scenario RCP8.5. In this scenario, in the 3 °C level, the treeline is projected to shift from 523 m a.s.l. in the reference period to 859 m a.s.l. (Figure 13A). Comparable elevational shifts were projected in the northern Scandes, though in this region the treeline in the reference period is at a lower altitude of 386 m a.s.l. (Figure 13B).

In the 3 °C warming level under RCP8.5 elevational shifts of the treeline are projected to surpass the maximum altitude in the Sudetes Mountains (~1,600 m a.s.l.). Therefore, projected elevation of the treeline for this warming level/scenario was not indicated in this region in Figure 13H and successive figures.

Our study shows that projected treeline shifts are comparable between RCP4.5 and RCP8.5 in the 1.5 and 2 °C warming levels. That means that regarding the delineation of treeline both scenarios provide analogous results when assessing the same warming level (Figure 13A to P).

As expected, the analysis of the climatic treeline across the 16 regions indicates that with increasing latitude, the treeline elevation decreases. This association holds in the reference period and across scenarios and warming levels. Figure 15 shows a steady decrease of the treeline altitude from around the 2000 m a.s.l. in the range of the 35-40° N latitude to the 250-400 m a.s.l. in the extreme northern latitudes between 65 and 70° N in the reference period. The assessment of the association between treeline elevation and latitude of Figure 15 revealed that projected treeline shifts are more pronounced at lower latitudes. This is indicated by a decreasing gap with increasing latitude between the regression curve of the reference period and that of the future scenarios. For example, the shift from the reference period to the 3 °C level under RCP8.5 is projected at 642 m in the Pyrenees, in contrast with the projected 271 m in the North Scandes (Figure 13B and K). This finding means that shifts are projected to be faster at lower latitudes as shown in Figure 16. For example, in the 1.5 °C level treeline shift velocity is projected at

6.2 and 7.3 m/yr under RCP4.5 and RCP8.5, respectively, at the lower latitudes of our study area. Nonetheless, at this warming level shift velocity decreases with latitude until 2.1 and 2.8 m/yr under RCP4.5 and RCP8.5, respectively, at the higher latitudes. In consequence, projected shifts are faster in RCP8.5 than in RCP4.5 across warming levels, this was expected according to the fact that a warming of either 1.5 or 2 °C is projected to occur earlier in RCP8.5 than in RCP4.5 (see Table 4 in annex 1). This aspect has implications for adaptation, as shown later.

Producing a cartographic representation of the results of the treeline assessment is challenging because of the linear character of the output (e.g. Figure 14) and the large extent of the geographic domain. To minimise these difficulties, we have created example maps of treeline elevation averaging the results at 10-km grid size. Figure 20 (in annex 3) shows, as an example, average treeline elevation in the reference period and in three warming levels using the CCLM4-8-17-ICHEC-EC-EARTH RCM under the RCP8.5 scenario. The maps show treeline elevation on each period and the changes in the spatial distribution of the treeline areas. For instance, it is evident that the extent of the area hosting treelines in the Alps is projected to shrink from the reference period to the 3 °C period. This is the result of the projected elevational shifts of treelines. A similar effect is evident in other mountain regions. In some other mountain areas, treeline zones are projected to disappear progressively in the three warming levels. This occurs in areas where the treeline is projected to overpass the maximum elevation of that area. In those cases, the treeline ecotone is projected to shift over the alpine and nival zone.

The approach used for treeline delineation assumes that moisture shortages limiting tree growth are not specific to high elevations (Körner and Paulsen 2004). For verifying that this assumption holds in the future we computed the minimum annual precipitation in the areas above the treeline using the 11 simulations, two scenarios and three warming levels. Then we compared projected minimum annual precipitation with that of the reference period. Results of the comparison indicate that the minimum annual precipitation across all the grid cells above the treeline in the reference period is 286 mm. Then, it was projected at 274—288 mm in the 1.5 °C level, 279—293 mm in the 2 °C level, and at 282 mm in the 3 °C level. In all cases the minimum annual precipitation is above the 200—250 mm/year that is considered the limit at the highest elevations were trees grow (Körner 2012). Therefore, moisture shortages should not represent a limiting factor of tree growth in the assessed domain.

Figure 13. Projected shifts of the climatic treeline under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the period 2036-65. Dashed line: mean climatic treeline in the reference period 1981-2010. The mean (horizontal line in boxes), 25—75% range (boxes), and minimum to maximum range (whiskers) across the 11 RCM simulations for each scenario, warming level and period. A to P mountain regions according to Figure 17 (in annex 1). *Treeline elevational shifts projected to surpass the maximum altitude in the region (~1,600 m a.s.l.).

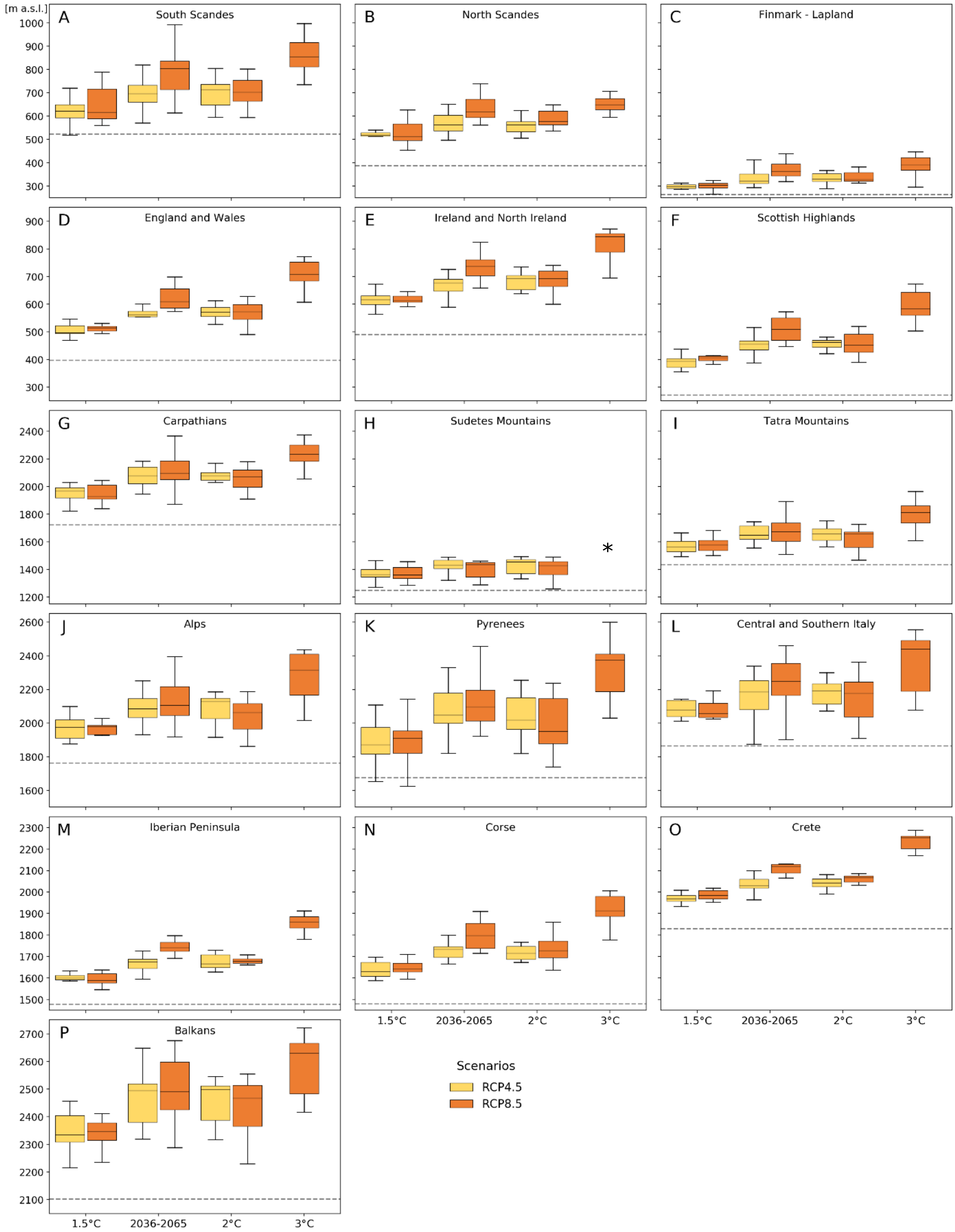


Figure 14. Natural climatic treeline delineation in the reference period and in three warming levels, 1.5 °C, 2 °C and 3 °C, according to the CCLM4-8-17-ICHEC-EC-EARTH Regional Climate Model under scenario RCP8.5 in the western Alps. Source of base maps: DigitalGlobe WV02 29/10/2014 and Esri, USGS, NOAA, Garmin, NPS.

