Climate change in the Pyrenees: Impacts, vulnerabilities and adaptation

Bases of knowledge for the future climate change adaptation strategy in the Pyrenees

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Report on climate change in the Pyrenees

Since its launch in 2010 under the presidency of Midi-Pyrénées, the Pyrenean Climate Change Observatory of the Working Community of the Pyrenees (CTP) has worked in analyzing the vulnerability to climate change of different populations, social, economic and natural sectors of the Pyrenean crossborder territory. This was achieved through the development of efficient methodologies and in a mindset of cooperation. In 2018, following the guidelines of the Observatory, the CTP has elaborated a report which updates knowledge of the repercussions of climate change in the Pyrenean crossborder territory. This report gathers the scientific bases of knowledge on the impacts of climate change and its repercussion on the territory, in the form of a compendium of sectorial adaptation recommendations proposed in consequence. These bases of knowledge are indispensable to efficiently orientate climate change adaptation policies, to take advantage of emerging opportunities and maximize positive synergies with other sectorial policies. The added value of the report resides indubitably in the spirit of cooperation that permeated its conception as well as its writing, in which more than 100 scientifics and experts of reference from both sides of the Pyrenees have participated. They have collaborated in its writing as well as in the different processes of revision which give this document a wide ranging scientific consensus. It is necessary to highlight that without the long process of cooperation, networks mobilisation and international projection with organizations such as the Alpine Convention, the Carpathian Convention or the European Environment Agency, it would be impossible to create reference documents such as the present report. The views of this report are those of the Observatory, which conceives the Pyrenees as a unique "bioregion" without administrative borders and of which the socioeconomic amd biophysical systems are particularly vulnerable to climate change. The scientific evidence gathered in this report exposes, as much as other reports in different territories, that the mountain areas are experimenting increases in temperatures superiror to lower altitude areas and as such, the impacts of climate change affect them more intense. Concretely, for the Pyrenees, we can already witness impacts on all natural and socioeconomic sectors, with for instance the accelerated disappearing of sensistive ecosystems and iconic elements like glaciers; the alteration of the living environment of numerous species, among which some are endemic; the incidence of climate change on natural risks, activities linked to tourism, agriculture and the changes observed in the hydric cycle. C limate change represents a factor of additional stress which aggravates problems in the Pyrenean territory, like depopulation, changes in land use or the lack of generational relay in the primary sector. For the CTP, the fight against climate change is primordial as well as the adaptation to its effects through the development of cross-cutting instruments to face challenges in the Pyrenees, which are also global challenges. In this way, the CTP, with local action, contributes to the achievement of the 13th Goal of the 2030 Agenda of Sustainable Development of the United Nations, Action for Climate.

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CTP President

1. Climate and climate variability in the Pyrenees

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1.1 The climate during the last glacial and deglaciation periods

Although the succession of cold and warm periods is synchronous on the scale of the planet, the maximum extension of the Pyrenean glaciers did not occur 22000 year ago during the Last Glacial Maximum (LGM)[1] but about 60000 years ago (Lewis et al., 2009), with small variability among the different valleys. This lack of synchrony is related to the southerly location of the Pyrenees and the fact that the climate in the Pyrenees has been controlled by the interaction between North Atlantic processes and the subtropical dynamics (González-Sampériz et al., 2017; Bartolomé et al., 2015). During the LGM (between 22000 and 19000 years ago) the Pyrenean glaciers experienced a relatively smaller advance, although the glaciers did not reach the extension of previous periods about 30 or 40000 ago, probably because the climate was relatively drier during full glacial conditions.

The onset of the last deglaciation, 19000 years ago, corresponds with a rapid increase in temperature and humidity, well documented in glacial (Bordonau, 1992; Palacios et al., 2017), and lacustrine records (Millet et al., 2012; González–Sampériz et al., 2017). The Pyrenean glaciers retreated up to the head of the valleys. The last deglaciation was a period of climatic unstability, with changes at the millennial scale but also at smaller scales (abrupt changes) caused by the instability of glacier sheets and North Atlantic dynamics. After a relatively dry initial period, a new expansion of glaciers occurred about 17000 years ago, followed by warmer and wetter conditions (14700 - 12900 years ago), interrupted by a cold period that represented a return to climatic conditions similar to glacial times: the Younger Dryas. During this period in the Pyrenees the temperature dropped 2ºC (Bartolomé et al., 2015) and the glaciers experienced a minor advance on both Pyrenean slopes. This period was the last cold snap of glaciation and the onset of the current interglacial period: the Holocene.

1.1.1 The Holocene climate

The Holocene onset, 11700 years ago, was characterized by a significant climatic change at a global scale, with a generalized increase in temperatures in middle latitudes associated with the increase of summer insolation in the northern hemisphere and the disappearance of ice sheets. The increase in precipitation associated with the onset of the Holocene at a global scale was delayed in the southern Pyrenees, and occurred about 9500 years ago (Leunda et al., 2017). In general, the climate during the Early Holocene (11700 - 8200 years ago) was warmer and wetter in the Pyrenees than during the last deglaciation but with differences between each slopes and between the Mediterranean and Atlantic zones (González-Sampériz et al., 2017). The climate during the Early Holocene was characterized by higher seasonality caused by the orbital parameters configuration, provoking a larger snow accumulation in winter and higher melting rates during summer. In the southern Pyrenees (Basa de la Mora lacustrine sequence), the climatic instability of the Early Holocene is marked by four events of rapid climate change of short duration which took place 9700, 9300, 8800 and 8300 years ago.

From 8100 years ago and until 5700 years ago approximately, the climate was more stable and with more abundant precipitations. Like in other northern hemisphere mountain ranges, most of the Pyrenean glaciers disappeared during the Early Holocene when temperatures in Europe were probably the highest of the interglacial period (Rius et al., 2012; CLIVAR, 2010).

(1) The Last Glacial Maximum (LGM) was the most recent time during the Last Glacial Period when ice sheets were at their greatest extent. Vast ice sheets covered much of North America, northern Europe, and Asia. The ice sheets profoundly affected Earth's climate by causing drought, desertification, and a large drop in sea levels.

1.1 THE LITTLE ICE AGE IN THE PYRENEES

The Little Ice Age was the last global climatic phase of the Holocene, which took place between ca. 1300 and 1850 CE, before the current global warming (Oliva et al., 2018). In our latitudes it was characterized by colder temperatures and an increase in extreme phenomenons, but with a great regional variability. Three cold phases in 1650, 1770 and 1850 CE seem to be associated with solar activity minimums (minimums in the Maunder, Spörer and Dalton sun spots), though other factors such as volcanic eruptions (Tambora in Indonesia in 1815) contributed to the decrease in temperatures. During these centuries, much of the Pyrenean glaciers were reactivated and advanced up to their maximum extension of the Holocene, leading to the adaptation of landscapes and ecosystems of the Pyrenees to colder conditions before the Global Warming of the 20th century. The medium temperatures, estimated from Glaciar Equilibrum Lines, were about 0,9ºC inferior to the current temperatures (López-Moreno, 2000).

In the Pyrenees, maximal temperatures occurred probably at the end of the Early Holocene and during the Mid Holocene, 7000 to 6000 years ago (Millet et al., 2012). The progressive decrease in precipitations during the Mid Holocene triggered a transition to drier and probably colder conditions about 5500 years ago. This change occurred earlier in the Atlantic regions of the Pyrenees than in the Mediterranean ones (González-Sampériz et al., 2017; Leunda et al., 2017). Additionally, in the central Pyrenees, a period of glacier advance called the Neoglacial has been documented around 5100 to 4600 years ago (García-Ruiz et al., 2016).

1.1.2 The last 2000 years

The climate variability during the last 2000 years has been controlled by internal natural processes of the climate system and by variations in external forcings, natural or anthropogenic. The internal processes are a result of the non-linear interactions of the climate system and are manifested as different atmospheric (such as the NAO, the North Atlantic Oscillation, and the EA, Oscillation of the Eastern Atlantic and SCAN, the Oscillation of Scandinavia) and/or oceanic patterns. The variations in the external forcings are due to natural causes (for example, changes in the insolation or volcanism) and anthropogenic effects (such as variations in greenhouse gases and/or aerosols) (Giralt et al., 2017). All these processes and interactions can also explain the spatial and temporal humidity and temperature gradients.

Four climatic phases well-characterized at a global scale took place in the last two millennia: the Warm and Humid Iberian-Roman period (from 250 BCE to 500 CE), the Early Middle Ages (or "Dark Ages", 500-900 CE), the Medieval Climatic Anomaly (MCA, 900-1300 CE) and the Little Ice Age (LIA, 1300-1850 CE). The intensity but also the chronology of these phases is very variable in the Iberian Peninsula (Cisneros et al., 2016; Moreno et al., 2012; Giralt et al., 2017). During the Iberian-Roman period, an increase in temperatures both at higher (Pla and Catalán, 2011) and lower altitudes (Morellón et al., 2012) in the Iberian Peninsula has been documented. In terms of humidity, in the Pyrenees the climate was more arid than in the south of the Iberian Peninsula (Morellón et al., 2012).

During the Early Middle Ages, mean temperatures decreased, but the humidity was very variable at a regional scale, with an increase in aridity in the Mediterranean (Menorca and Cisneros, 2016) and in the Pyrenees (Morellón et al., 2012). Nevertheless, some Pyrenean records suggest an increase in precipitations and extreme meteorological events (Corella et al., 2016). The MCA may serve as an analogue of present day global warming conditions to better evaluate the natural climate variability before the great human impact on climate during the Anthropocene. This period was more arid and warmer in the Western Mediterranean region (Moreno et al., 2012). The climate was also drier in the northern areas (Morellón et al., 2012), but some mountain sites in the Pyrenees documented some humid phases (Pla and Catalán, 2011), together with higher frequency of storms in lower altitudes (Corella et al., 2016).

The LIA (1300 – 1850 CE) was generally a colder period characterized by alternating humid and dry phases, showing a great variability in the Iberian mountains (Morellón et al., 2012; Oliva et al., 2017). A decrease of 1% in solar radiation may have caused an average 1 - 2ºC drop in global temperatures that would have been enough to account for those cold episodes. Some of the coldest phases, around 1650, 1770 and 1850 CE seem to be associated with solar activity minima (with minimum number of sunspots: Maunder, Spörer and Dalton). However, some other factors such as the enormous volcanic eruptions that took place at the time (Laki volcano in Iceland in 1783-1784 or Tambora volcano in Indonesia in 1815) contributed to the temperature decrease. Other periods characterized by warmer temperatures occurred at 1480- 1570, 1715-1760, 1800-1815 and post 1850 CE. Some records suggest that the wettest period, at least at low altitude,

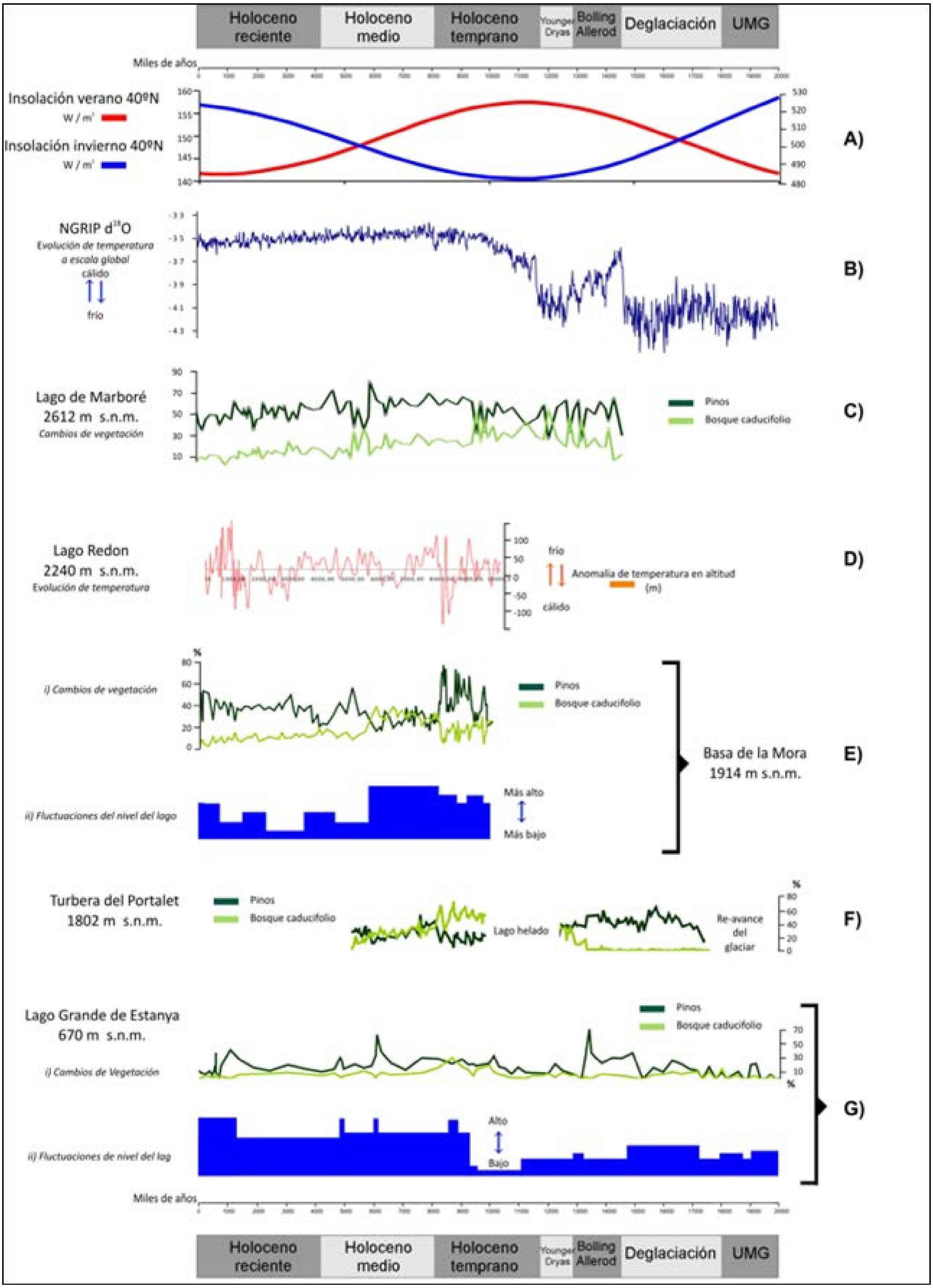
Holoceno reciente
Holoceno medio
Holoceno temprano
Younger Dryas
Bolling Allerod
Deglaciación
UMG
Miles de años
Insolación verano 40ºN
W / m²
Insolación invierno 40ºN
W / m²
A)
NGRIP d18O
Evolución de temperatura a escala global
cálido
frío
B)
Lago de Marboré
2612 m s.n.m.
Cambios de vegetación
Pinos
Bosque caducifolio
C)
Lago Redon
2240 m s.n.m.
Evolución de temperatura
frío
Anomalía de temperatura en altitud (m)
cálido
D)
i) Cambios de vegetación
Pinos
Bosque caducifolio
Basa de la Mora
1914 m s.n.m.
E)
ii) Fluctuaciones del nivel del lago
Más alto
Más bajo
Turbera del Portalet
1802 m s.n.m.
Pinos
Bosque caducifolio
Lago helado
Re-avance del glaciar
F)
Lago Grande de Estanya
670 m s.n.m.
i) Cambios de Vegetación
Pinos
Bosque caducifolio
G)
ii) Fluctuaciones de nivel del lag
Alto
Bajo
Miles de años
Holoceno reciente
Holoceno medio
Holoceno temprano
Younger Dryas
Bolling Allerod
Deglaciación
UMG

Figure 1.1.1 Pyrenean records of climate variability since the Last Glacial Maximum. The graphs and temporal scale are organized in thousand of years before present, being the oldest period towards the right of the figure while the present is on the left side. The bar includes the climatic periods known for the last 20000 years and their chronological boundaries (LGM, correspond to Last Glacial Maximum). The different records are organized by altitude, starting at the top with indicators of global scale (orbital scale). From top to bottom: a) insolation variability (energy that the Earth receives from the Sun) in summer (red) and winter (blue) at 40ºN; b) temperature evolution at a global scale reconstructed from the stable isotopes measured in the Greenland ice core NGRIP (the more negative values are indicators of lower temperatures corresponding to the glacial period); c) changes in the arboreal vegetation reconstructed in the Marbore lake sediments based on the percentage of Pinus pollen (dark green) and other species characteristic of deciduous forest (Betula, Corylus, Quercus, Tilia etc in light green). d) winter-spring temperatures anomaly during the last 10000 years reconstructed from the Redón lake crysophite communities from the Central Pyrenees; e) arboreal vegetation changes (pine pollen in dark green, deciduous forest in light green) and lake level fluctuations from Basa de la Mora lake; f) arboreal vegetation changes (pine pollen in dark green, deciduous forest in light green) from El Portalet peatbog and g) arboreal vegetation changes (pine pollen in dark green, deciduous forest in light green) and lake level change from Estanya Lake. References to these sequences and proxies can be found in González-Sampériz et al., (2017).

was the XIX century (Morellón et al., 2012). The first phase of the LIA seems to have witnessed an increase in storm frequency (Corella et al., 2016). Dendroclimatic reconstructions show high frequencies of extreme events during the XVIII century that decreased during the XIX century (Oliva et al., 2018). During the coldest phases, with a decrease in temperature of about 1ºC, the Pyrenean glaciers advanced on both slopes (Copons and Bordonau, 1997; López-Moreno, 2000).

1.2 AN UNUSUAL GLOBAL WARMING AT PRESENT TIMES.

The climate changes along the Quaternary have modeled the Pyrenean landscape and controlled the evolution of ecosystems. During the last deglaciation, the changes in average temperatures were up to 6 ºC, with periods of abrupt climate change characterized by temperature changes of up to 1ºC in a few decades. During the Holocene, temperature variability was less important but hydrological changes dominated with the occurrence of numerous humid and dry phases. During the last millennium, a warm phase characterized by aridity (the Medieval Climate Anomaly, MCA, 900-1300 CE) took place and was followed by the Little Ice Age (LIA, 1300 - 1850 CE), a cold phase with temperatures up to 0.9 ºC colder than present day and an increase in extreme events. At that time, many glaciers were reactivated and advanced to reach their maximum extension during the Holocene. Thus, landscapes and ecosystems in the Pyrenees were adapted to cold conditions before the global warming of the XXth century. The rate of temperature changes during the global warming of the XXth century is higher than the one observed during glacial/interglacial transitions and the changes experienced during the Holocene.

1.2 The current climate

The current availability of instrumental meteorological data allows a major improvement of the knowledge of the Pyrenean climate and the evaluation of the impacts of climate change. That being said, the study of mountainous areas is complex, as the topography generates a great diversity of local contexts in which the value of the climate variables is hard to determine. Additionally to the absence of records with long data series, there are less and less observatories and stations located at higher altitudes. For this reason, understanding what occurs at higher altitudes is complicated, despite the importance of climatic information in mountains both from a scientific and a socioeconomic point of view, given that so many human activities and ecological processes are concentrated in these zones.

On the French side, the interest for meteorological observation was first manifested at the end of the XVIIIth century with a register of measurements in Mont-Louis, at an altitude of 1600m. Later, the Pic du Midi Observatory was created in 1880, at 2880m; and new observatories appeared during the XXth century. However, before the development of automated networks in the 1990s, the measurements remained irregular and scarce above 1500m. On the Spanish side of the Pyrenees, the situation was very similar. The recent establishment of automatic stations and a climate network based in mountain refuges constitute a valid data base for the study of climate change, but the short timescale reduces the scope of the diagnosis. To minimise this problem, it is necessary to create more observatories, launch operations to recover data and ensure the survival of the existing observatories, as well as maintaining the quality levels of the observations. In this sense, the example of the Alps is noteworthy, where with the HISTALP project it has been possible to work for years on the building of climatic data series (Böhm et al., 2009).

Despite these limitations, there exist numerous studies of the Pyrenean climate, in particular on precipitation and temperature (among others, the studies by Balseinte, 1966; Creus, 1983; Gottardi, 2009; Pérez Zanón et al., 2017), snow coverage (Esteban et al., 2005; López Moreno, 2005 y 2009; Durand et al., 2012), climate in general and leisure activites (Pons et al., 2012 and 2015; Gilaberte et al., 2014), variability and climate changes (Bücher and Dessens, 1991; Vicente Serrano et al., 2007; López-Moreno and Vicente Serrano, 2007; Espejo et al., 2008; López Moreno et al., 2011; Esteban et al., 2012; Buisán et al., 2015) and climate forecasts (López Moreno et al., 2011; Verfaillie et al., 2017 and 2018). Nonetheless, the majority of the work presents Findings limited to one region, Andorran, French or Spanish; effectively considering only one slope of the Pyrenees, therefore not supporting a global understanding of climate processes at the scale of the whole range.

The actions undertaken by the Pyrenean Climate Change Observatory (OPCC) have permitted to overcome these limitations, optimize the use of information sources and achieve a better interdisciplinary approach. A fundamental step was the creation of the first homogenized single data base, with a quality monitoring and covering the 1950-2010 time span, using a common methodology to characterise the Pyrenean climate and to observe its variability. With this information - generated in the framework of the OPCC - progress towards knowledge of the temporal and spatial patterns of temperature and precipitation and analysis of trends is being made for the whole Pyrenees (Soubeyroux et al., 2011; Miquel, 2012; Cuadrat et al., 2013; Deaux, et al., 2014).

1.2.1 Evolution of the mean annual temperature and seasonal temperature

Both the regional studies from Andorra, France and Spain, and the general studies from the whole Pyrenees range indicate a clear increase in temperature at every moment of the year (Spagnoli et al., 2002; Maris et al., 2009; López Moreno et al., 2010; El- Kenawy et al., 2011; Esteban et al., 2012); furthermore, this increase has been regular in the last three decades, in line with the global diagnosis produced by the Intergovernmental Panel on Climate Change (IPCC, 2013).

In Andorra, the estimation of the trend realised based on the results of three observatories indicates for the period 1935-2008, a significant augmentation of the annual maximum mean temperature (0.13 to 0.15 °C per decade), the summer maximum (0.22°C per decade) and minimum temperatures (0.11 °C per decade). These trends for thermal increment are reinforced when the analysis is centered on the period 1950-2008 (Esteban et al., 2012). In the central Spanish Pyrenees, Pérez Zanón et al (2017) have found regional anomalies of 0.11 °C per decade for the maximum temperatures and of 0.06 °C per decade for the minimum ones for the period 1910- 2013, with an increase of between 0.57 °C and 0.23°C per decade in the latest period 1970-2013. These values partly coincide with those observed on the French side: Deaux et al (2014), for the Tarbes-Ossun series, indicate a warming of mean temperatures of 0.25 to 0.36 °C per decade, with an uncertainty range of 0.15 to 0.48 °C per decade, in the period studied. Furthermore, they indicate that the warming trend is especially strong since the 1980s, echoing the results in other Pyrenean observatories.

When the analysis is extended to the whole Pyrenean range, the result is identical: in the most recent decades the temperature has clearly increased. This is the conclusion of the research under the Climate action axis of the project OPCC-POCTEFA EFA 235/11, based on the study of 32 temperature series, high quality and homogenized, for the period 1959-2010. The trend for the indicator for medium annual temperature for the whole period analysed is positive and statistically significant, with a value of around 0.2 °C per decade. This thermal increase is general throughout the range, with systematically positive anomalies starting in 1980 up to the present day, and with few differences between the north and south slopes of the range.

Considering the whole series of 1959-2010, the warmest year was 1997, with an upper temperature equivalent to 1.5 °C above the mean value for 1961-1990, followed by the years 2006 and 2003. In the opposite sense, 1972 was the coolest year, being 0.8 °C cooler than the reference mean temperature, followed by the years 1963 and 1980. The indicator for mean temperature for the four seasons shows that the thermal increase during the past five decades is most evident in summer: with a value of 0.4 °C rise per decade, it is statistically significant. In spring, the increase is lessened: around 0.2 °C per decade though this again is statistically significant. The seasonal anomaly in autumn and winter is less significant statistically in these two seasons, where its value is subject to a higher degree of uncertainty. For the seasonal study, in addition, few differences can be seen in these indicators between the north and south slopes of the Pyrenean range.
From the analysis of concrete events it can be seen that the warmer anomalies (positive values) flag especially the mean summer temperature of 2003, with temperatures 3.6 °C above the mean from 1961-1990 (in the context of a noticeable heatwave which affected a large part of the European continent), and the value for the winter of 1990, with 2.8 °C above the mean. In the opposite sense, the most important cold anomalies (negative values) were those of the winter of 1963, at -2.5 °C below the mean, and that of autumn 1974, with an anomaly of -2.2 °C.

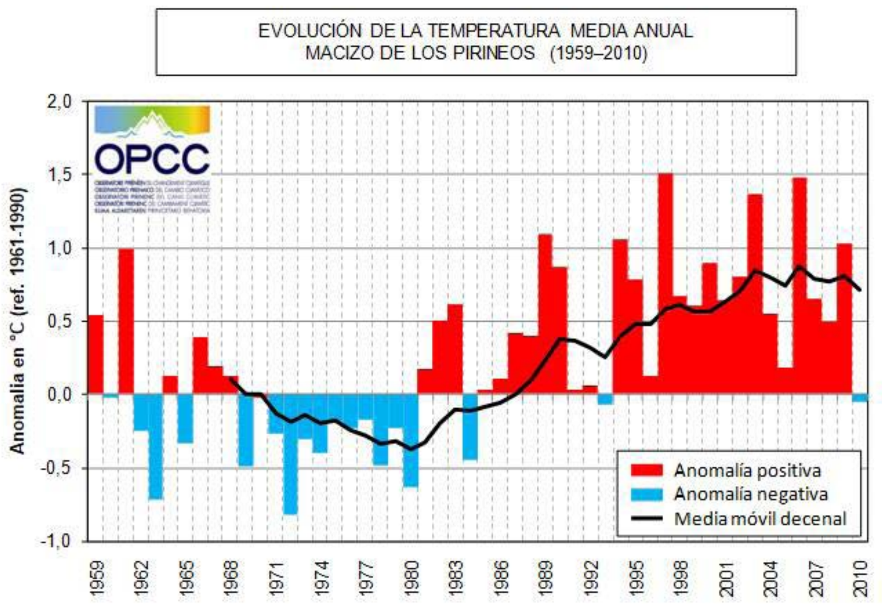

Figure 1.2.1 Evolution of the mean annual temperature in the whole Pyrenees during the 1959-2010 period. It shows the annual anomaly in relation to the mean value for the period 1961-1990 (in red, positive; in blue, negative) and to the trend in temperatures for successive periods of ten years (black line). Source: OPCC, 2013