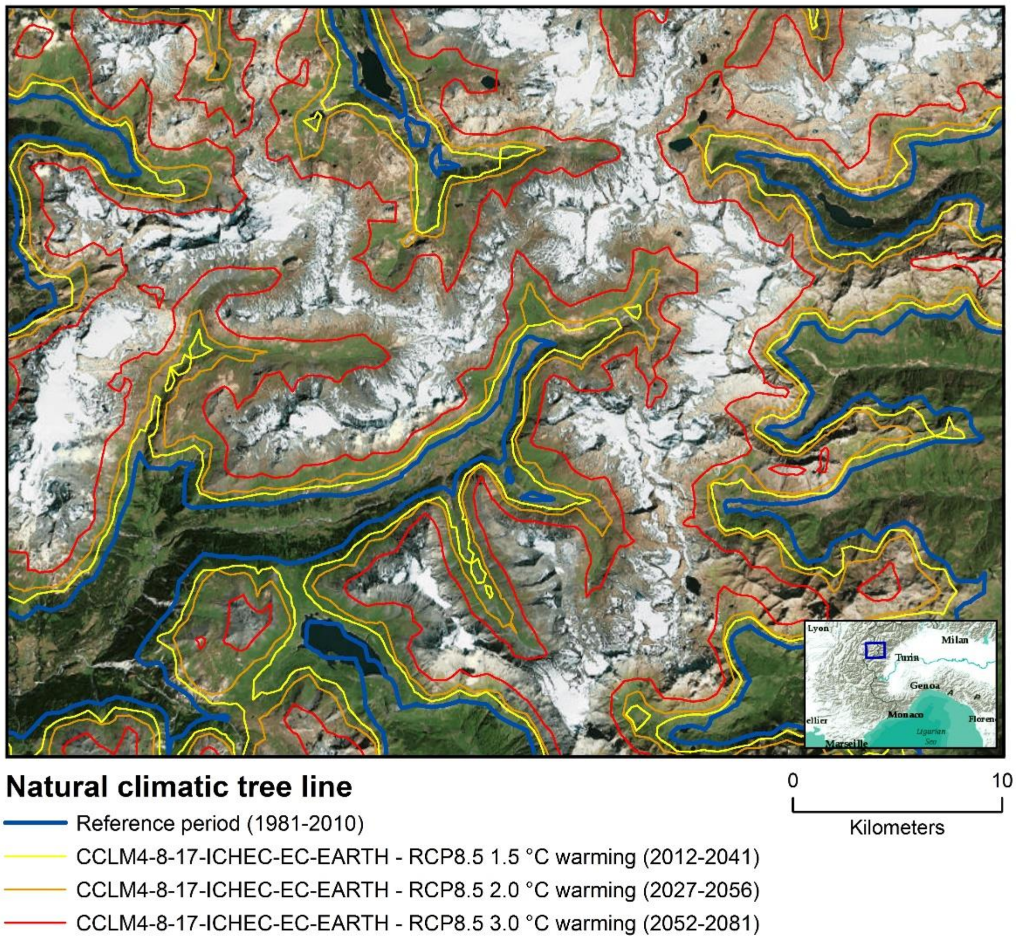


Figure 15. Relationship between climatic treeline mean elevation and mean latitude per region in the reference period (1981-2010) and under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C). Correlation coefficient (*r*) of the curves (~0.9) significant at <0.01 level.

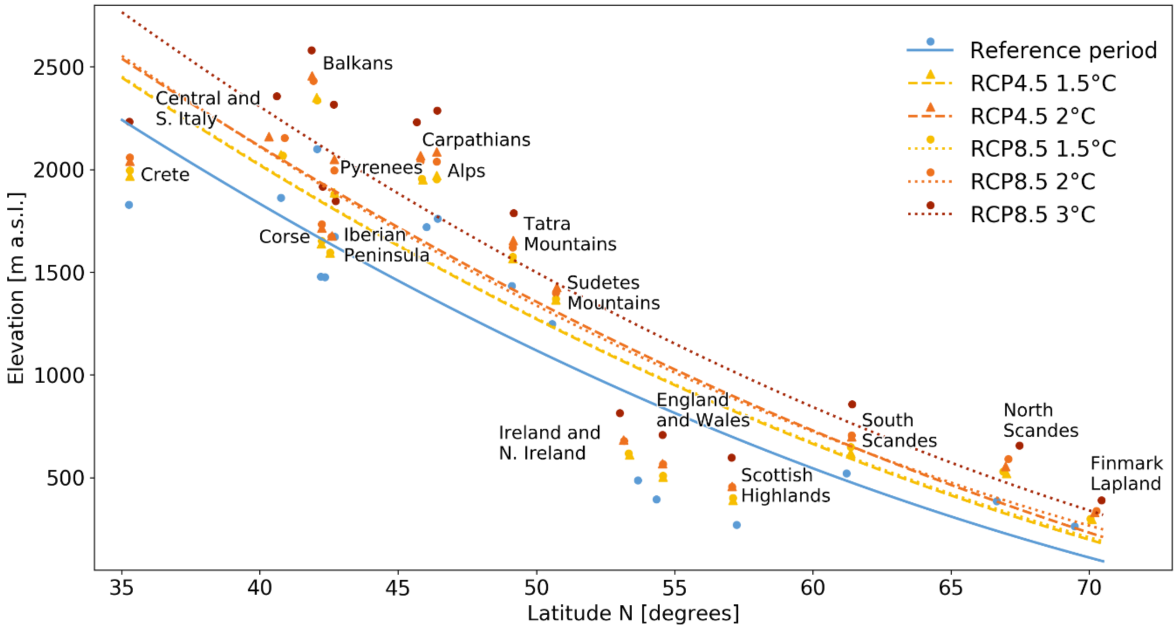
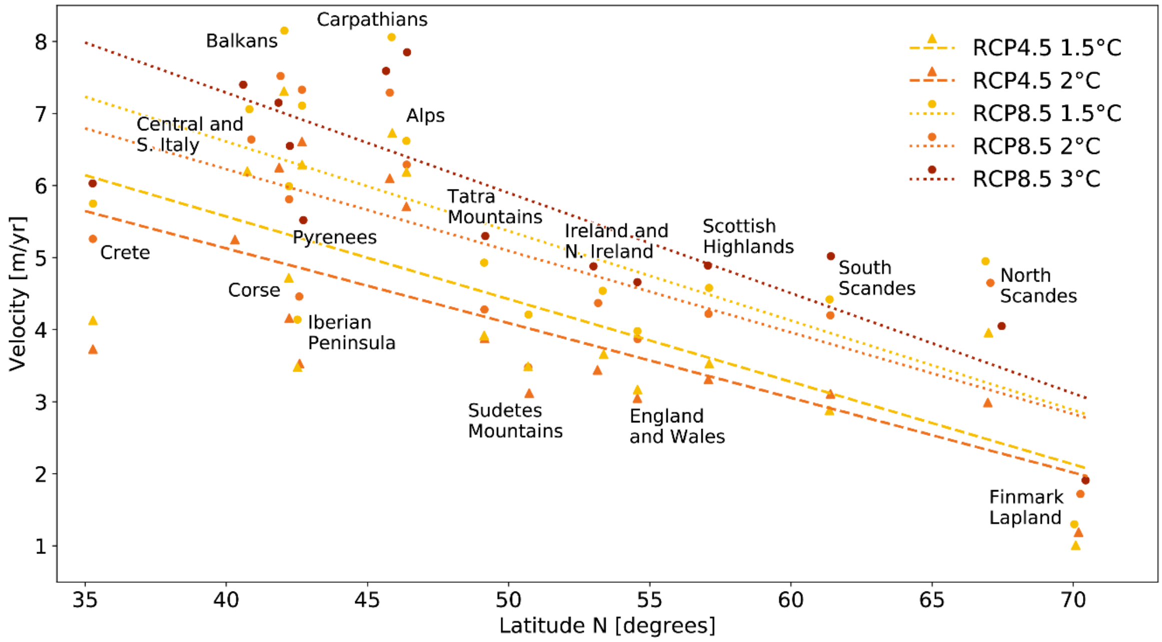


Figure 16. Relationship between climatic treeline mean shift velocity (m/yr) and mean latitude per region under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) with respect to the treeline elevation in the reference period (1981-2010). Correlation coefficient (*r*) of the lines (>0.7) significant at <0.01 level.



4. Impacts and adaptation: Alpine tundra domain contraction and treeline shift

Treeline upward shift and ATD contraction are simultaneous processes. The ATD occurs above the treeline ecotone as an island biome (Butler et al. 2009), therefore the upward elevational movement of the treeline reduces the extent of the ATD. The faster the treeline shift, the faster the ATD contracts. Both processes are the result of increasing temperatures and are consistent with changes in species diversity and composition, and the function of high altitude mountains ecosystems. In this section, we assess potential impacts and adaptation options using key questions of interest for policy makers. Additionally, we identify a set of adaptation options for mountain habitats and illustrate the constraints of these options from past and on-going initiatives. Finally, we discuss trade-offs between adaptation options in different sectors.

1) What are the expected effects of treeline shifts and ATD contraction for mountain environments?

The treeline is a highly responsive bioindicator, in the treeline ecotone a number of key factors and ecological processes change abruptly within just a few altitudinal meters of difference i.e. passing from the treeline ecotone to the alpine tree-less zone (part of the ATD), for instance, wind, snowpack accumulation, water storage and release, albedo[5], soil temperature, plant productivity, biodiversity, soil development, and carbon and nutrient cycling (Fagre 2009; Hagedorn et al. 2014; Holtmeier 2009; Kammer et al. 2009; Loranty et al. 2014). In consequence, treeline advance and ATD contraction can have an important impact on ecosystem functions and consequently on its services (Walker et al. 2006). For example, regarding water services, winter snowpack accumulation and snow retention in summer occurs in the ATD above the treeline. The retention of snow is critical because it releases water from the mountains during the summer months. Therefore, contraction of the ATD is consistent with the shrinking of the area of snowpack accumulation, thus impacting low elevation biota and changing mountain hydrology (Fagre 2009; Hock et al. 2019). A declining snow cover and ice reservoir in the Alps will prolong periods of low river flow in summer in many parts of Europe. This can have severe consequences for several economic sectors including agriculture, hydropower generation, water supply and river navigation (CH2014-Impacts 2014; Hock et al. 2019). An indication of the importance of this process is that the Alps alone provides a mean contribution of 25%, 34%, 41% and 53% of the total discharge of the Danube, Rhine, Rhone and Po rivers, respectively (EEA 2010). Nevertheless, despite the great importance of the potential impacts of temperature increase in mountain systems, our understanding of the processes involved is limited (Greenwood and Jump 2014).