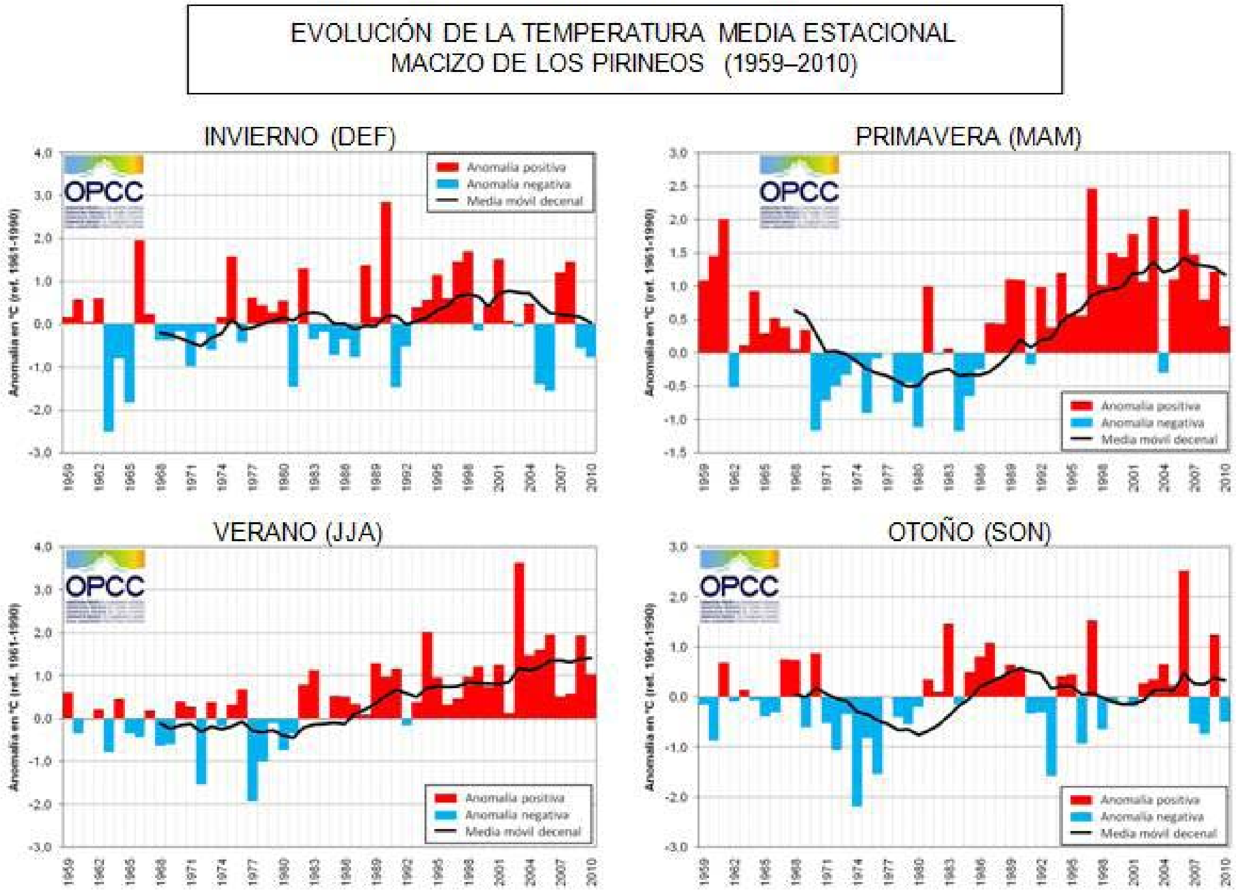

Figure 1.2.2 Evolution of the seasonal mean temperature in the whole Pyrenees during the 1959-2010 period. The annual anomaly is calculated with relation to the mean value of the reference period 1961-1990 (in red, positive; in blue, negative) and to the trend in the temperatures for successive periods of ten years (black line). Source: OPCC, 2013

The tendency to warming seems likely to be extended through the XXIst century and at the annual level could oscillate between 2.8 and 4 °C, according to the worst scenarios. In addition, the effects of climate change will be more pronounced in the central slopes of the Pyrenees and in the coastal zones (López Moreno et al., 2008). That being said, it must be recognised that our capacity to estimate with adequate precision the possible future changes is very limited.

1.2.2 Trends in annual and seasonal precipitation

Temporal and spatial patterns for precipitation show a certain tendency towards the shrinking of the total pluviometry, and in particular towards a descent in the frequency of high intensity events and the greater frequency of long dry periods. Nonetheless, the high spatial diversity of the Pyrenean region forces one to interpret these changes with reserves, given that the changes caused by relief in atmospheric circulation may be highly relevant.

In Andorra, Esteban et al (2012) confirm decreasing and statistically significant trends for the 1935-2008 period, which are generalised and reinforced between 1950-2008. On the other hand, in the precipitation series nothing statistically significant is reported for the period 1935- 2008, although various series show statistically significant declines for the sub-period 1950-2008. In the central sector of the Spanish Pyrenees, Pérez Zanón et al (2016) have observed an important interannual variability, without statistical significance, with some changes vis-a-vis seasonal averages. The percentage of years with normal annual rainfall diminished in the 1950- 2013 period compared to the period 1910-1949, with a corresponding increase of dry and humid years. The largest decline is seen in winter, with around 2.25% per decade, coinciding with the investigations of López Moreno et al (2005), who identified a notable reduction in the snow cover for the 1950-1999 period. In turn, they detected a thermal augmentation in autumn of 2.25 °C per decade.

The decrease in rainfall is also seen in the Aragonese Pyrenees along the second half of the 20th century, as much in the total volume as in the number of days of rainfall, the dry periods and the extreme rainfall periods (Vicente Serrano et al., 2007). In this Pyrenean sector it is noted that the reduction is notable in spring and summer; in autumn there are few observatories which show significant tendencies, and in winter there is a marked spatial contrast, with declines in the central Pyrenees while in the eastern region the changes are not significant or may even be positive.

These analyses coincide in large parts with the results of the OPCC Climate Study action for the whole Pyrenees, with data for 101 series for the 1959-2010 period. In the last 50 years, the descent in annual pluviometry was around 2.5% per decade. The value is statistically significant, but presents a high interannual variability: during the past two or three decades the dry years dominated, with annual precipitation noticeably inferior to the mean of the reference period, followed by various wet years, which exceed the average data level. Concerning the spatial differences, the diminution of annual precipitation is larger in the southern gradient than in the north, although the differences are limited. The wettest years from the series were 1992 (with a mean 23.2% above the reference period 1961-1990), as well as the years 1979 and 1996; while the driest years from the past five decades were 1989 (23.1% below the mean of the reference layer), 1985 and 1983.
The indicator for the four seasons of the year does not show a clear behaviour, although in all of these there is a slight reduction, slightly marked in winter and summer. It should be noted that the seasonal differences are not statistically significant, so that from this data one should not attempt to deduce solid Findings. A large interannual variability can be observed through all seasons of the year, mixing dry periods with rainy seasons; we can note that in the past two decades there were extended dry spells, as in the winters of the periods 1989-1993 and 2005- 2008. Nevertheless, and with the prudent interpretation of the results, this general pattern of pluviometric descent can be read in relation with similar behaviour observed elsewhere in the Mediterranean region. This tendency seems likely to continue in coming years according to the current climate change models.

The predictions for precipitation in the Pyrenees show a marked decline throughout the XXIst century, with a decrease in the frequency of wet days, an augmentation in the intensity of the most extreme phenomena and a notable increase in the length of the dry periods (Vicente- Serrano et al., 2007). Nonetheless, it is necessary to take into account that the spatial resolution of the current models is insufficient to represent the climatic diversity which characterises the Pyrenees as a consequence of their topographical diversity, their important altitudinal gradients and their interaction with atmospheric circulation, so that the results of these predictions for such complex mountain regions must be interpreted cautiously.

1.2.3 Evolution of the snow cover in the Pyrenees

The limitations mentioned for the climatic information available in the high mountain regions become even more obvious when we refer to the existence of data registers with length and quality sufficient to analyse the evolution of the Pyrenees snow cover during recent decades. This fact explains the absence of an adequate global evaluation of the snow cover for the whole Pyrenees. Up to now, the only information available on the Spanish slope is based on synthetic series generated on the basis of a robust statistical relationship between the climatic series of the area and the data on snow thickness in a network of snow poles used to measure the snow cover on the southern slope of the central Pyrenees (figure 1.2.5). From these one could deduce a statistically significant reduction of the snow cover in this sector for the 1950-2000 period (López-Moreno, 2005). The reduction was confirmed for the 1950-2010 period (figure 6) in a later study (García-Ruiz et al., 2011), this reduction being confirmed by a significant loss in the snow influence over rivers of the southern slope of the Pyrenees (Morán-Tejeda et al., 2013, Sanmiguel-Vallelado, 2017).

The reduction in winter precipitation seems to be the main cause of the snow cover decrease. However, these tendencies appear superimposed on a higher interannual variation, which is explained by strong oscillations in temperature and precipitation over time. Such variability is to be interpreted fundamentally by the annual frequency of the different weather types in southwest Europe during the winter months, largely controlled by the North Atlantic Oscillation (NAO, López-Moreno et al., 2011). In this way, a high accumulation of snow in the southern central Pyrenees is associated with a higher frequency of flows from the west, southwest and northwest which are produced, fundamentally, in years in which the NAO index is negative (López-Moreno y Vicente-Serrano, 2006, Buisán et al., 2015). Even though the NAO index has

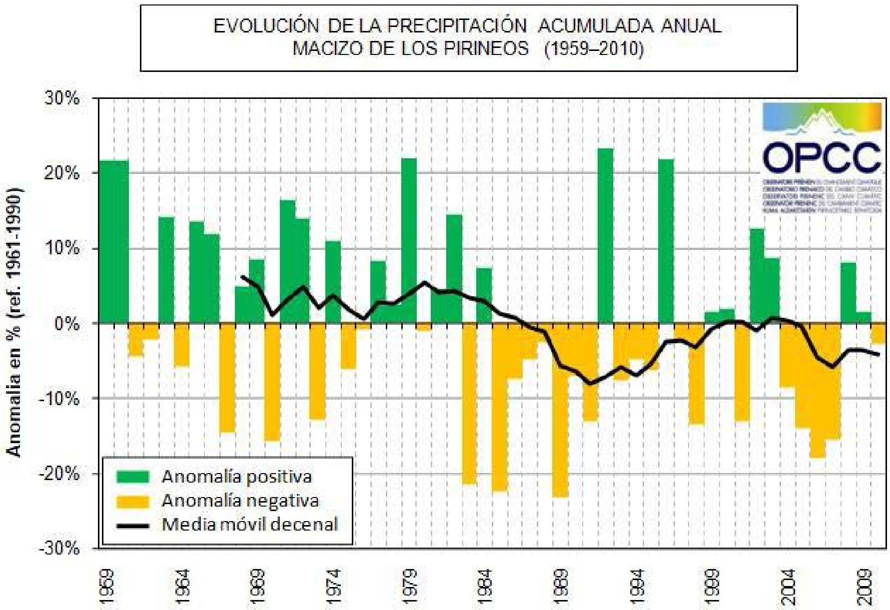

Figure 1.2.3. Evolution of annual precipitation in the whole Pyrenees during the period 1959-2010. The annual anomaly is calculated with relation to the mean value of the 1961-1990 reference period (in green if positive, in yellow if negative) and to the trend in precipitation for successive periods of 10 years (black line). Source: OPCC, 2013

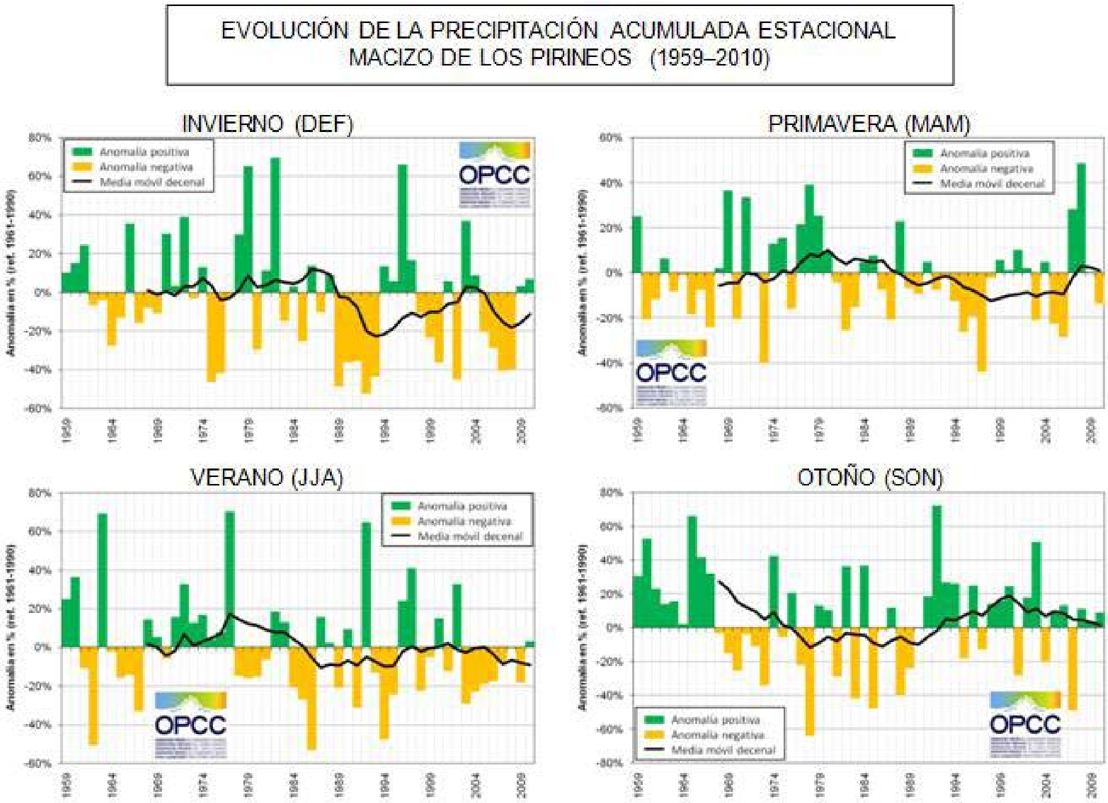

Figure 1.2.4. Evolution of the seasonal precipitation for the whole Pyrenees during the 1959-2010 period. The annual anomaly is calculated with relation to the mean value of the reference period 1961-1990 (in green if positive, in yellow if negative) and to the trend in precipitation for successive periods of 10 years (black line). Source: OPCC, 2013

shown a positive trend in the long term, it has a strong decadal variability (Vicente-Serrano and López-Moreno, 2008), which explains how in the most recent decades negative anomalies have been frequent, bringing to the Pyrenean range an important snowpack, especially in the high mountain ranges. In fact, when analysing snow data series from the past two decades, most observations do not show statistically sensitive changes, and indeed may show a slight upward trend (Buisán et al., 2015).

Despite the lack of equivalent studies for the French slope of the Pyrenees, the existence of common trends in precipitation and temperature in the two slopes suggests that on the French side as well there has been a descent in snow accumulation over the long term, but with a very variable signal during the two most recent decades.

KEY IDEAS

• For the whole Pyrenees the mean annual temperature has showed a clear increase around 0.2 °C per decade, with small differences between the two slopes of the range

• The increase is very clear starting from the 1980s, this being the last and warmest decade since official records exist.

• For seasonal data, the increase has been most significant in summer, around 0.4 °C per decade; smaller changes were seen in spring, around 0.2 °C; smaller changes were noted in autumn and winter.

• A trend can be observed to smaller annual volumes of precipitation, due mainly to the reduction of seasonal mean precipitations in winter and spring periods, though the tendency is not well defined. There exist significant spatial differences and the interannual variability in high.

• At a broad level, these results coincide with those observed in neighbouring regions and with the general tendency of the climate in Mediterranean Europe.

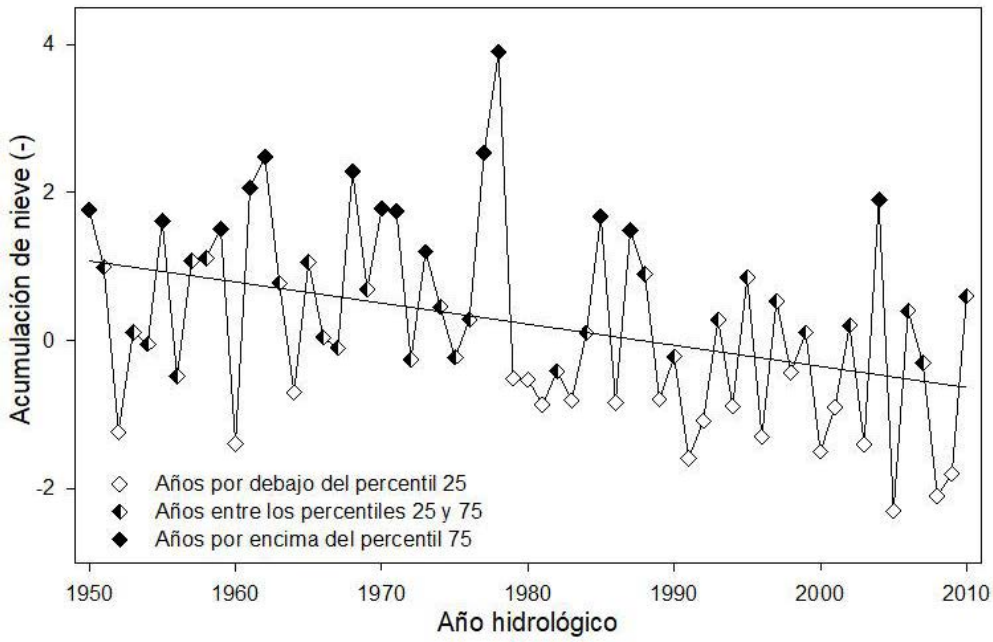

Figure 1.2.5. Evolution of the snow cover in April simulated starting from the relation between temperature, winter precipitation and snow accumulation in a network of snow poles on the southern slope of the Pyrenees. Source: OPCC Project, 2013.

1.3 Climate change projections in the Pyrenees

The study of the climate system and its future changes is normally achieved through the use of climate models. These models are digital representations of the climate system based on the physical, chemical and biological properties of its components, in their interactions and in their feedback processes. When such models cover the whole system one may speak of global climate models. Nonetheless, such models do not currently provide the resolution needed for specific studies, so that it becomes necessary to use regionalised methods. Such methods are usually grouped in two large categories: dynamic methods and statistical methods. The first group includes the regional models, which are climate models applied to a determined region.

Among various causes which could induce climate change the alteration of the composition of the global atmosphere is included, given that this is occurring due to human activity. In order to incorporate the possible effects of these alterations in climate models, the scientific community has defined a group of scenarios termed Representative Concentration Pathways (RCP). These scenarios are centred on the anthropogenic emissions, and represent the total radiative forcing calculated for the year 2100 with respect to the year 1750 (for example, the RCP 2.6 signifies 2.6 W/m^2). They are based on a combination of integrated evaluation models, simple climate models, atmospheric chemistry models and carbon cycle models; indeed, each scenario may cover a variety of climate policies, so that each RCP may be the result of different combinations of economic, technological, demographic and political futures. The simulations obtained under these scenarios constitute the defined climatic projections (IPCC, 2013).
In the Pyrenean region the projections depend on two complementary methodologies based on dynamic and statistical algorithms, and on the generation of a reference analysis for temperature and daily precipitation with a high horizontal resolution (5 km grid) (Peral et al., 2017) and vertical resolution (SAFRAN reanalysis for 300 m vertical resolution) (Verfaillie et al., 2017). The forecasts have been obtained starting with the outputs of a set of global climate models (GCM) from CMIP5 (19 models), as well as from a group of regional climate models (RCM) from Euro-Cordex (13 GCM/RCM combinations), considering four emissions scenarios (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5). This set of projections makes it possible to explore the uncertainties associated with the emissions scenarios, with the climate models and with the regionalisation methods.

Starting from a preliminary evaluation of these projections, a first approximate probabilistic prediction of the future climate offers these results:

- The maximum and minimum daily temperatures will increase during the 21st century under the three RCPs analysed (RCP 8.5, RCP 6.0 y RCP 4.5) (Figure 1.3.1), in all seasons of the year and throughout the Pyrenees. This increase will be faster for RCP 8.5, which is associated with high emissions scenarios throughout the present century.

- The uncertainties associated with the RCPs and the global climate models for temperatures increase over the century, as shown in Figure 1.3.1, and one may appreciate not only the separation between the forecast lines (between RCPs) as well as those between the increments of the shaded zones (between global climate models).

- As far as the projection of future precipitation is concerned, given the scenarios analysed and the methodology used, no significant changes are to be expected during the 21st century, and the different emissions scenarios have little influence on the expected pluviometry (Figure 1.3.2c). The number of models which show an increase in precipitation is similar to the number of models which show a decrease. The uncertainties increase throughout the century, especially in the case of RCP 8.5.

Taking windows of 15 years centred on 2030, 2050 and 2090, and estimating uncertainty linked to the models through the 17 and 83 percentiles, one can see:

- For the 2030 window, the change in the medium

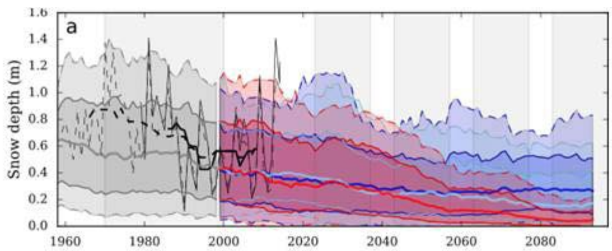

Figure 1.3.2 Evolution of the statistical distribution of average snow depth in the central Pyrenees (altitude 1800 m), taken from the observations of La Mongie (continuous black line), the historical simulations (grey) and the SAFRAN reanalysis (dotted black line), for the future of the EURO-CORDEX ensemble, with RCP 2.6 (dark blue), RCP 4.5 (light blue) and RCP 8.5 (red). Source: Météo France

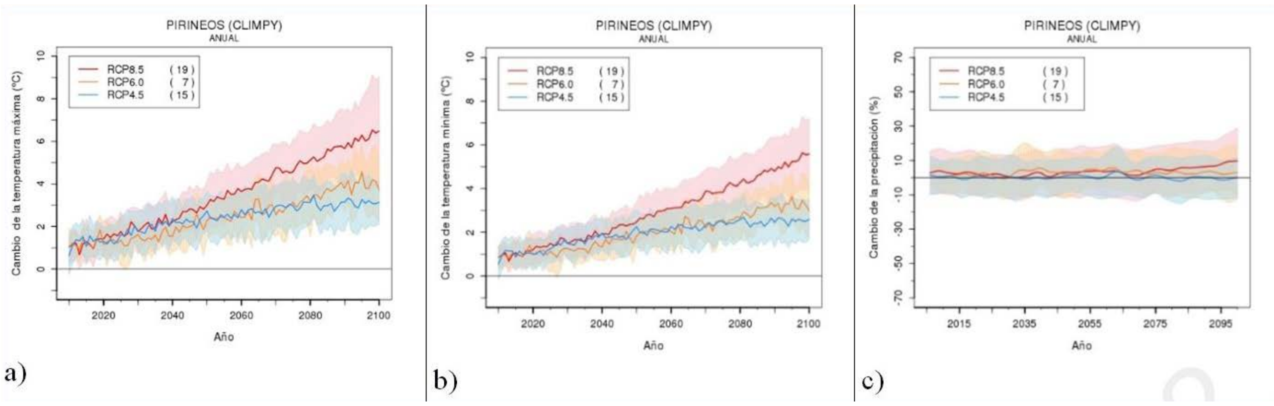

Figure 1.3.1 Proyections of the annual mean anomalies for (a) maximum temperature (b) minimum temperature and (c) precipitation, for the Pyrenees. Source: Météo France

annual value for maximum temperature relative to the reference period (1961-1990) may oscillate, on average and for the Pyrenees, between 1 °C and 2.7 °C for RCP 8.5 (with similar values for the other RCPs). For minimum temperatures, similar or slightly lower changes are seen: between 0.9 °C and 2.2 °C for RCP 8.5.

• For the 2050 window, the warming would be somewhat higher, with an uncertainty range increasing with temperature increases. Therefore, for the maximum temperature, the ranges would be from 2.0 °C to 4.0 °C and from 1.4 °C to 3.3 °C for RCP 8.5 and RCP 4.5 respectively, while for the minimum temperature, the ranges would be from 1.7 °C to 3.3 °C, and from 1.2 °C to 2.8 °C. The increase of minimum temperatures continues to be slightly less important than that of maximum temperatures.

• For the end of the century, the value ranges are even more increased, along with the intensity of the changes. Furthermore, the separation between forecasts associated with the RCPs is even clearer. For the maximum temperature and for RCP 8.5, on average, the annual change would be between 4.3 °C and 7.1 °C, while for RCP 4.5 it would oscillate between 1.9 °C and 4.2 °C. For the minimum temperature, the corresponding intervals would be between 3.6 °C and 6 °C, in the first case, and 1.6 °C and 3.5 °C, in the second case.

The simulations for changes affecting snow coverage are based on the same climatic scenarios and will allow future changes to be tracked relatively to the current climate (Verfaillie et al., 2018). The first results for the Pyrenees indicate a significant reduction in the snow cover, though maintaining a strong interannual variation. So, in the central Pyrenees at an altitude of 1800m (Figure 1.3.2), the medium snow cover could decline by half in the 2050 horizon, compared to the current climate; while the period of snow cover on the ground would be reduced by more than one month, between autumn and spring during the cold period. Nonetheless, these estimates vary according to altitude, with a tendency to noticeable reduction above 2000m, as well as depending on the emission scenarios considered (López-Moreno et al., 2009).

KEY IDEAS

• The future climate projections for the Pyrenees show a progressive increase both of the maximum temperatures as well as of the minimum temperatures throughout the XXIst century. In the highest emissions scenarios, this increase will be faster.

• This warming will also have effects both in reducing snow cover thickness as well as on the length of the time period during which snow covers the ground.

• For precipitation, the concordance between projections is smaller than for temperatures and significant changes cannot be identified.

2. Impact of climate change on biophysical sectors

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ABSTRACT

Climate changes during the Holocene (last 11700 years) have had important impacts on the Pyrenean territory and its biophysical systems. Particularly significant have been the changes in water availability and vegetation cover, as well as in the dynamics of the cryosphere and the surface processes of erosion and sediment transport. On a millenary scale, the Holocene presents a tripartite structure with an initial phase with progressive development of the forest and intensification of the superficial processes of erosion and transport until about 8000 years ago, followed by one with the maximum development of the forest on the mountain floor until about 4500 years ago, decrease of the erosive processes and less water availability and finally a relatively humid one until today. The impact on the territory of the warmest and driest phases during the Medieval Climate Anomaly (900-1300 CE) and the coldest and wettest of the Small Ice Age (1400-1850 CE) is strongly modulated by anthropogenic activity. Recent changes show synergies between Global Warming and Great Acceleration (of human activity).

The significant climate oscillations occurring during the Holocene caused changes of different intensity and duration on the vegetation distribution, erosion processes, flood generation, mountain ecosystem dynamics, hydrological resources and human activities in the Pyrenees (García-Ruíz et al., 2015). In this chapter, the main impacts on the hydrosphere, cryosphere, biosphere and human societies during this period are summarized, based on the study of glacial deposits, fluvial and lacustrine records and speleothems.