Regarding plant assemblages, observational evidence of effects of increased warming in mountain systems above the treeline in Europe indicates a decline of cold-adapted species and the increase of more warm-adapted species. This process, referred to as thermophilization, suggests a progressive decline of cold mountain habitats and their associated biota (Gottfried et al. 2012; Lenoir et al. 2008; Walker et al. 2006). Nevertheless, there is great uncertainty regarding potential impacts in plants diversity in mountain systems (Greenwood and Jump 2014; Urban et al. 2012), and there is controversy regarding whether the impacts of climate change will be negative in absolute terms or there could be beneficial aspects as well (Crawford 2008; Kullman 2010). For instance, Engler et al. (2011) suggest that 36-55% of alpine plant species will lose more than 80% of their suitable habitat by the end of the century in Europe. In contrast, Rixen and Wipf (2017) indicate that extinction of high mountain plants may be mitigated

[5] Albedo is the proportion of sunlight (solar radiation) reflected by a surface or object. Clouds, snow and ice usually have high albedo; soil surfaces cover the albedo range from high to low; whereas photosynthetically active vegetation have low albedo (source: IPCC).

considerably by the high diversity of microhabitats, the longevity of alpine plants and positive plant-plant interactions in harsh environments.

According to available evidence assessing treeline species migration due to global warming (Cudlín et al. 2017; Harsch et al. 2009) it is reasonable to expect future changes associated with shifts of the natural climatic treeline. Nevertheless, the response of individual trees, and tree species, varies as result of local factors, such as nutrient availability, microclimates, soil conditions, landscape fragmentation, some species-specific traits (e.g. dispersal capacity), and interspecific interactions between species (Cudlín et al. 2017; Davis and Gedalof 2018; Grace et al. 2002; Liang et al. 2016). Therefore, it is expected that the natural climatic treeline will shift faster than trees due to a slower dispersal velocity of trees, resulting in that tree movement may be asynchronous with the rate of natural climatic treeline advance. In consequence, it is likely that these newly forested areas will deviate from the established forests at the treeline due to community disassembly, leading to profound effects on ecosystems structure and function. In turn, changes in plant species abundance and composition at community level could reasonably modify ecosystem functions leading to a number of impacts. A review conducted by Greenwood and Jump (2014) of the impacts of treeline movement as consequence of elevated temperature indicates effects on biodiversity, carbon sequestration and storage, nutrient cycling, hydrological properties of ecosystems and slope stabilisation.

One of the most notable impacts of warming, associated with ATD contraction, is the widespread retreat and disintegration of glaciers (Diolaiuti et al. 2011; Hock et al. 2019; Zemp et al. 2007). Rapid changes in glaciers result in multiple impacts in social-ecological systems, including formation of ice-marginal lakes, ice avalanches and mass movements (Mourey et al. 2019), runoff volume and sediment fluxes. The impacts affect not only biophysical systems, but also sectors such as agriculture, tourism and cultural values. For instance, in the last twenty years several lakes have formed in the Alps at the terminus of glaciers rising the concern of hazards in case of a lake outburst (Stoffel and Huggel 2012). Observational evidence indicates a consistent reduction of glacier mass across mountains at global level, with the Alps and Pyrenees among the most affected zones (Hock et al. 2019). Projected end-of-century global scenarios of glacier mass loss indicate that the Alps and Pyrenees will be among the most affected zones exceeding 80%. But also in Scandinavian glaciers the losses are projected over 75% in the RCP8.5 scenario (Hock et al. 2019).

ATD contraction and treeline shifts present a major threat for alpine Natura 2000 sites. The impacts on habitats and biodiversity mentioned in this section will affect these biodiversity rich sensible areas. Additionally, options for adaptation are limited due to the tight ecological and climatic bands in high mountain systems. A summary of current knowledge on likely impacts of treeline advance and alpine tundra contraction is shown in Table 2.

Table 2. Summary of likely impacts of treeline advance and alpine tundra contraction in ecosystems and their services, and adaptation options.

Ecosystem features and services	**Likely effects of treeline advance and alpine tundra contraction**	**Adaptation options**
Biodiversity	- Reduction in alpine habitats (Dullinger et al. 2012). - Shifts in plant community composition and structure. New plant species assemblages will form (Pauli et al. 2003). - Decline and/or local extinction of alpine plant species (Gottfried et al. 2012; Pauli et al. 2003; Pauli et al. 2007; Walker et al. 2006). Habitats of open and scattered subnival species would be colonised by species of alpine grasslands, thus reducing the extent of high-elevation habitats. - Upslope migration of trees can represent a threat to many plant species due to outcompetition for space and substrate. This could probably lead to species loss and reduction in diversity due to the proliferation of widespread species form lower altitudes (Greenwood and Jump 2014; Jump et al. 2012). - There is high uncertainty regarding these effects due to the individualistic response of species (Grabherr et al. 2010). This makes challenging a complete understanding of the effects at plant community level (Greenwood and Jump 2014; Liang et al. 2016).	- Migration corridors and expansion of conservation areas. - Protect areas that are specific to vulnerable species. - Assisted migration from contraction areas to stable areas or to areas with micro-climate conditions that allow the survival of alpine species. - Ex-situ conservation and seed-banks. For a discussion see Klein et al. (2014), Noble et al. (2014) and Hock et al. (2019).
Carbon sequestration and storage	- Tree range expansion at, and above, the treeline suggests that carbon accumulation at the treeline will increase. However, such increases may be offset by carbon release from low altitude mountain forests, therefore the overall balance remains unclear (Zierl and Bugmann 2007). - The impact of increased temperatures and a longer growing season at the treeline will be influenced by several local factors, thus it is thought to vary between regions (Greenwood and Jump 2014). - Expansion of forest in the ATD could lead to increased soil respiration potentially offsetting the carbon stored in the new forests. Nevertheless, there is contradictory evidence depending on the region assessed (Greenwood and Jump 2014). In alpine ecosystems it is probable a net increase of the carbon content.	

Ecosystem features and services	Likely effects of treeline advance and alpine tundra contraction	Adaptation options
Nutrient cycling	- Several studies provide mixed, and in some cases contradictory, evidence on the likely effects of treeline advance for nitrogen cycling and availability. - An association between treeline expansion over the ATD and effects on nitrogen cycling has yet to be elucidated.	
Hydrological properties	- Mountain areas, in particular the alpine tundra biome, are extremely important regarding water regulation, supply and quality. While more research is needed for a better understanding of the impacts of treeline advance on hydrology, the effects of the ATD contraction will likely lead to a decreased snowpack accumulation and in turn in snow retention and water regulation, changing mountain hydrology (Fagre 2009; Pauli et al. 2003). Most of the retention of snow in summer occurs in the ATD above the treeline. This is a critical process because it regulates water provision and release during the drier summer months, and these changes could have far-reaching effects in water provision. - Declining snow cover and ice reservoir could have severe consequences for several economic sectors including agriculture, hydropower generation, water supply and river navigation (CH2014-Impacts 2014). - One notable impact of warming, associated with ATD contraction, is the shrinkage of alpine glaciers. This is likely to accelerate erosion processes, thus leading to large debris flows and increased sediment loads in rivers that in turn affects water quality downstream (Pauli et al. 2003).	- Long-term water management strategies to sustain agriculture and hydropower generation (Hock et al. 2019).

Ecosystem features and services	Likely effects of treeline advance and alpine tundra contraction	Adaptation options
Slope stabilisation	- Evidence suggests that an increased forest density at the treeline and above will contribute to lessening avalanche and landslide hazard. - Conversely, permafrost thawing and glacier melt will likely lead to increasing landslides and debris flow. - The number and size of glacial lakes will increase. In turn, the risk of outburst floods will increase downstream (Probst et al. 2013).	- Risk monitoring and risk reduction. - Prepare adequate emergency management plans. - Train emergency and rescue services. - Diversification of tourism revenues. - Infrastructure prone to be affected by active rock glacier and its front zone should be avoided. - Setting security zones below rock glaciers. - Hazard assessment and monitoring of trails crossing rock glaciers or passing down below its front. For a discussion see OECD (2007) and Probst et al. (2013).
Recreational services	- Retreat of the nival zone associated with contraction of the ATD on higher mountains will likely restrict winter sports (Elsasser and Bürki 2002; OECD 2007) and in general on recreational mountain activities (Mourey et al. 2019).	- Artificial snowmaking. - Grooming of ski slopes. - Moving ski areas to higher altitudes and to glaciers. - Diversification of tourism revenue. - Ensuring access and improving security of access trails to high mountains (Mourey and Ravanel 2017). For a discussion see Hock et al. (2019).

In conclusion, the most relevant expected impacts on ecosystems and functions from treeline advance and ATD contraction relates to alpine biodiversity, hydrological properties, water quality, erosion protection and recreational services including winter sports. However, available information is in most cases insufficient to make reliable predictions on the magnitude of the impacts (Greenwood and Jump 2014). Still, findings of this study indicate significant changes in alpine and subalpine habitats as consequence of temperature increase.

2) <u>What adaptation options can be implemented?</u>

In this report we assessed human-assisted adaptation (extrinsic adaptation), which means a range of human interventions oriented to increase the capacity of organisms and ecosystems to survive and function at an acceptable level in the presence of climate change (Settele et al. 2014). Human-assisted adaptation options include an array of strategies and measures for addressing adaptation needs. We provide a summary of adaptation options for high mountain environments (Table 2). Nevertheless, research challenges remain to be addressed before we can fully understand if and how humans can provide conservation options in alpine areas to prevent, for instance, extinction of alpine species (Rixen and Wipf 2017).