2.1 Climate change impacts in the Pyrenees during the Holocene

Paleohydrology

The rising temperatures and humidity at the onset of the Holocene were reflected on high elevation lacustrine environments under Atlantic influence by an increase in lake levels. On the contrary, in the areas located at a lower altitude more sensitive to summer dryness, the increase of temperatures together with the maximum summer insolation, caused the prolongation of the arid, and cold, Younger Dryas phase (12900-11700 years BP) [2] delaying the humidity increase for two millennia, until 9500 years BP. At a millennial time scale, the paleohidrological evolution during the Holocene in the Pyrenees presents a tri-phase structure, with a humid interval initially, followed by a dry phase and finally a new increase in humidity (González-Sampériz et al., 2017). As a whole, the Early Holocene (11700 – 8000 years BP) represents a period with more water availability in the Pyrenees, with a progressive decrease in humidity along the Mid Holocene (after 5500-4500 years BP) and specially dry conditions around 3000 – 2500 years BP. Afterwards, during the last 2000 years, a slight recovery in Pyrenean lake levels is observed.

Besides this millennial-scale variability, other rapid hidrological changes (secular or even decadal) characterized by higher runoff associated to intense rainfall or snow melt are recorded. In general, those events are correlated to cold phases in North Atlantic and Mediterranean regions. The last two large climatic oscillations (the Medieval Climatic Anomaly, MCA, and the Little Ice Age, LIA) were recorded during the last millennium with a very significant impact in the hydrology of the Pyrenean region. The MCA (900-1300 CE[3]) was characterized by a generalized lake level lowering, with increased salinity in low altitude lakes, and large runoff variability. On the contrary, during the LIA (1300-1800 CE), a generalized increase in lake levels is observed coherent with glacier advances (Morellón et al., 2012). This succession of arid and humid conditions (MCA vs LIA) during the last millennium has been related to changes in the North Atlantic Oscillation (NAO) dominant phase. The NAO is a large scale atmospheric phenomenon that brings more rainfall of Atlantic origin during winter in northern (positive phase) or southern Europe (negative phase), such as the Pyrenees. The available reconstructions indicate that during the MCA the positive phase of the NAO was dominant while during the LIA, the NAO- phase, with more precipitation in the Pyrenees, was the most frequent one. It is worth to note that the local effect of the NAO on the aridity conditions at our latitude is very variable at a decadal scale (Vicente-Serrano and López-Moreno, 2008). Additionally, the Montcortes lake record, very well laminated, points to the onset (1347-1400 CE) and the final (1844-1894 CE) decades of the LIA as periods with particularly intense precipitations (Corella et al., 2017). Finally, during the XXth century and in the present global warming context, there is multiple evidence of a decrease in water availability in the Pyrenees, with lower water levels in low altitude lakes and much less frequent events of intense precipitation. Besides, the Pyrenean rivers have experienced a decrease in their flow during the last decades that is attributed, apart from climatic causes, to the increase of forested surfaces due to rural abandonment (Beguería et al., 2003; García-Ruiz et al., 2016).

Erosion and surficial processes

The study of fluvial sediments has permitted the reconstruction of periods with the most important frequency of paleofloods in Iberian rivers (Benito et al., 2008). In the Atlantic basins, the floods result from intense rainfall events associated to Atlantic fronts driven by the NAO. In the Mediterranean basins, extreme precipitation events are induced by convective processes more common during autumn. The increase in torrentiality recorded in lakes located at a high altitude during the Early Holocene (Basa de la Mora: Pérez-Sanz et al., 2013; Marboré: Oliva- Urcía et al., 2018) or at a lower altitude during more recent periods (Montcortés: Corella et al., 2016) is associated with more water availability and strong seasonality. For example, the laminated sediments in Montcortés lake provided the first annually-resolved record of the last three millennia, allowing to characterize extreme rainfall events (> 90 mm). This record shows that extreme rainfall events in the Pyrenean areas under Mediterranean influence were more frequent during warm periods (MCA) than during the cold ones (LIA). In fact, the highest variability was recorded in the transition from the MCA to the LIA (XIVth century). During some periods of the LIA when winters were cold and dry, the river flow would have decreased, as the frequency of floods, in relation to the MCA (900-1300 CE). The denudation[4] rates during the Holocene have changed depending on the rainfall intensity, vegetation cover, land use and sediment availability. At a regional scale, fluvial supply of sediments probably increased during the Early and Late Holocene, periods with more fluvial activity. The Ebro delta experienced a notable advance during the Roman period likely due to the large agrarian and mining activity in the basin increasing the input of sediments. In the Iberian basins, the phases with larger fluvial aggradation[5] correspond to the Medieval period (1000-1500 CE), as a response to the anthropic impact at the end of the MCA and beginning of the LIA (Benito et al., 2008). The presence of an ash layer in the Tramacastilla lake record (Gallego valley) corresponding to the Xth-XIth centuries indicates a period of generalized fires provoked to create larger subalpine grasslands to be used for the summer transhumant stockbreeding (Montserrat, 1992). In the southern slope of the Pyrenees, the following period with intense erosion occurred contemporary to a maximum in population at the end of the XIXth century and at the beginning of the XXth century when rural resources were exploited more intensively (García-Ruiz et al., 2015). This process was favoured by the higher frequency and intensity of paleofloods during the last decades of the LIA (XIX century).

The most recent changes in the intensity of erosive processes and in fluvial sediment transport are strongly correlated to changes in land use in the last decades (rural abandonment, reforestation). The trend towards a larger hydric deficit and less extreme rainfall events in the last decades was not unusual in the Late Holocene context in the Western Mediterranean. However, longer temporal series suggest that the frequency of torrential rainfalls may increase in the global warming scenario.

The evolution of the cryosphere

Most of the Pyrenean glaciers disappeared or are reduced to the most elevated cirques (García- Ruíz et al., 2014). Most of these glaciers expanded during the Neoglacial (5000 years BP) and in several cirques other fluctuations were reported such as the glacier retreat during the Bronze Age and the Roman Humid Period and a small advance during the Dark Ages (600-800 CE). Many Pyrenean glaciers reached their maximal extension of the Holocene during the LIA. During the mid XIXth century, after the end of the LIA, the glaciers responded very rapidly to the following warming.

(2) For the time periods BP (Before Present), 1950 is considered as the "present"

(3) The notation systems "Common Era" (CE) and "Before Common Era" substitue the traditional archeological notations AD and BC.

(4) (5) The denuadation is the erosion of grounds and sediments of the reception basins. The aggradation is the accumulation of sediments in rivers, brooks or lakes.

Since 1850 CE, the glaciers have continuously receded although there were short periods of stabilization or some minor advances. Their degradation has been particularly important since 1980 CE. In a century and a half, many glaciers have disappeared, others have become simple snowfields and few others remain as glaciers but with their size and thickness considerably reduced. The evolution of some glaciers and the snowpack in the subalpine zone shows that even during years of high snowfall, the glaciers keep on retreating (García-Ruiz et al., 2015; López-Moreno et al., 2016). Small areas with permafrost are still present above 2600 m asl where polygonal soils were described and up to 13 rock glaciers were yet active.

Vegetation evolution

The onset of the Holocene in the Pyrenean region with more Atlantic climate influences leads to forest development in montane and subalpine zones. The variations among conifer and deciduous development during the first millennia reveal a rapid response of vegetation to climatic fluctuations. The intense seasonality contrast during this period, together with the high evaporation during summers, caused a delay in the onset of humid conditions in areas with more Mediterranean influence, where the stepic landscape lasted until 9200 years BP. Afterwards, the increase in winter temperatures and higher water availability, allowed the expansion of deciduous forests, mostly dominated by oaks and hazels (González-Sampériz et al., 2017). During the Mid-Holocene, among 6000-82000 years BP, and as a response to warmer winters and more humid conditions with precipitation distributed uniformly along the year, a Mediterranean forest developed in Central and Eastern Pyrenees. Those forests were composed by semi-deciduous Quercus in montane zones, while the conifers retreated and the deciduous forest grew in altitude, being established in the subalpine zone. The period from 6000 to 4800 years BP was a transition phase at a regional level characterized by stronger seasonality with an intensification of the dry season, especially at low altitude. It was in those low altitude areas that the deciduous communities were particularly affected, in the alpine and subalpine zones where pines, junipers and savines expanded. The final establishment of arid conditions 4800 years ago lead to the dissapareance of important deciduous forest in montane zones and favoured the expansion of semi-deciduous Quercus (gall oak) and evergreen (holm oak) and pines at higher altitude. Vegetation adapted to particularly arid conditions during two periods: 2900-2400 years ago and during the Medieval Climate Anomaly (900-1300 CE). During the Little Ice Age, and especially during cold and humid phases, there were changes in forest structures and composition, influenced as well by the decreasing human activity in mountain areas. The upper limit of the forest experienced a small decrease in the areas where it was still in a natural position (Camarero et al., 2015).

Since the end of the Little Ice Age, human activitiy and changes in land use seem to be the main driving force for vegetation changes in the Pyrenees. However, during the last decades, the growth of Pinus nigra above the forest limit in some areas of the Ordesa and Monte Perdido National Park suggests that this altitudinal expansion of the vegetation may be related, on the one hand, with the reduced anthropic pressure and more importantly on the other hand, with higher mean temperatures in altitude allowing the expansion of woody vegetation.

Fires

Fire is a perturbation regulating the ecosystems while being regulated by the internal dynamics of those. In the Pyrenees, during the onset of the Holocene (10500 – 7700 years BP) and at about 1900 – 2200mof altitude, there was a high frequency and intensity of fires, probably due to the maximum summer insolation that favoured summer dryness. Besides, the expansion of the mesophytes provided the necessary biomass to this higher frequency of fires in the Pyrenean treeline which occurred naturally (Gil-Romera et al., 2014). During the Mid Holocene, fires were less frequent in the southern Pyrenees; with moderate fire activity which may have been related to the anthropogenic impact on changes in forest composition. Since the end of the Bronze Age and the Roman Period (approximately 2500-1800 years BP) an increased human impact is recorded in this mountain environment. Fires of anthropogenic origin are common since the Bronze Age, associated to temporal crops, mining and grazing activities, especially around 2900 and 2650 years BP, 1850 and 1550 years BP. Since then, the human impact on vegetation and consequently, on the dynamic of fires, sensibly increased. It is worth highlighting that temporal variability in fire activity during the Holocene in the southern Pyrenees may be related to local spatial patterns of combustible distribution and flammability, resulting from local anthropogenic actions, not necessarily found at a regional level. It is possible to detect an altitudinal difference in the occurrence of fires, then being more frequent and occurring earlier in lowlands where fuel and vegetation cover continuity were not limiting factors and where human activity would have allowed a larger impact

Figure 2.1.1 Summary of the impacts in the Pyrenean región associated with climate change during the Holocene (last 11700 years). Note the scales are qualitative, from the smallest impact (0) to the highest. Source: Own content

Rapid changes

Paleoclimate and paleoenvironmental records show that Pyrenean ecosystems and surface processes were very sensitive to rapid changes, responding rapidly to climate fluctuations during the Holocene. During the Rapid Climate Change events (RCCs) defined at a global scale (Mayewski et al 2004) vegetation, water availability, cryosphere and surface processes were affected in a rapid way leaving an archive of those impacts on Pyrenean records. An event of such characteristics occurred 8200 years ago, one of the most intense globally. Temperatures dropped and aridity increased at our latitudes. In the Pyrenees, a decrease of mesophytes is recorded, those plants being more sensitive to the increase of aridity and decrease of temperatures than conifers. On the other hand, the isotherma of 0ºC descended in altitude, as interpreted from the chrisophyte record in Redo lake (Pla y Catalán, 2011). During the last 2000 years, the rapid transitions in temperature and precipitation during the MCA and the LIA (Giralt et al., 2017; Oliva et al., 2018) are reflected in the Pyrenean territory, demonstrating the vulnerability of mountain ecosystems to rapid climate changes.

Climate change and human impact

Several studies show an intense human impact in vegetation, hydrology and erosive processes in the Pyrenees, often difficult to separate from responses to climate change. The first evidence of a significant human impact in the Pyrenean landscape dates from the Neolithic, but some changes in vegetation cover can be interpreted as human deforestation or response to climate change. During the last 2000 years, the landscape transformation has been intense and occurred continuously, particularly in low lands, more than in the subalpine zone where human pressure was seasonal and linked to grazing activities. The first clear evidence of human impacts at low altitudes is dated to 3100 years ago, with the first deforestation phase and the apparition of Cerealia type pollen in Estanya lake records (Morellón et al., 2008). Changes in the composition of the vegetation cover at higher altitude have been interpreted as responses to climate fluctuations or human deforestation.

Since the medieval ages, numerous evidence of landscape changes due to deforestation and human activities have been found. The largest changes in the Pyrenean landscape occurred during the Middle Ages, coinciding with a warmer climate period – the MCA. Deforestation in subalpine and montane zones together with the planting of crops in lowlands deeply transformed the landscape in the Pyrenean high mountains and changed the hydrology and geomorphological processes. During the LIA, the impacts of human presence were reduced in higher areas due to colder temperatures. However, in the lowlands the end of the LIA (mid XIXth century) corresponds with the starting point of the phase of maximum human occupation that extended until the mid XXth century. Global changes since the mid XXth century coincide with a rural exodus and the human abandonment of the Pyrenean mountains.

BOX 2.1.1 THE PYRENEES DURING A WARMER CLIMATE PERIOD: THE MEDIEVAL CLIMATE ANOMALY

During the Low Medieval Ages and coinciding with a relatively warmer climate period– the Medieval Climate Anomaly (MCA, 900 -1300 CE) – enormous changes occured in the Pyrenean territory, still observable at present times. More human pressure in the mountains due to the increased population was contemporary to a climatic phase of higher temperatures and irregular hydrology, with more seasonality in precipitations, higher torrentiality and frequency of arid phases. In the subalpine zone, at the time when the surface occupied by deciduous forests decreased while the presence of pines, junipers and stepic plants such as Artemisia increased. In the lowlands, crops expanded, particularly cereals, olive trees, vineyards, chestnuts and walnuts.
The alpine prairies that characterize the actual Pyrenean landscape in the southern slope above 1600 m altitude expanded notably after the subalpine zone deforestation. Deforestation, together with land use, deeply transformed the landscape in the Pyrenean mountains and at the same time, modified the hydrological and geomorphological processes. Can we use the MCA as an analogue to the present day Global Warming? Although the first phases of global warming in the XXth century corresponded with a decrease of human activities in mountains due to a rural exodus, currently the global change in the Pyrenees is characterized by warmer temperatures and intense anthropogenic transformation. Although the causes of climate changes are not identical, both periods share the rapid increase of temperature, large hydrological variability and elevated human pressure.

2.2 Mountain biodiversity: fauna

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ABSTRACT

Climate conditions play a decisive role in the composition, structure and functioning of natural systems. High mountain ecosystems-characterised by a high richness of endemic species which have a narrow range, effectively small population size, specific habitat requirements and limited dispersal capabilities-are particularly vulnerable to variations in climate conditions. Climate is one of the main regulators of ecosystem functions in mountain areas, and even small temperature variations can impact the distribution and abundance of many species. The impacts of climate change on the fauna of the Pyrenees may manifest in different ways, including i) general changes in the physiology of some species (such as physiological adaptations via microevolutionary processes), ii) alteration in species phenology (such as variations in the number of reproduction events, the egg hatching date or migration start and end dates), iii) variations in the abundance, composition and geographical distribution of populations (which manifest as latitudinal and altitudinal changes to the distribution of some species), which along with phenological changes can lead to iv) deeper ecological changes owing to mismatching of the biological cycles of interconnected species (such as predator/prey or plant/herbivore systems) and which can alter the function of the entire ecosystem. Climate change can also increase the v) risk of invasion and/or expansion of some non-native species by assisting their movement and subsequent establishment as a result of new favourable climate conditions and less interspecific competition with native species. There are also several factors which act in synergy with direct climate change impacts. Most of these are anthropic, and their magnitude presents an even greater challenge to the Pyrenean fauna conservation. Among these are habitat destruction and fragmentation, changes in land use, overexploitation of water resources, atmospheric and water pollution, abandonment of agropastoral activities and the introduction and spreading of non-native species. The changes mentioned above, caused by the combined action of anthropic and climate change impacts, can alter Key ecological processes in high mountain ecosystems, which could in turn compromise their survival and limit their capacity to provide goods and services to society.

2.2.1 Changes in species productivity and abundance

Climate change can affect the physiology of many species, influencing their productivity and, ultimately, their long term survival. The correlation between climate variability and demographic parameters for high mountain species has been thoroughly demonstrated by the scientific community. The impact of climate change on the physiology and productivity of some species is more evident in the Alpine biogeographic region than in others. Climate is the main ecosystem regulator in this area, and its animal and plant communities are therefore in a delicate balance with climate variables.

Observed and predicted impacts

The reduction in the amount and persistence of snowfall recorded over recent decades in the Pyrenees is impacting various species which inhabit snow-covered environments, including large mammals which live at high altitudes such as the Pyrenean chamois (*Rupicapra pyrenaica*). Several studies have demonstrated the correlation between demographic changes in the Pyrenean population of this ungulate and years with less snow cover at a certain threshold (Jacobson et al., 2004; Willisch et al., 2013; Kourkgy et al., 2015). In particular, it has been shown that phenological changes in plant species which the Pyrenean chamois feeds on trigger important stages in their life cycle such as reproduction, conception or the length of gestation. Similarly, climate-induced changes in physiology and abundance of some bird species characteristic of high altitude environments have been observed, such as the rock ptarmigan (Lagopus muta pyrenaica). García-González et al (2016) have shown that increased temperatures could reduce the amount of snow coveerage or its duration, thus reducing the size of the preferred feeding grounds of the rock ptarmigan. Reduced growth of mountain vegetation has a direct impact on food availability for this species, and therefore on its physiological state, reproductive success and survival. According to Novoa et al (2016), the variables which best explain the difference in reproductive success of this species in the Pyrenees are the date of full thaw and rainfall patterns after hatching of spring eggs. These two variables are being affected by climate change (Buisan et al., 2015; Morán-Tejeda et al., 2017).

Amphibians are among the groups of vertebrates most vulnerable to physiological changes induced by climate change. Their permeable skin, biphasic6 life cycle and eggs with no shell render them extremely sensitive to small temperature and humidity changes (Carey and Alexander, 2003). Their reproductive success, immune functions and degree of sensitivity to chemical contaminants have been shown to be highly sensitive to climate change (Pound et al., 2006; Araujo et al., 2011; Dastansara et al., 2017). One of the most pronounced negative effects on amphibian physiology is caused by changes in the length of the winter hibernation period, a clear example of which is the increased mortality and reduced reproductive capacity of some populations of common toad (Bufo bufo): increasingly mild winters shorten their hibernation period, leading to a general worsening of the physical state of many individuals (Reading, 2007). In addition, increasingly milder temperatures prevent these amphibians from entering complete hibernation throughout the winter period, meaning they continue to consume their reserves and experience reduced body mass as a result. Loss of body mass has a direct impact on survival capability (Bonardi et al., 2011; Caruso et al., 2014). Extreme climate events such as droughts and heat waves are also generating negative effects in some amphibian populations. The 2003 heat wave had a considerable negative impact on the survival of Perez's frog (*Pelophylax perezi*) in Europe (Neveu. 2009). Piracés et al (2015) have confirmed considerable year-on-year decreases in populations of the Pyrenean newt (Calotriton asper) in nine gullies in the Ordesa and Monte Perdido National Park which are directly related to those years with a greater incidence of extreme climatic events (mainly flash floods and droughts). Lastly, invertebrate physiology and behaviour can also be affected by changes in climate conditions. This is the case for the pine processionary (*Thaumetopoea pityocampa*), the populations of which have increased their reproductive success and distribution in recent years in some areas of the Pyrenees as a result of an increase in minimum temperatures and a reduction in the number of rainy days (Buffo et al., 2007; Rousselet et al., 2010; Taïgo et al., 2017).

2.2.2 Changes in life cycle (phenological changes) and interspecies interactions

One of the most evident effects of climate change on fauna are life cycle changes (Knudsen et al., 2011). Significant events in animal's lives such as reproduction, laying, migration and hibernation are happening at different times as a result of temperature increases. The biological cycle of several species is changing significantly and climate change seems to be the main cause. Phenological responses to climate change differ from one species to another and may lead to desynchronisation of some Key interspecies interactions. Desynchronisation can result in considerable alterations to the structure of high mountain communities. Migratory species and those species both terrestrial and aquatic whose body temperature depends on environmental temperature are particularly vulnerable to changes in climate conditions (Dell et al., 2005; Jiguet et al., 2010; Parmesan, 2006; Dingemanse and Kalkman, 2008; Schlüter et al., 2010; Tryjanowski et al., 2010; Barthès et al., 2014). Phenological changes, in addition of good being a good indicators of climate change, have a strong critical ecological importance, as they can have an impact on on the competitive capacity of the different species and therefore in the structure of the communities and in the in the functioning of the ecosystem.

Migratory species and those (both terrestrial and aquatic) whose body temperature depends on the temperature of the environment are particularly vulnerable to these changes. Phenological changes are not only good climate change indicators but are also hugely significant from an ecological perspective. They can affect the ability of different species to compete and therefore the structure of communities, in effect changing how the ecosystem functions as a whole.

Observed and predicted impacts

In the case of migratory birds, the greater climatic variability of recent years is changing the migratory patterns of some species in the Pyrenees (Walther et

(6) Life cycle consisting of two different phases (larva and adult) with metamorphosis between them.

al., 2002, Rubolini et al., 2007; Panuccio et al., 2016). The main changes recorded include earlier arrival on the European continent in spring, observed in more than 100 species (Bradley et al., 1999; Rubolini et al., 2007), leaving later in autumn, and general changes in migratory patterns, the latter being particularly pronounced in birds which migrate short distances (Møller et al., 2008; Saiano et al., 2011; Panuccio et al., 2017).

Earlier arrival to Europe has been linked to the increase in winter temperatures in Sub- Saharan Africa (where the majority of these species winter), and the later exit in autumn seems to be related to the high temperatures recorded in migratory destinations. In particular, Saiano et al (2011) have calculated an average advance of the arrival date of around 0.16 days per year since 1959, up to a maximum of 0.27 days per year for some species.

Climate change seems to be affecting the various species of migratory birds in Europe differently. A greater number of individuals are migrating long distances, to the detriment of the number of resident individuals and short distance migrants (Møller et al., 2011. Various studies predict more intense phenological changes in the future, which could even cause significant changes in the proportion of long and short distance migratory birds in Europe (Bloom et al., 2012; Charmantier, 2014).

Extreme climate events also appear to be related to some phenological changes in birds. The greater incidence of heat waves and droughts have been linked to greater variability in the arrival date in Europe of the barn swallow (*Hirundo rustica*), a migratory species which winters in Africa and nests each year on both sides of the Pyrenees (Saino et al., 2004).

When conditions are better in the wintering grounds (mild, with few extreme climate events), habitat quality improves. The greater availability of food which comes along with it means that adults can arrive sooner to their breeding grounds in Europe, increasing the chances of laying a second clutch successfully (Saino et al., 2004). More intense extreme climate events in wintering grounds in the future could affect reproductive success and reduce the number of pairs capable of laying a second consecutive clutch (Walther, 2010).

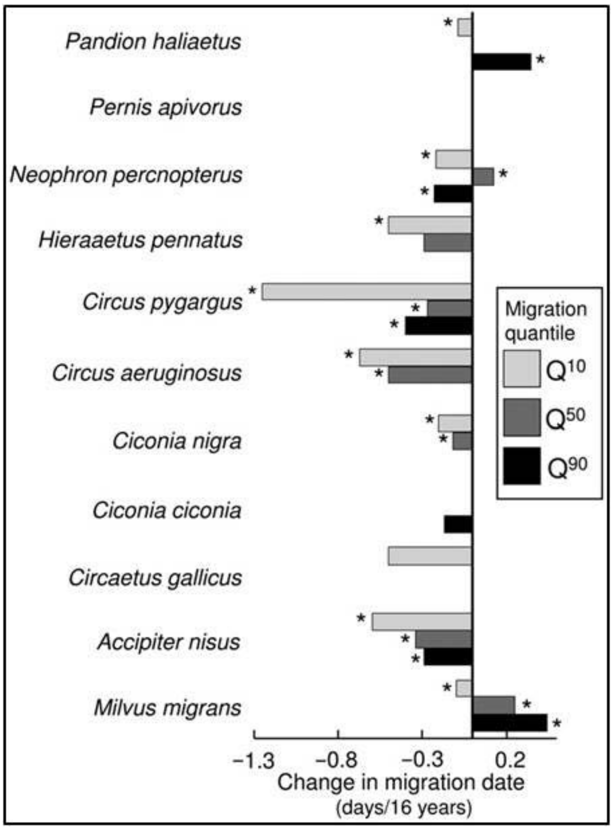

Figure 2.2.1. Estimated advance of arrival on the Iberian Peninsula of 11 species of migratory birds between 1999 and 2011 (no. days/16 years). Light grey (Q10) corresponds to 10% of the birds counted, dark grey (Q50) to 50% and black (Q90) to 90%. Source: Panuccio et al., 2017

BOX 2.2.1. LINDUS 2 PROJECT: MONITORING MIGRATORY BIRDS AND ENHANCING ENVIRONMENTAL EDUCATION AND ECOTOURISM IN THE CROSS-BORDER AREA OF THE PYRENEES

The Western Pyrenees is an exceptional location for studying the thousands of birds which use the western European migration route each year. LINDUS-2 is a cross-border collaboration in the Pyrenees, which from 2010 to 2014 was implemented through the Lindus project. Its main aim is the study and recording of the migratory movements of birds through mountain passes in the Pyrenees. Unusually, the program also encompasses the study of bats, which use this migration route in great numbers and even hibernate in Navarre. As well as identifying and counting birds in four strategic areas (Lindus, Organbidexka, Portalet and Somport), Lindus-2 raises social awareness by working with eco-volunteers and through many other initiatives. The project also promotes eco-tourism linked to birdwatching in the Lindus area and showcases its natural and cultural heritage.

Lindus-2 was being implemented from 2016 to 2018. It enables bird monitoring during three migratory seasons and will offer valuable observational data to help us understand changes in the phenology of the migratory birds which cross the Pyrenees annually. LINDUS-2 also includes citizen science initiatives such as the cuentapájaros (bird count), which invites the public to actively participate in counting bird life using a mobile app called "eBIRD". The project is part of the Cooperation Programme Spain-France-Andorra (POCTEFA 2014-2020), 65% of which is funded by the European Regional Development Fund (ERDF). It is a cross- border collaboration between the Regional Government of Navarre, its public agency GAN-NIK (Gestión Ambiental de Navarra, S.A.), the Town Hall of Burguete, SEO/BirdLife and the Ligue pour la Protection des Oiseaux (LPO-Aquitania), therefore covering a wide geographical area in Navarre, Aragon and Aquitaine.