Regarding adaption for biodiversity conservation, migration corridors and expansion of conservation areas are suggested. However, the establishment of migration corridors is challenging due the scattered character and the magnitude of the projected contraction of the alpine tundra. Similarly, expansion of conservation areas is limited by the large extent of ATD projected to be lost in the future, even under the 1.5° C warming. The implementation of these two options should consider local level characteristics of the assessed zones. To facilitate the conservation of valued species, assisted migration is suggested. This measure is proposed when fragmentation of habitats limits migration potential or when the pace of climate change outstrips natural migration rates (Noble et al. 2014). However, there is great uncertainty and lack of knowledge concerning the potential impact of assisted migration on the ecosystem of the new colonised areas.

Ex-situ conservation is another option that could be considered, especially for those species that are located in the upper limit of the alpine tundra and that as consequence of alpine tundra contraction will not be able to migrate further up (Müller et al. 2017). This option consist in conserving plant seeds in dedicated seed-banks. With regards to this option several issues remain largely unresolved and the physiological, institutional and economic sustainability of this option is unclear (Settele et al. 2014; Wyse et al. 2018).

Climate impacts in hydrological properties of mountains can be mitigated through improved management of flow releases from reservoirs (Arthington et al. 2010). Additionally, hydropower generation is a cost-effective option in mountain systems. Other options such as protection and restoration of riparian vegetation could provide an effective alternative to protect water quality for downstream ecosystems and human use (Settele et al. 2014).

Regarding slope stabilisation, natural hazard mapping and monitoring technology as well as early warning systems could be applied to areas presenting high risk. However, their application to the alpine tundra might consider local level features and economic sustainability.

A range of adaptation options are proposed for mountain recreational services, specifically winter sports. Nevertheless, the cost-benefit of these options should be considered on a case-by-case basis given the different characteristics of ski areas and regions. Options such as snowmaking and the extension of ski areas to higher elevations can be considerably expensive (Hock et al. 2019; Mathis et al. 2003; OECD 2007). In addition, it is essential to avoid severe disturbances in these biodiversity sensitive alpine areas (Rixen and Wipf 2017).

The adaptation options illustrated in this section, which were collected from previous initiatives, should be interpreted in the light of the unprecedented changes projected in this study. Therefore, a closer look at local level is necessary for understanding the feasibility and cost-effectiveness of the proposed options. We believe that the magnitude of the projected changes and the adaptation constraints in high mountains could certainly limit adaptation in many cases. Moreover, adaptation challenges and limitations increase with warming level. The projected impacts resulting from the contraction of the ATD in the 3 °C warming would require higher adaptation efforts than in the 1.5 or 2 °C level. Likewise, adaptation efforts in the 2 °C are higher than those required in 1.5 °C warming. In the author’s opinion some of the foreseen impacts could overcome adaptive capacity of both physical and human systems.

3) <u>Adaptation constraints in alpine environments</u>

Adaptation options in high mountain environments face constraints arising from the unique topographic, edaphic and climatic characteristics of these zones. For instance, migration of species could be constrained by lack of sufficient altitude to migrate vertically or due to limiting soil conditions for plant growth. In alpine systems physical constraints could reduce adaptation options for conservation (Klein et al. 2014). Additionally, regarding ecosystem-based adaptation options, e.g. ecological restoration, increasing biological diversity, assisted migration or managed translocation, ecological corridors, ex-situ conservation and seed banks (Noble et al. 2014), local level traits should be considered for proper implementation. Additionally, limits to adaptation in high mountains and long-term sustainability of the options should be assessed taking into consideration, among other factors, the magnitude of the projected changes and the feasibility of the options (Klein et al. 2014).

Potential trade-offs between adaptation options in different sectors is an aspect that should be considered. One example is the effect that adaptation options in winter tourism may have on biodiversity and conservation. Adaptation options found in ski areas are divided into two main categories: technological and behavioural. The four key typologies of technological adaptation i.e. landscaping and slope development, moving to higher altitudes and north facing slopes, glacier skiing and artificial snow-making, could represent a threat to nature conservation (Rixen and Wipf 2017). For instance, the construction of new ski resorts at higher elevations might have a negative effect on high alpine biota or the use of massive amount of water for snowmaking might have a negative effect on water reservoir and in cascade to the hydropower sector (Bosello et al. 2011).

5. Conclusions

We assessed projected contractions of the ATD and upward elevational shifts of the natural climatic treeline under RCP4.5 and RCP8.5 scenarios of climate change in Europe. ATD contraction and upward shifts of the treeline are simultaneous processes and are the result of increasing temperatures. Results of this study are consistent with previous evidence highlighting the sensitivity of high mountain systems to climate change. For instance, there is evidence of ongoing alpine tundra contraction, treeline upward shift and range contraction of high mountain species.

Results of this study indicate a pronounced projected contraction of the ATD across regions, scenarios and warming levels (Table 3). In the 1.5 °C warming, the ATD is projected to lose an extension of around 31-36%, 48-52% and 74-76% in the Alps, Scandes and Pyrenees, respectively, with respect to the present. The contraction is projected to increase in the 2 °C and 3 °C warming levels. In the 3 °C warming the contraction is projected at 75%, 87% and nearly the totality, of the present area, respectively in the three regions.

Table 3. Projected relative contraction (confident and likely) of the alpine tundra domain (ATD) in three warming levels (1.5 °C, 2 °C and 3 °C). Changes with respect to the reference period (1981-2010) extent of the ATD in three regions: Alps, Scandes and Pyrenees. Ranges computed using the projected contraction in RCP4.5 and RCP8.5. Numbers in percentage.

Region	1.5° C	2° C	3° C
Alps	31-36	49-51	75
Scandes	48-52	59-62	87
Pyrenees	74-76	90-92	99

Our results indicate that the treeline is projected to shift upward across mountain regions, scenarios and warming levels. Projected shifts are less pronounced at higher latitudes, where the climatic treeline occurs at lower elevations. For instance, in the south Scandes (~58-63° N latitude) the shifts were projected at between 128 m in the 1.5 °C warming and 336 m in the 3 °C warming. In contrast, in the Alps, at a lower latitude (~43-47° N), the projected shifts fall between 192 m in the 1.5 °C warming and 526 m in the 3 °C warming.

<u>What do these changes imply for high mountain ecosystems?</u>

The projected changes suggest a range of impacts for the diversity and function of high mountain ecosystems and their services. Among the services assessed, five were considered the most affected, i.e. habitat provision (biodiversity), water provision and regulation, erosion protection, water quality and recreational services.

We include here a few examples of the impacts to illustrate the potential effects of the projected changes. First, projected changes suggest a progressive decline of cold mountain habitats and their associated biota, restricting the habitat for alpine species. Changes in species composition of plant communities are consistent with reduced biodiversity, however community wide changes are hard to predict (Greenwood and Jump 2014; Urban et al. 2012). Second, winter snowpack accumulation and snow retention in summer occurs in the ATD above the treeline. Therefore, ATD contraction and upward shifts of the treeline are consistent with changes in snowpack accumulation, which in turn change mountain hydrology by a reduced water regulation capacity. Third, contraction of the ATD is associated with the shrinkage of glaciers. This is likely to accelerate erosion processes, thus leading to large debris flows and increased sediment loads in rivers that in turn affects water quality downstream. Finally, the retreat of the nival zone associated with the contraction of the ATD on higher mountains will likely restrict winter sports.

Limits of adaptation

Treelines and the ATD occurs in high mountains where harsh conditions have contributed to delineating plant and animal species assemblages over millennia. Alpine systems are highly complex and fragile, therefore they are highly sensitive to environmental changes (Seddon et al. 2016). Climate change is a main threat for alpine flora and the alpine system, furthermore adaptation constraints arising from the unique topographic, edaphic and climatic characteristics of high mountains should be considered. For instance, migration of species could be constrained by lack of sufficient altitude to migrate vertically or due to limiting soil conditions for plant growth. In alpine systems physical constraints could reduce the range of adaptation options for nature conservation (Klein et al. 2014). Additionally, regarding ecosystem-based adaptation options, e.g. ecological restoration, increasing biological diversity, assisted migration or managed translocation, ecological corridors, ex-situ conservation and seed banks (Noble et al. 2014), local level traits should be considered for proper implementation. Lastly, limits to adaptation in high mountains and long-term sustainability of the options should be assessed taking into consideration, among other factors, the magnitude of the projected changes and the feasibility of the options (Klein et al. 2014).

One aspect deserving attention is the potential trade-off between adaptation options in different sectors. One example is the effect that adaptation options for winter tourism may have on biodiversity and conservation. Adaptation options found in ski areas could represent a threat to nature conservation. Therefore, trade-offs between adaptation for nature and biodiversity conservation and adaptation for winter tourism should be considered.

In this report we assessed a suite of ecosystem-based and technological adaptation options for several ecosystem services. However, decisions in high mountain ecosystems should take into consideration local level environmental traits and the specific limitations of adaptation, trade-offs and the adaptation objective of each zone in a case-by-case basis.

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List of abbreviations

ATD	Alpine tundra domain
CORDEX	Coordinated Regional Downscaling Experiment
DEM	Digital elevation model
GCM	General circulation model
IPCC	Intergovernmental Panel on Climate Change
RCM	Regional climate model
RCP4.5	Representative Concentration Pathway 4.5 W/m^2
RCP8.5	Representative Concentration Pathway 8.5 W/m^2
WCRP	World Climate Research Programme

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Annexes

Annex 1. Methodology

The objective of the first part of the method is to map the European alpine tundra and the treeline under historical climate, i.e. the reference period (1981—2010), and two different Representative Concentration Pathways (RCPs) adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment report, namely RCP4.5 and RCP8.5 (Moss et al. 2010; van Vuuren et al. 2011). The first scenario, RCP4.5, is a trajectory corresponding to a projected change in global mean surface air temperature of + 1.8 °C (likely range 1.1–2.6 °C) relative to the reference period of 1986–2005 (Collins et al. 2013). The second scenario, RCP8.5, is seen as a business as usual (high emission) scenario (Moss et al. 2010; van Vuuren et al. 2011), corresponding to a + 3.7 °C (likely range 2.6–4.8 °C) world by the end of the century relative to 1986–2005 (Collins et al. 2013). In accordance with the PESETA IV project we used 11 Regional Climate Model (RCM) simulations for three warming levels i.e. 1.5 °C, 2 °C and 3 °C, the latter reached only in RCP8.5, and one additional period centred on the 2050s (2036-2065). The warming levels were computed centred on the year when the driving general circulation model (GCM) projects a global 1.5 °C, 2 °C and 3 °C warming, with respect to pre-industrial levels, according to IMPACT2C (2015) project (Table 4).

Maps accounting for changes in the alpine tundra and the treeline were implemented for the 11 simulations, the two scenarios and four periods. In the second part of the method we identified Natura 2000 sites that are projected to be affected by changes of the alpine tundra. The maps of alpine tundra change were overlaid with a map of Natura 2000 sites, then the area and number of sites affected by the changes were computed.

Table 4. Regional climate model (RCM) simulations used in this study with 30-year time ranges when the driving general circulation model (GCM) projects a global 1.5 °C, 2 °C and 3 °C warming according to IMPACT2C (2015).

Institute	RCM	Driving GCM	Scenarios	+ 1.5° C	+ 2° C	+ 3° C
CLM-Community	CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	RCP4.5	2021-2050	2043-2072	-
			RCP8.5	2015-2044	2030-2059	2053-2082
CLM-Community	CCLM4-8-17	ICHEC-EC-EARTH	RCP4.5	2019-2048	2042-2071	-
			RCP8.5	2012-2041	2027-2056	2052-2081
CLM-Community	CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP4.5	2020-2049	2050-2079	-
			RCP8.5	2014-2043	2030-2059	2053-2082
DMI	HIRHAM5	ICHEC-EC-EARTH	RCP4.5	2018-2047	2040-2069	-
			RCP8.5	2014-2043	2029-2058	2051-2080
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR	RCP4.5	2009-2038	2028-2057	-
			RCP8.5	2008-2037	2021-2050	2040-2069
KNMI	RACMO22E	ICHEC-EC-EARTH	RCP4.5	2018-2047	2042-2071	-
			RCP8.5	2040-2069	2028-2057	2051-2080
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5	RCP4.5	2021-2050	2043-2072	-
			RCP8.5	2015-2044	2030-2059	2053-2082
SMHI	RCA4	ICHEC-EC-EARTH	RCP4.5	2019-2048	2042-2071	-
			RCP8.5	2012-2041	2027-2056	2052-2081
SMHI	RCA4	IPSL-IPSL-CM5A-MR	RCP4.5	2009-2038	2028-2057	-
			RCP8.5	2008-2037	2021-2050	2040-2069
SMHI	RCA4	MOHC-HadGEM2-ES	RCP4.5	2007-2036	2023-2052	2055-2084
			RCP8.5	2004-2033	2016-2045	2037-2066
SMHI	RCA4	MPI-M-MPI-ESM-LR	RCP4.5	2020-2049	2050-2079	-
			RCP8.5	2014-2043	2030-2059	2053-2082

Climate data processing

High-resolution climate model simulations were sourced from the Coordinated Regional Downscaling Experiment (CORDEX) (http://www.cordex.org) of the World Climate Research Programme (WCRP). The EURO-CORDEX (Jacob et al. 2014) initiative, part of the CORDEX project, provides regional climate projections for Europe at ~12.5 km horizontal resolution by downscaling the global climate projections of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012). In this study, we used simulations of daily air temperature for 11 RCMs, 2 RCP scenarios and 5 periods (reference period, 2050s, 1.5 °C, 2 °C and 3 °C warming levels). Departing from daily data we calculated monthly mean air temperature values. The spatial domain of this study covers the EU-28, Switzerland, Norway and the five European microstates (Andorra, Liechtenstein, Monaco, San Marino and Vatican City).

Given that the alpine tundra biome and treeline ecotone are located in high mountain areas, and that these are characterised by complex topography and large elevational gradients, using RCMs simulations at ~12.5 km horizontal resolution for mapping alpine tundra and treeline is problematic. This is because horizontal variations in temperature in high mountain areas cannot be captured properly at the resolution of RCMs (Ekström et al. 2015). Therefore, we used the change factor approach (Baker et al. 2010; Barredo et al. 2016; Ekström et al. 2015; Klausmeyer and Shaw 2009; Tabor and Williams 2010) for reduce model bias and spatially disaggregate temperature fields from RCMs to a higher horizontal resolution of 1 km, compatible with high mountain (Rubel et al. 2017) and biodiversity (Ekström et al. 2015) studies.

Anomalies (differences) of monthly mean temperature were computed from the RCM future simulations (2050s, 1.5 °C, 2 °C and 3 °C warming levels) and the reference period (1981-2010). Then, temperature anomalies were interpolated using the spline method (Franke 1982; Mitas and Mitasova 1988) to the 1 km spatial resolution of the baseline data i.e. CHELSA ver. 1.2 (Karger et al. 2017). Finally, temperature anomalies were added to the corresponding month of the CHELSA dataset for producing high resolution maps of future monthly mean air temperature. The CHELSA dataset, that covers the period 1979-2013, approximates well the reference period of this study, which was agreed in the PESETA IV Project. The error introduced by the use of the change factor approach in the original RCM temperature is negligible. A previous assessment using RCM data suggests a discrepancy of 0.03 °C in one degree of temperature (Barredo et al. 2016).

Mapping alpine tundra domain

Alpine tundra was mapped using the Köppen-Geiger climate classification (Hantel 1989; Kottek et al. 2006). The alpine tundra domain (ATD) domain is equivalent to the polar climates classified in Köppen-Geiger as E-type (Diaz and Eischeid 2007). Polar climates are defined as occurring if the mean temperature of the warmest month is less than 10 °C. These, include two Köppen-Geiger sub-types, i.e. tundra climate (ET) and frost climate (EF). Tundra climate occurs where the mean temperature of the warmest month is in the range of less than 10 °C and 0 °C, and frost climate occurs where the mean temperature of the warmest month is less than 0 °C. No precipitation differentiation is included in the Köppen-Geiger classification for these two sub-types. The EF sub-type is present in the study domain in a few marginal areas. Therefore, we defined the ATD as equivalent of polar climates (E-type) according to Diaz and Eischeid (2007).

Binary maps (0, 1) of ATD were produced for the reference period and for each scenario, period and simulation. Thus, we obtained 44 maps (11 simulations times 4 periods) for RCP8.5 and 33 maps (11 simulations times 3 periods) for RCP4.5. Summary maps describing changes of ATD containing three potential categories (stable, contraction and expansion) were then computed between the reference period and the future. As a result, we obtained one map of projected changes for each scenario/period. The category expansion is absent in the summary maps and was therefore excluded from the assessment. The maps were summarised according to Table 5 following Klausmeyer and Shaw (2009). Therefore, the number of simulations predicting changes of the ATD (stable or contraction) was used to define the level of confidence on each grid cell.

Table 5. Categories of projected change of the alpine tundra domain (ATD) to the different scenarios and warming levels. Note that the category expansion was not included because none of the simulations project expansion of the ATD.

Projected change	Confidence	Number of simulations (out of 11)
Stable	Confident	10-11
	Likely	7-9
Stable/contraction	Uncertain	1-6
Contraction	Confident	10-11
	Likely	7-9

According to Klausmeyer and Shaw (2009) changes in regions in which more than 66% of the simulations agree are considered likely changes, and confident changes where more than 90% of the simulations agree. Regions exhibiting agreement of less than 66% are considered uncertain changes. Therefore, the uncertain category represents cases when stable or contraction occurs in a range between 1 to 6 simulations. For example, if 10 simulations suggest that a grid cell is within the ATD in both the reference period and in the 3 °C warming level, then that grid cell is confident stable in that warming level. Unprojected latitude/longitude climate data were used for mapping the ATD, and equal-area projected maps for area change computation, taking the curvature of the earth into consideration.

Mapping treeline

The treeline is the high altitude limit of forests, it is also known as forest line (Figure 1). Treeline position is strongly dependent on air temperature, although other factors such as precipitation, nutrient availability, orographic and anthropogenic influences (e.g. grazing, deforestation, fire) may also play a role in tree position at local level (Greenwood and Jump 2014; Holtmeier and Broll 2005). The focus of this assessment is the natural climatic treeline in mountains that is driven by temperature.

We used the method of Körner and Paulsen (2004) for mapping the treeline position in the reference period and future climate projections. Using a global sample of root temperature measures at natural climatic treelines obtained between 1996 and 2003, Körner and Paulsen (2004) found that treelines are associated with a growing season mean root temperature of 6.7 °C (±0.8 SD). Thus concluding that there seems to be a common thermal threshold for forest and tree growth at high elevations. Additionally, they indicate that root-zone temperature mirrors canopy temperature on a daily to weekly basis (canopy temperature is often close to air temperature), and that canopy temperature can be predicted with a relative high confidence using the following equation:

$$T_r = 3.2\,°C + 0.50 * \ T_c \tag{1}$$

Where: T_r is 7-day mean root zone temperature and T_c is 7-day mean canopy temperature, both during the growing season. The beginning of the growing season was defined as that date at which weekly T_r exceeds 3.2 °C (T_c >= 0 °C) in spring, and the end as the date at which weekly T_r reaches 3.2 °C (T_c = 0 °C) in autumn.