Phenological changes also affect invertebrates. Among insects, studies of Lepidoptera and the main pollinators have showed these to be particularly sensitive to temperature changes. Earlier first-sighting dates have been recorded for the majority of Lepidoptera species studied, seemingly related to the increase in average temperatures (Herrera et al., 2014). With regard to lepidoptera, in recent decades there have been advances in the date of first sightings in most of the species studied, apparently related to the increase in average temperatures (Diamond et al., 2011). Amphibians are also clearly affected by climate-induced phenological changes. Over the last thirty years the date of the start of reproductive activity and egg laying has come forward by between one and three weeks per decade for many amphibians (Scott et al., 2008; Phillimore et al., 2010; Green et al., 2017). Reptiles also seem to have undergone considerable temporal advancements in their phenology over the last 30 years. Excluding the coldest years, the emergence date of more than 15 species of reptiles in the Pyrenees comes gradually earlier each year (Prodon et al., 2017).
It is highly likely that the current trend in phenological changes in many animal species will remain the same or even intensify in the future as temperatures and climatic variability increase because of global warming (Vitasse et al., 2018. In addition to modifying the phenological calendars of some species, the combined effect could seriously alter some inter-species interactions, with consequences at all levels of the food chain and impacts on the dynamics of many species and high mountain ecosystems (Gordo et al., 2005; García et al., 2014; MacCarty et al., 2017).

2.2.3 Geographical distribution changes

One of the most common faunal responses to climate change is displacement towards higher latitudes and/or altitudes in search of areas where climate conditions are still suitable, therefore modifying their original range. Most studies-conducted using different models and with different focuses-concur in predicting a general displacement of current ranges towards the north, shrinking of ranges more to the south, and displacement of mountain species towards higher altitudes (Parmesan et al., 2006; Dirnböck et al., 2011). The effects of such displacement could be particularly negative for those species already at the extreme or margin of their current range, as is the case for many mountain species. Overall, variations in current species' distribution could cause changes in existing mountain communities. These could be characterised generally by increases in certain generalist species, to the detriment of some, more-specialist species (Singer and Parmesan, 2010). There is a consensus that the intensity of these displacements will depend not only on how climate change unfolds and the response capability of each species, but also (and undoubtedly to a greater extent) on the development of other non-climate factors integrated into the concept of global change[7] (Schweiger et al., 2008).

Observed and predicted impacts

In general terms, it has been estimated that the distribution range of European species has been displaced by an average of roughly 17 km towards higher latitudes and/or 11 m towards higher altitudes per decade o (Chen et al., 2011). A critical factor affecting mountain fauna is that ascending displacement is often limited by other human-derived factors such as habitat fragmentation or land use changes. These factors can alter connectivity between geographical areas and hinder migrations towards higher altitudes, therefore affecting the capacity of different species to adapt to the new climate conditions (Dirnböck et al., 2011). Furthermore, displacements in high mountain areas entail loss of habitat, since species range inevitably reduces with increasing altitude. As a result, some species run the risk of being gradually isolated in the small remaining areas of suitable habitat, thus increasing their vulnerability and even their risk of extinction owing to food scarcity and decreasing genetic variability[8] in their populations (Schneider et al., 2002; Maclean y Wilson, 2011; Flousek et al., 2015). This phenomenon could have particularly negative effects on species and populations with low genetic diversity, such as the alpine marmot (Marmota marmota). A recent study by Bichet et al (2016) has shown that genetic variability is low in the current populations of this species—following its extinction in the Pyrenees more than 10,000 years ago, it was successfully reintroduced using just two different alpine populations which had little genetic exchange with one another. The low number of founding individuals (some 400 were reintroduced over 40 years), together with geographic and genetic isolation, could considerably reduce the adaptation capability and resilience of the alpine marmot to the effects of climate change.

For the majority of high mountain species, the lower limit of their range is restricted by unsuitable climate conditions, while the upper limit is determined by the availability of certain vegetation, plant species or habitat. Hence, changes in the distribution of Pyrenean species will also depend on the capacity of vegetation to shift its range over time: if plant communities are displaced more slowly than the rate at which climate conditions change, the potential new distribution areas of many animals could be considerably smaller than their original ranges (Costa et al., 2009; Alexander et al., 2017).

Moving on to mammals, endemic high mountain species with low dispersal capability seem to be more sensitive to the effects of climate change on their range. One example is the Pyrenean desman (*Galemys pyrenaicus*). According to the Findings of a study by Murueta-Holme et al (2010) into the impact of climate change on this small mammal in the main massifs in the north of the Iberian Peninsula, its range could be significantly reduced throughout this century. The average summer temperatures and water balance seem to be the main factors which determine the presence and potential distribution of *G. pyrenaicus*, and both are predicted to vary significantly throughout this century as a result of global warming. If the projections in this model are validated, the effects of climate change could act in synergy with habitat loss to endanger the future of the species.

Some bird species could also see their ranges reduced in the Pyrenees. Although their ability to fly considerably increases their dispersal capability, the reduced range of the plant communities on which many species depend could be decisive for some, such as the Pyrenean rock ptarmigan (*Lagopus muta pyrenaica*) (García-González et al., 2016: Novoa et al., 2016).

(7) Global change refers to planetary-scale human-induced environmental changes, particularly those affecting processes which are intrinsic to how the Earth system functions.

(8) Genetic variability is the variation in the genetic material (genome) of a population or species. The capacity to adapt to the negative effects of climate change requires high genetic diversity in order to activate adaptive genetic mechanisms and counteract negative environmental impacts. As this variability reduces in the populations of certain animal and plant species, these become more vulnerable to changes in environmental conditions. However, adaptation to environmental change can also take place through what is known as phenotypic plasticity (e.g. see Kourkgy et al. 2016, among others)

BOX 2.2.2. PROMOTING CLIMATE CHANGE ADAPTATION IN PROTECTED AREAS MANAGEMENT

Fundación Fernando González Bernáldez and EUROPARC-España are taking forward the project titled *Promoting climate change adaptation in protected areas management in Spain*, with the support of Fundación Biodiversidad through the call for grant applications for climate change adaptation projects. The project is part of one of the priority workstreams of the National Adaptation Plan for Spain, which aims to incorporate adaptation into the different government sectors, in this case biodiversity conservation. The main objective of the project is to facilitate the integration of climate change adaptation criteria into the planning and management of protected areas. It will do this by promoting exchange of knowledge and pilot experiences between protected areas managers and developing practical tools for incorporating existing scientific evidence into management.

To achieve this, applications have been opened for an award for good practices in adaptation in protected areas. The award will identify and disseminate adaptation work taking place across Spain. In parallel, adaptation criteria are being experimentally incorporated into the preparation of management plans for three protected areas: the Sierra de Santo Domingo Protected Landscape (Zaragoza), the Urbasa y Andía Special Area of Conservation (Navarre), and Teide National Park (Tenerife).

It is hoped that the results of these pilot experiences, together with the actions compiled with a view to the award, will serve as relevant material for the network of protected areas managers by means of an online tool and the reprinting and distribution of Manual 13 "*Protected areas in the context of global change: incorporation of climate change adaptation into planning and management*".

The potential ranges of some amphibian species could also be significantly reduced in the coming decades as a result of global warming. The specific environmental requirements of this group and their high physiological sensitivity to changes in abiotic variables, combined with increasing fragmentation of the already-narrow areas of suitable habitat, mean it is highly likely that the potential range of these vertebrates will be further restricted in the future. Some populations could end up increasingly isolated and therefore less resilient[9] to climate change as a result (Araújo et al., 2006; Hickling et al., 2006; Maiorano et al., 2011).

In a study on the impact of climate change on the potential distribution and genetic variation of the Pyrenean newt Calotriton asper, Pou et al (2015) concluded that between 2020 and 2080, even for the most optimistic scenarios, this endemic Pyrenean species could suffer a considerable reduction in its potential distribution partly caused by the minimal possibilities for dispersal at its disposal. Despite the huge loss of potentially suitable areas for this amphibian, the models also reveal some areas which could remain relatively stable over time, especially in the central zone of its current range (see figure 2.2.2.).

The future projections for populations of some insects such as butterflies are particularly alarming. In general, in the 80% of the European butterfly species in Europe is expected a contraction of the current distribution range, while only only 20% of species could benefit from the potential positive effects of increases in mean temperatures (Settele et al., 2008). It is important to underline that the Pyrenees concentrate the highest density of catalogued butterfly species in the annexes to the Habitats Directive (Romo et al, 2015). This is because in the Pyrenees bioregion vonverge ecological and bioclimatic requirements of many of these species. Having in mind that the extension of the distribution ranges of these butterflies is mainly limited by the climatic conditions (Romo et al., 2015), to consider the evolution of climatic conditions in current and future conservation policies is of the utmost importance for conservation strategies in the medium and long term.

(9) Resilience is the term used in ecology to indicate the capacity of communities and ecosystems to respond to disturbances without significant alterations to their structure and how they function, being able to return to their original state once the disturbance has stopped.

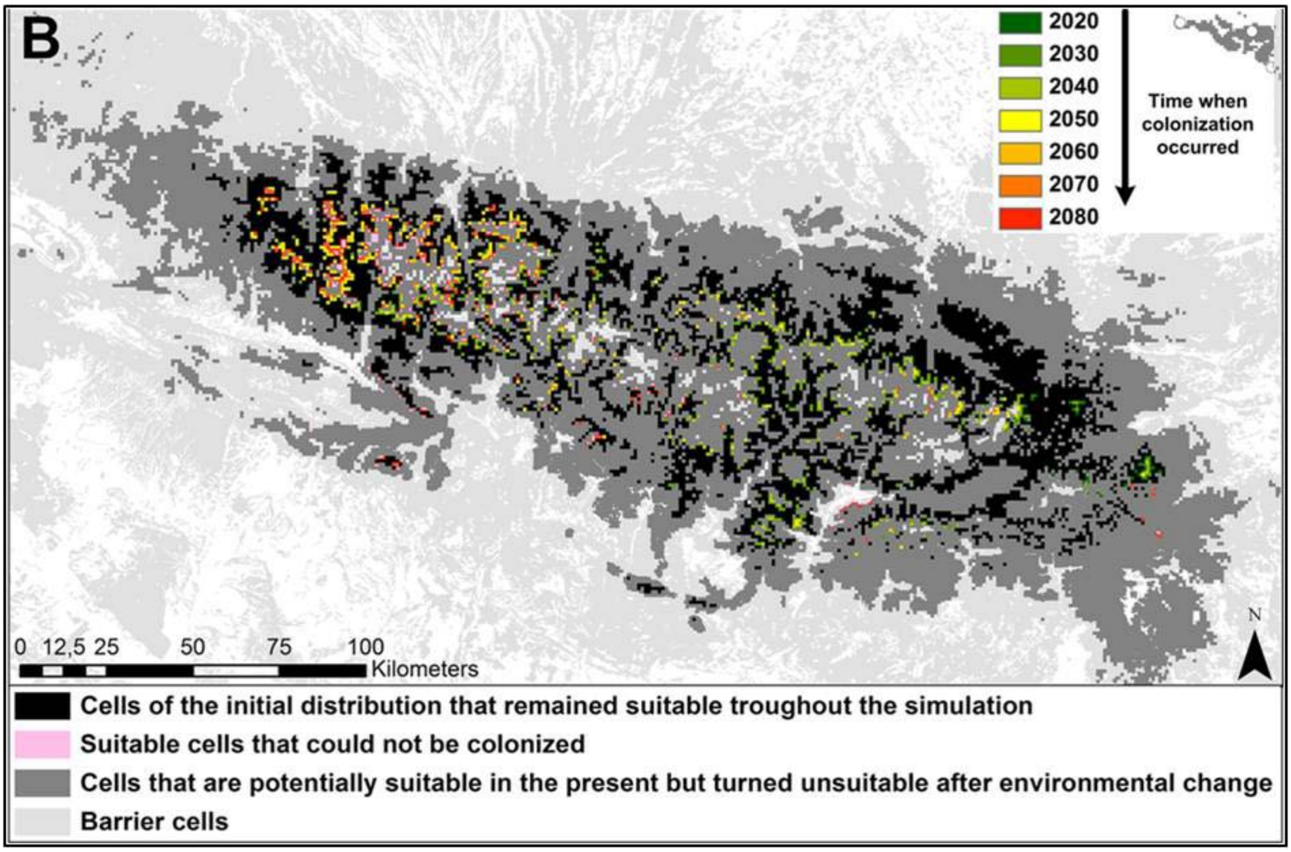

Figure 2.2.2. Estimated evolution of the potential distribution of Calotriton asper in 2080 with respect to its current distribution, using the average of three general circulation models (GCM: CCCMA, HADCM3 and CSIRO) and the SRES A2 emissions scenario. The zones in grey are potentially suitable for Calotriton asper currently but probably will not be in the future. Zones in black are areas of the Pyrenees which will remain potentially suitable despite changes and limitations on dispersal of species. The different colours indicate the estimated time of colonisation of the new areas. Source: Pou et al., 2015