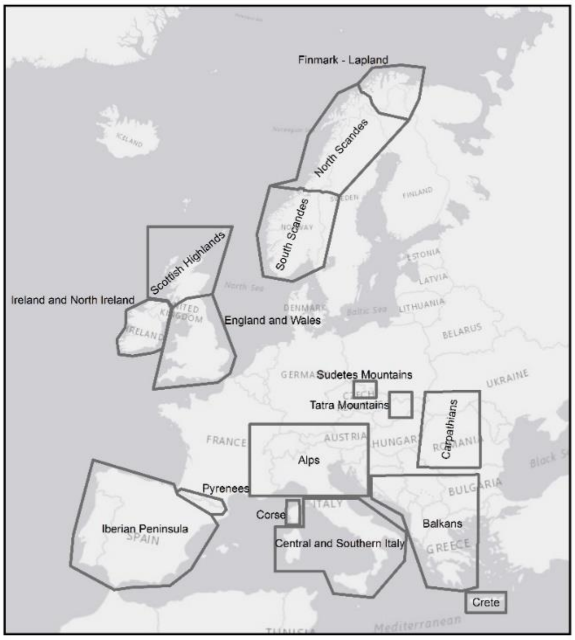
According to Körner and Paulsen (2004) the mean temperature during the growing season showed minor variations across the global sample, therefore a common 7 °C threshold of root zone temperature (7.6 °C canopy temperature) seems like a very reasonable approximation of the treeline for high latitudes (30° to 70° N). Therefore, we selected the 7 °C threshold of root zone temperature for our study zone that falls within the range of high latitudes. We used air temperature that according to Körner and Paulsen (2004) approximates canopy (and root zone) temperature at 6–7 °C.

Accordingly, we followed four steps for mapping the treeline using the monthly data of the reference period and future simulations at 1 km grid size:

1) Monthly to weekly air temperature interpolation: A weekly air temperature dataset was created for the current and future climates. The interpolation was conducted using CDO tools (CDO 2018; Schulzweida 2018).
2) Computing mean weekly air temperature of the growing season (as defined above) in grid cells where the growing season is at least 3 months. Zones with a growing season of less than 3 months are considered tree-less zone, thus located above the treeline.
3) Delineation of the treeline using the 7.6 °C isotherm from the mean weekly air temperature of the growing season.
4) Computing mean elevation of the treeline per mountain regions in Europe using the European Digital Elevation Model (EU-DEM v1.0) (Copernicus 2018; Dufourmont et al. 2014) at 25m grid size.

A set of treeline datasets of the current climate and the combination of scenarios/warming levels was produced. Then, an assessment of treeline shifts was done in 16 mountain regions in Europe, from Mediterranean islands to boreal and from the Iberian Peninsula to the Carpathians, where the more prominent treeline ecotones are located in Europe (EEA 2010; Virtanen et al. 2016) (Figure 17).

Figure 17. Mountain regions focus of the treeline assessment (source of base map: Esri, HERE, DeLorme and OpenStreetMap).



Annex 2. Validation

Alpine tundra domain mapping

To determine the ability of our methodology to reproduce a faithful delineation of the ATD a validation procedure was implemented using independent maps of the alpine tundra biome. However, lack of independent pan-European maps of alpine tundra with sufficient spatial detail to allow a fair comparison with the ATD makes this task challenging. Beside the very coarse maps of tundra biomes available in (e.g. EEA 2002; Harrison and Prentice 2003; Myers et al. 2000), to the best of our knowledge the only map representing the alpine tundra biome is the alpine vegetation map of Bohn et al. (2004). This map is ideal for comparison, because it represents the potential distribution of vegetation in Europe that is the vegetation that would occur without human intervention. This is similar to the climatic approach used in this study, where other effects beyond climate are not taken into account for mapping the ATD. There is controversy regarding the map of Bohn et al. (2004) because it is not based on a quantitative analysis but on expert knowledge. However, the map has proven to be robust in recent applications of simulated vegetation distribution in Europe (Hickler et al. 2012) and the degree of naturalness of European forests (Strona et al. 2016).

For the validation we used a map of the ATD computed using WorldClim data (Version 1.4) at 1 km grid size (Hijmans et al. 2005) instead of the CHELSA dataset. This is because the reference period of WorldClim v1.4 (1960-1990) is in agreement with the map of Bohn et al. (2004), which refers to around the same period. The validation is aimed to assess the capacity of the method for mapping the ATD, independently of the climate dataset used.

We assume that the ATD approximates the alpine tundra biome represented by the subunits subnival vegetation of high mountains (A.2), alpine vegetation (B.2) and glaciers as described in Bohn et al. (2004). The alpine vegetation formation includes alpine grasslands, low creeping shrub, dwarf shrub and shrub vegetation, rock and scree vegetation. These subunits occur above the treeline in high mountain regions, where trees are completely absent, similarly as in the ATD (Figure 1).

For the comparison we calculated a buffer of 5 km from the categories of the two maps to avoid a large number of background grid cells that may bias the validation towards agreement (this avoids that background cells are considered as agreement). The maps were previously cropped to a common extent fitting that of the climate simulations. As result, we obtained two binary maps (0, 1) where 1 represents ATD and alpine vegetation, respectively, and 0 the background within the 5 km buffer. The validation was implemented independently in three mountain regions, i.e. Alps, Scandes and Pyrenees where the more prominent zones (98%) of ATD are located.

We assessed agreement of the categorical maps using two metrics, the Cohen's Kappa statistic (Cohen 1960; Monserud and Leemans 1992) and overall accuracy (Congalton 1991). The Kappa statistic indicates the degree of agreement between categorical maps, with metric ranges from 0 (total disagreement) to 1 (perfect agreement). It reflects the difference between actual agreement and the agreement expected to occur by chance. A commonly cited scale of the Kappa statistic indicates slight agreement in the range of 0.01—0.20, fair agreement 0.21—0.40, moderate agreement 0.41—0.60, substantial agreement 0.61—0.80 and almost perfect agreement 0.81—0.99 (Landis and Koch 1977). Overall accuracy is one of the simplest descriptive techniques for map comparison, which is computed by dividing the total coincident number of grid cells in a comparison matrix.

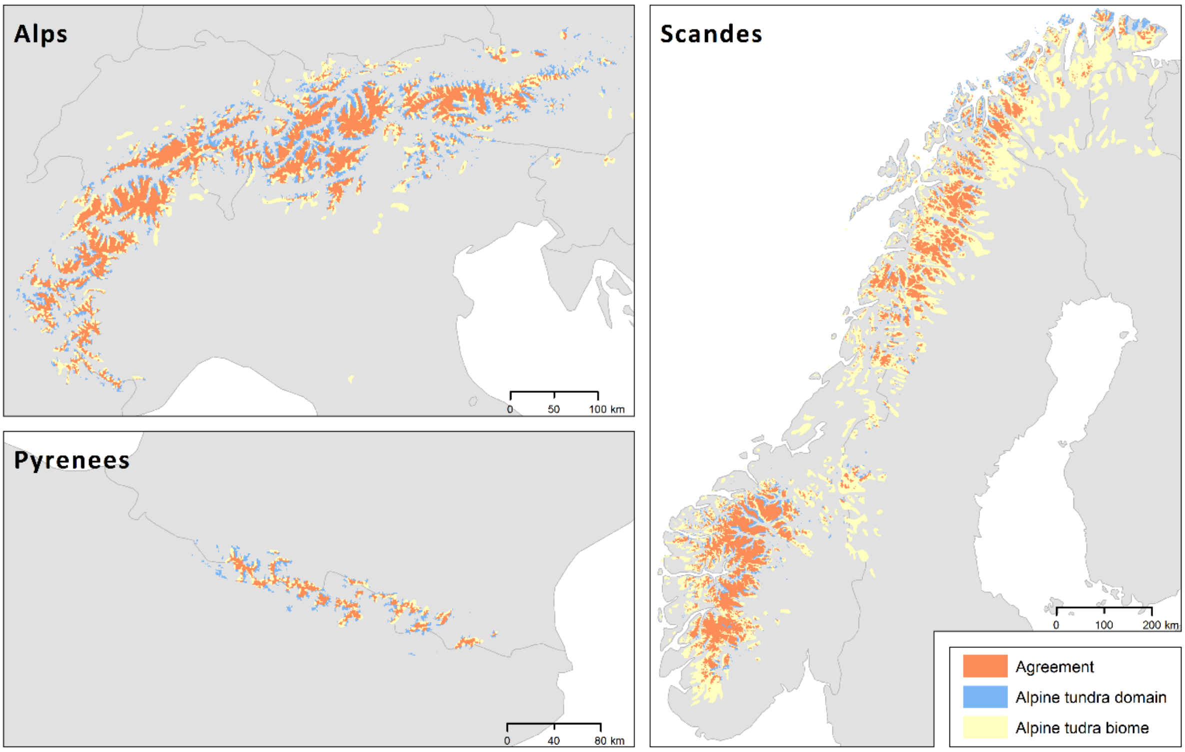
Despite differences in the methodology between the climatic approach used in this study and the expert knowledge approach used in Bohn et al. (2004), results of the validation indicates a reasonable level of agreement (Table 6). The match is moderate to substantial in the Alps and Pyrenees. Then, in the Scandes both maps are in correspondence except in the northernmost region, where the alpine vegetation is extended further south and east (Figure 18). The discrepancy is reflected in the 70%

overall accuracy and the 0.40 kappa statistic of the Scandes. The reason for this discrepancy has yet to be elucidated.

Table 6. Degree of agreement between the alpine tundra domain (ATD) mapped using WorldClim data (Version 1.4) at 1 km grid size (Hijmans et al. 2005) versus the alpine tundra biome (alpine vegetation, subnival vegetation of high mountains and glaciers) according to Bohn et al. (2004), using Cohen's Kappa statistic and overall accuracy.

Region	**Alpine tundra domain (ATD) versus alpine tundra biome (Bohn et al. 2004)**	
	Kappa	**Overall accuracy (%)**
Alps	0.51	78%
Scandes	0.40	70%
Pyrenees	0.42	81%

Figure 18. Comparison between the alpine tundra domain (ATD) delineated using climate data from WorldClim (Version 1.4) at 1 km grid size (Hijmans et al. 2005) and the alpine tundra biome (alpine vegetation, subnival vegetation of high mountains and glaciers) according to Bohn et al. (2004). Agreement describes coincident areas in the two maps.



Treeline delineation

To determine the ability of the method to faithfully delineate treelines we implemented a validation procedure. However, the validation was subject to some constraints. First, a pan-European treeline dataset is not available. Second, tree cover is not dependent solely on climatic factors, on the contrary, human activity is a key driver that modifies forest landscapes. This second point creates some comparability issues and make it difficult a comparison between the natural climatic treeline delineation of this study and external datasets representing observed forests and tree cover, thus one would not expect perfect agreement between them.

Using the reference period map of mean temperature of the growing season a binary map of tree zone/tree-less zone was created using the 7.6 °C isotherm as threshold, i.e. the isotherm that defines the natural climatic treeline. Grid cells having 7.6 °C or more were considered tree zone, and grid cells below 7.6 °C tree-less. The resulting map was compared with a forest/non-forest map derived from the tree canopy cover for year 2000 dataset (v1.4) of Hansen et al. (2013), where tree canopy cover is defined as canopy closure for all vegetation taller than 5m in height. The dataset is encoded as a percentage per grid cell of 1 arc-second (~30 m). Then, firstly, a 1 km grid size map was created by averaging the 30 m grid cells. And secondly, we used the 20% tree canopy cover threshold, similarly to Potapov et al. (2008) and Heino et al. (2015), to define whether the grid cells are classified as forest or non-forest.

The forest/non-forest map was clipped to the extent of the tree/tree-less zone map. We assessed only an area of interest (AOI) covering the tree-less zone and a buffer of 5 km around it to avoid large areas far from the treeline that may bias the validation results. The validation was implemented independently in five mountain regions, i.e. Alps, Scandes, Pyrenees, Scottish Highlands and Carpathians. We assessed agreement of the categorical maps using two metrics, the Cohen's Kappa statistic (Cohen 1960; Monserud and Leemans 1992) and overall accuracy (Congalton 1991).

Despite the differences between the approach used for delineating the treeline and the resulting tree/tree-less zone map, and the forest/non-forest map, results of the comparison indicates a reasonable level of agreement. Table 7 shows Kappa statistic and overall accuracy obtained from the comparison between both maps in the five regions.

Results of the validation indicate that Kappa lies between 0.37 and 0.64, fair to substantial agreement, in all regions except in the Scottish Highlands, where Kappa is 0.06. Similarly, overall accuracy is over 74% in all regions except in the Scottish Highlands where it is only 45%.

An example of the forest/non-forest map and the natural climatic treeline in the Alps is shown in Figure 19. In the zone exhibited the natural climatic treeline is fairly in accordance with the observed forest/non-forest distribution. Overally, in the Alps, a Kappa statistic of 0.64 indicates substantial agreement between the maps, supported by a high overall accuracy of 83%.

As expected, larger agreement was found between the tree-less zone and non-forest categories than in the tree-zone and forest categories of the Kappa comparison matrices of both maps. This is because the natural climatic tree-zone is in some cases hardly comparable with the forest cover zone because it is subject to disturbances such as deforestation, fires and land cover changes. This issue pushes Kappa statistic and overall accuracy down. This effect is especially relevant in the case of the Scottish Highlands where the observed treeline is almost always hypothetical because human actions have removed the tress (Fielding and Haworth 1999). Extensive grazing for many centuries combined with other land uses is responsible for the current Scottish landscape of open moorlands (Tanentzap et al. 2013). A consequence of that is the lowest Kappa statistic and overall accuracy among the five regions. However, the producer accuracy[6] of the

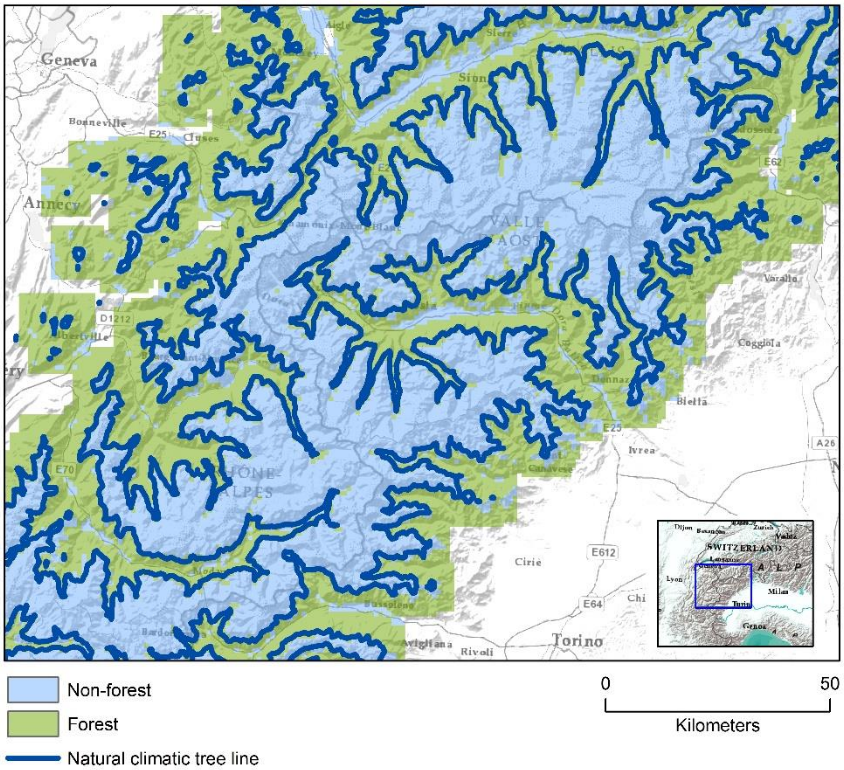
[6] Producer accuracy is the accuracy from the point of view of the map maker ("producer"). This is how often are real observations on the ground correctly shown on the produced map or dataset.

tree-less category in the Scottish Highlands is 80%, meaning that most of the disagreement occurs in the climatic tree zone where trees were removed, and therefore are not represented in the forest/non-forest map. In a similar way, in the Scandes the treeline is grazed by semi-domesticated reindeer (Moen et al. 2004) and grazing may affect the presence of trees in the forest/non-forest map, thus decreasing the accuracy of our validation in this region.

Table 7. Degree of agreement between the tree zone/tree-less zone map delineated using the treeline approach of Körner and Paulsen (2004) and climate data from CHELSA (reference period 1981-2010)(Karger et al. 2017) versus a forest/non-forest map created from Hansen et al. (2013), using Cohen’s Kappa statistic and overall accuracy.

Region	**Tree zone/tree-less zone map versus forest/non-forest map from Hansen et al. (2013)**	
	Kappa	**Overall accuracy (%)**
Alps	0.64	83
Scandes	0.45	74
Pyrenees	0.37	75
Scottish Highlands	0.06	45
Carpathians	0.52	90

Figure 19. Forest/non-forest map created using the Global Forest Change dataset (Hansen et al. 2013), and natural climatic treeline delineated in this study using climate data from CHELSA (reference period 1981-2010)(Karger et al. 2017) in the western Alps between Italy, France and Switzerland. Note that the forest/non-forest map in the figure shows the AOI corresponding to the buffer used in the validation. Source of base maps: Esri, USGS, NOAA, Garmin and NPS.



Annex 3. Supplementary tables and figures

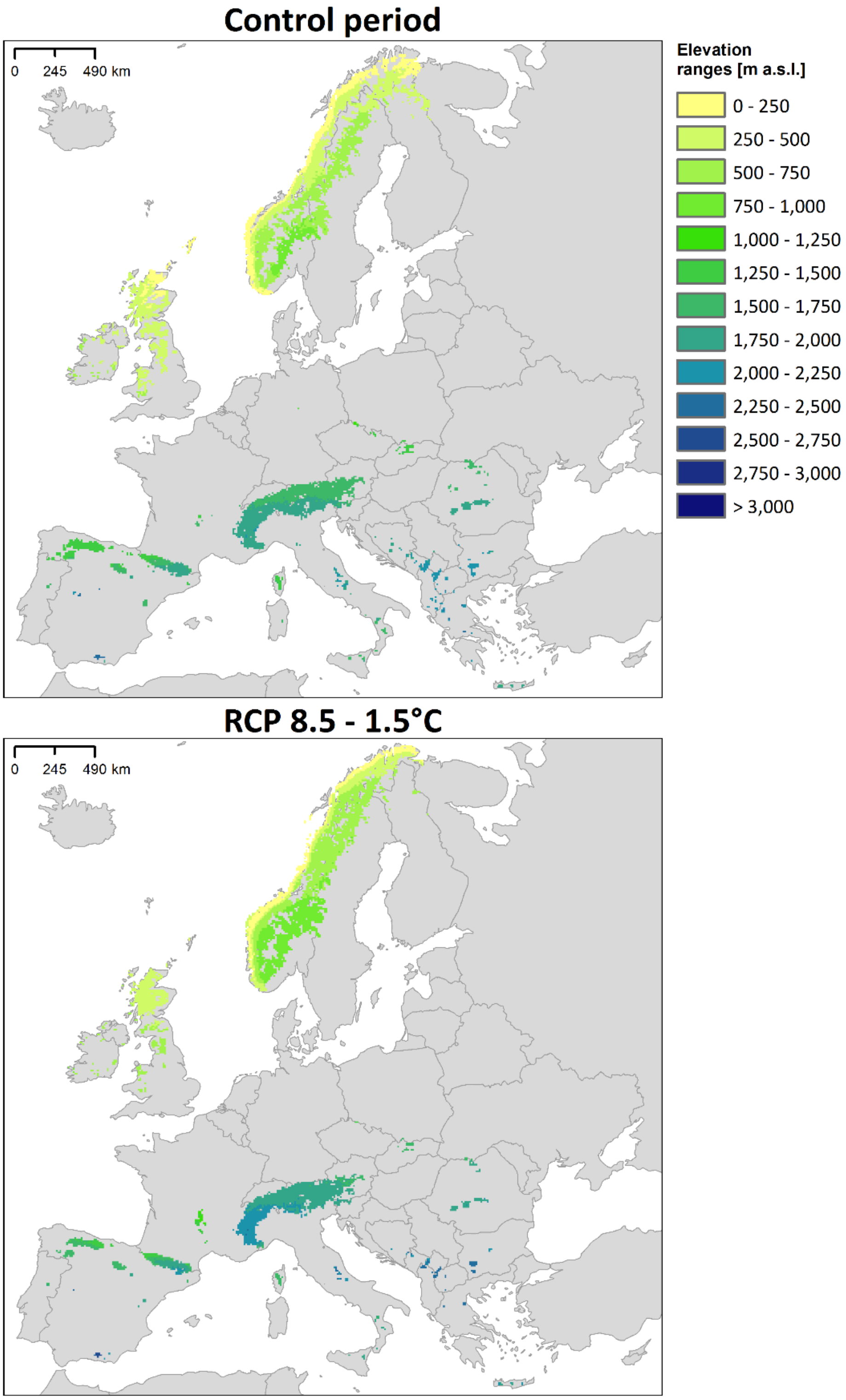
Table 8. Projected relative area of Natura 2000 sites within the alpine tundra domain (ATD) by category of change under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-65). Changes as percentages with respect to the area (indicated in sq. km) of Natura 2000 sites in the ATD in the reference period (1981—2010).

Domain (Natura 2000 area in ATD)	**Changes**	**RCP4.5**			**RCP8.5**			
		1.5 °C	**2050s**	**2 °C**	**1.5 °C**	**2050s**	**2 °C**	**3 °C**
Europe ($16\ 180\ km^2$)	Confident stable	40	26	28	39	14	25	9
	Likely stable	10	10	8	9	11	10	6
	Confident contraction	33	49	48	38	58	48	72
	Likely contraction	12	9	10	10	10	13	9
	Uncertain	5	6	6	4	7	4	4
Alps ($8\ 497\ km^2$)	Confident stable	53	34	36	51	23	34	14
	Likely stable	10	12	9	8	12	10	6
	Confident contraction	24	41	42	28	46	35	62
	Likely contraction	8	8	9	8	10	14	12
	Uncertain	5	5	4	5	9	7	6
Scandes ($5\ 319\ km^2$)	Confident stable	31	21	25	30	5	18	4
	Likely stable	10	11	10	11	12	11	6
	Confident contraction	37	50	45	44	66	58	79
	Likely contraction	16	11	12	10	10	7	7
	Uncertain	6	7	8	5	7	6	4
Pyrenees ($1\ 316\ km^2$)	Confident stable	10	1	2	8	1	1	0
	Likely stable	9	4	3	10	1	4	1
	Confident contraction	52	80	78	60	80	68	96
	Likely contraction	19	8	11	14	15	23	3
	Uncertain	10	7	6	8	3	4	1

Table 9. Projected number of Natura 2000 sites by category of change of the alpine tundra domain (ATD) under scenario RCP4.5 and RCP8.5 in three warming levels (1.5 °C, 2 °C and 3 °C) and the 2050s (2036-65). Note that one site can be part of more than one category of change, e.g. one site can be partially in stable and partially in contraction areas. Therefore, totals do not equal the number of sites in the reference period 1981—2010 (in parenthesis).

Domain (number of Natura 2000 sites in ATD)	Changes	RCP4.5			RCP8.5			
		1.5 °C	2050s	2 °C	1.5 °C	2050s	2 °C	3 °C
Europe (210)	Confident stable	119	81	88	112	49	81	34
	Likely stable	130	98	96	128	81	94	43
	Confident contraction	196	201	199	199	208	207	208
	Likely contraction	140	115	119	135	114	141	85
	Uncertain	108	99	98	100	90	100	61
Alps (114)	Confident stable	77	52	57	71	40	54	28
	Likely stable	77	63	58	76	55	61	34
	Confident contraction	112	113	113	113	113	113	113
	Likely contraction	80	67	70	80	70	84	56
	Uncertain	60	55	55	62	58	65	44
Scandes (42)	Confident stable	19	18	17	19	4	14	3
	Likely stable	27	19	21	25	16	20	5
	Confident contraction	31	34	32	32	41	40	41
	Likely contraction	23	27	29	24	21	23	18
	Uncertain	22	20	25	22	15	16	12
Pyrenees (15)	Confident stable	6	1	2	6	1	2	0
	Likely stable	8	3	5	7	2	4	1
	Confident contraction	14	15	15	15	15	15	15
	Likely contraction	11	5	8	8	9	10	3
	Uncertain	7	7	5	7	4	5	1

Figure 20. Average treeline elevation within 10-km grid cells in the reference period (1981-2010) and in three warming levels, 1.5 °C, 2 °C and 3 °C, according to the CCLM4-8-17-ICHEC-EC-EARTH Regional Climate Model under scenario RCP8.5 (continued in next page).



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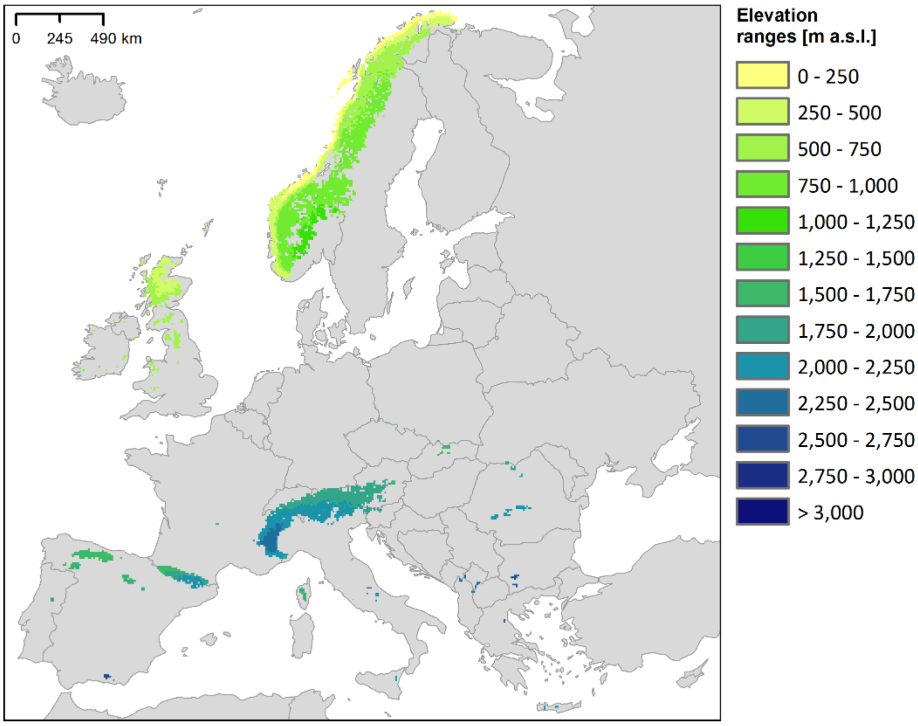
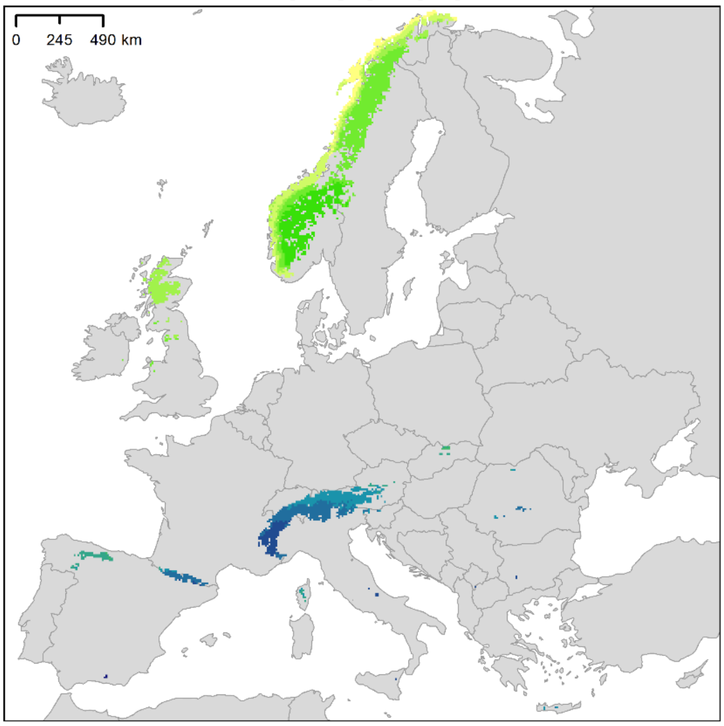
RCP 8.5 - 2°C



RCP 8.5 - 3°C



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