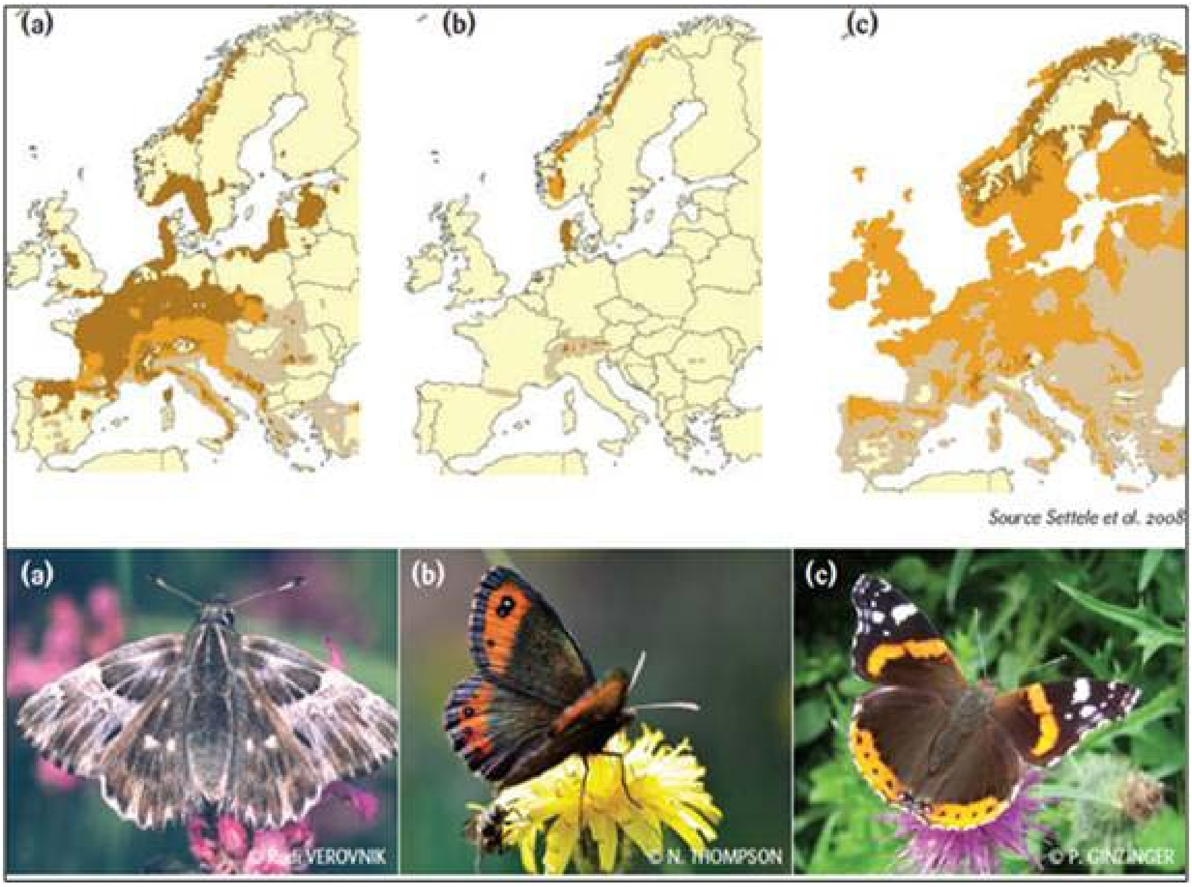

Figure 2.2.3. Expected changes to climatically suitable areas in 2080 (light brown=areas lost, dark brown = areas gained) using emissions scenario A2, for three European butterfly species: (a) *Carcharodus flocciferus*; (b) *Erebia montana* y (c) *Vanessa atalanta*, en 2080, empleando el escenario emisivo A2. Source: Settele *et al.,* 2008

Some butterfly species typical of European mountain areas have seen their potential distribution range reduced in recent decades and are expected to continue to do so in the future (Willson et al., 2015). This is the case of Parnassius apollo, a species tahs has experienced a strong ascent of its lower altitudinal distribution range limit in southern France and probably also in many mountainous areas of the southern Iberian Peninsula (Catalan et al., 2017). This regression seems to be directly related to a 34shorter annual duration of the snow cover, which worsens the thermal isolation of immature individuals of this butterfly, negatively affecting their survival rate.

The future projections for Erebia montana are particularly worrying. All the models used by Schmitt et al (2013) predict a high risk of disappearance of this species in the Pyrenees and Massif Central due at least in part to climate change. The potential distribution and diversity of some pollinating insects such as the bumblebee and bee could also be seriously affected by climate change (Lecocq et al., 2013; Groom et al., 2014; Miller-Struttmann et al., 2015). Gradual changes in climate conditions are altering the range and phenology of these Key insects (Kuhlmann et al., 2012), triggering spatial and/or temporal variations in their potential climate niches10 (MooLlanes et al., 2013). Various studies have shown that the current decline in

(10) Ecological niche is a term which describes the relative position of a species or population in an ecosystem. When we talk about an ecological niche, we are referring to the role that a certain species plays within a community. For example, the ecological niche of the squirrel is to live in trees and feed on plants and nuts.

bumblebee numbers in Europe can be partly attributed to climate change and particularly to the increased frequency and intensity of extreme climate events such as droughts and heat waves (Bartomeus et al., 2013; Groom et al., 2014). In the Pyrenees, Ornosa et al (2017) have identified a gradual displacement of the main species of bumblebee towards higher altitudes, driven by a search for suitable climatic and environmental conditions. Furthermore, Rasmont et al (2015) predict a considerable reduction in climatically suitable areas for many bumblebee species in the mountain range, particularly *Bombus barbutellus, B. bohemicus, B. campestris, B. confusus, B. cryptarum, B. terrestris* y *B. cullumanus* (figura 2.2.4).

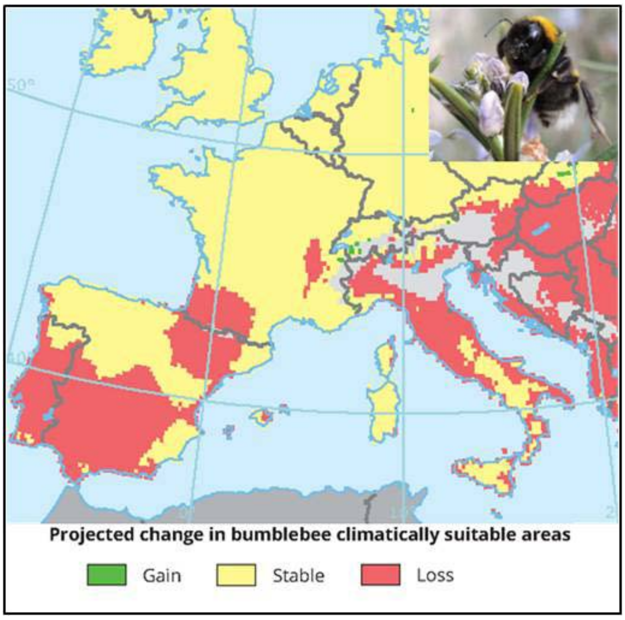

Figure 2.2.4. Projected change in the climatically suitable area for the bumblebee Bombus terrestris (the largest species of bumblebee and one of the most numerous in Europe) based on a combined scenario of climate change and land use changes and in line with the SEDG (Sustainable European Development Goal) and the SRES B1 emissions scenario. Gained areas are shaded green, stable areas yellow and lost areas red. Source: Rasmont et al., 2015 from EEA, 2016.

2.2.4 Changes to ecological interactions and ecosystem function

The combined action of climate change impacts may desynchronise the life cycles of ecologically interconnected species, such as those in predator/prey and parasite/host relationships. If these species respond differently to variations in climate conditions (different phenological changes), the interactions between them may become unsynchronous resulting in changes to the function of the entire ecosystem.

Observed and predicted impacts

Phenological responses and changes to species distribution entail potential negative repercussions on species at higher trophic levels[11] and generally on species which interact with one another via different types of synergies (interspecific relationships[12]). Some examples are herbivore/plant systems or predator/prey relationships. Changes in presence and/or abundance which affect a certain species also impact other related species by causing the temporal misalignment of their phenological calendars. Said misalignment can affect the capacity of some species to carry out Key functions in the ecosystem and how the ecosystem functions (Filadelfia, 2007).

One particularly alarming example is the desynchronisation between the phenology of plant flowering and the life cycle of bees (plant/pollinator interspecific relationship). It has been shown that climate change could be negatively impacting on the capacity of pollinating insects to pollinate plants (Schweiger et al., 2010). The repercussions on the ecosystem could be very serious given the importance of pollinators to ecosystem stability and to maintaining local and global biodiversity (Bascompte and Jordano, 2007).

Those more specialist species in plant/pollinator systems are likely to be most vulnerable to global warming, since in theory they are less flexible in terms of the species they interact with, though this has not yet been widely proven (Benadi et al., 2014). The common cuckoo (*Cuculus canorus*) provides an example of a change in interspecies interaction caused by global warming. This long distance migrant and brood parasite is losing synchrony with some of its main hosts (Saino et al., 2009; Kolář ová et al., 2017). According to Barret (2014), climate change is altering the association between the common cuckoo and its

(11) Trophic levels are each of the groups of species or organisms in an ecosystem which occupy the same position or role in the flow of energy and nutrients. That is, they occupy an equivalent place in the food chain.
(12) In population ecology, interspecific competition is the interaction which takes place when individuals of different species compete for the same resources in an ecosystem (such as food or living space).

main normal hosts. The latter, mostly short distance migratory birds, tend to advance their spring arrival date, more than the cuckoo, and to reproduce earlier as a result. This misalignment between the migration and nesting times of the cuckoo and its hosts can have serious implications on the reproductive success of this parasitic species.

Butterflies also appear to be vulnerable to desynchronisation between species. For the butterfly Boloria titania, there is an expected considerable reduction in size over the coming decades of the area where their ideal climatic conditions overlap with the climatically suitable area for the plant they depend on (*Polygonum bistorta*). This could considerably reduce their potential available niche in the Pyrenees and, consequently, increase the risk of extinction of this specialist butterfly (see figure 2.2.5.).

Trophic discrepancies such as those between these two species constitute an added pressure on certain specialist species which are characteristic of the Pyrenees bioregion, and increase their risk of future extinction.

2.2.5 Greater risk of invasion by, and/or spread of, non-native species

Although the cold environments characteristic of elevated zones and high latitudes have been considered less vulnerable to biological invasions, global warming could increase the risk of invasions and establishment of non-native species, including in high mountain environments (Pauchard et al., 2016). Climate change could encourage the establishment of new non-native species in the Pyrenees given that new favourable climate conditions (Pysek et al., 2013) and/or less interspecific competition[13] with native species enable their transport and subsequent establishment (Hellmann et al., 2008: Cubas et al., 2017). Invasive non-native species are mostly generalist and opportunistic and therefore tend to adapt better than most native species to rapid climatic variations (Hellmann et al., 2008). Furthermore, the increase in temperatures displaces climate barriers to higher altitudes, increasing the probability of new invasions (particularly of plants) and the establishment of some species which are already present (Capdevila Argüelles et al., 2011; Petitpierre et al., 2016).

Observed and predicted impacts

Altitudinal displacement of native species' ranges may favour the expansion and establishment of some non-native species, since these gain access to new climatically suitable niches and low levels of

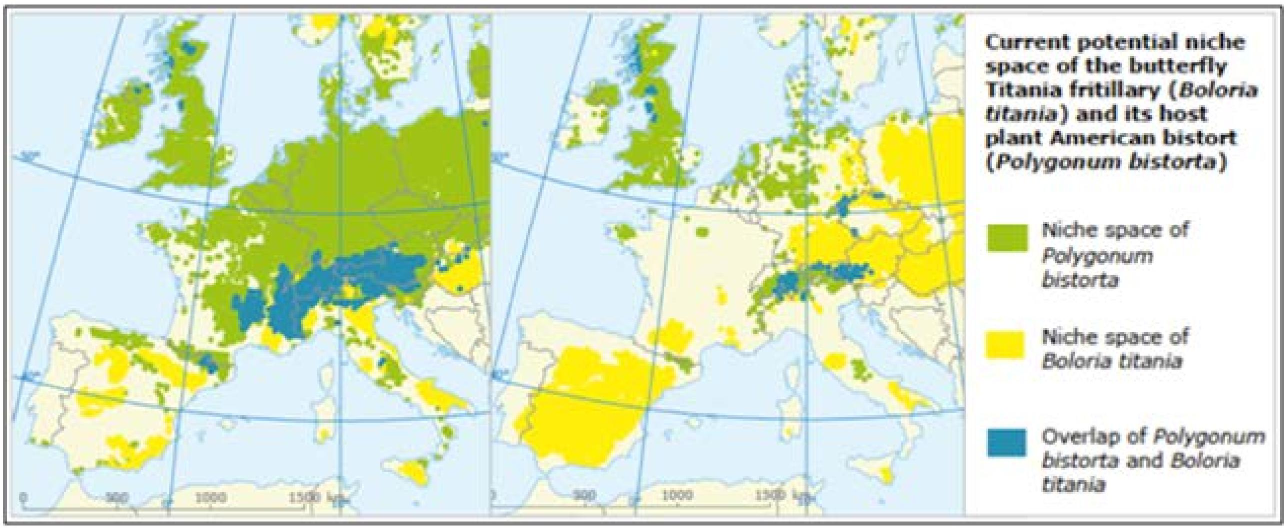

Figure 2.2.5. In population ecology, interspecific competition is the interaction which takes place when individuals of different species compete for the same resources in an ecosystem (such as food or living space).

competition for resources owing to the displacement of the species which originally occupied the area. According to the model used by Gallardo et al (2017), climate change could increase the size of climatically suitable areas for some non-native aquatic and terrestrial species present in Europe, facilitating expansion of their range by more than 70% with respect to their current range. The results of this study predict a greater number of invasions in mountain areas than in lower regions in the medium and short term future in Spain, France and Andorra. The authors of the study also highlight the Key role that European protected areas have played to date as a refuge for native species against biological invasions, and warn that climate change could seriously threaten this role in the coming decades.

Lastly, it is important to stress that although climate change could be a Key factor in the potential expansion and establishment of non-native species in the Pyrenees, the determining factor is still -and will continue to be- their previous introduction by man. For this reason, potential climate change adaptation initiatives include work to raise public awareness of the scale of the problem and to strengthen existing networks for monitoring, controlling and preventing the introduction of non-native species.

2.2.6 Impact on interconnection between protected areas networks

The movement of animals and plants towards areas where the climatic conditions are suitable could displace their ranges beyond the limits of current protected areas, increasing their vulnerability to different dangers and stress factors. Similarly, it is likely that some protected areas which are currently interconnected by natural or artificial corridors will end up being cut off for certain species which cannot tolerate the new climatic conditions in these corridors. This phenomenon could become particularly evident in protected areas housing endemic species with lower dispersal capability and a highly specialised ecology. The network of Natura 2000 protected areas is a Key element in the current and future management of the biodiversity of the Pyrenees. Tackling new climate challenges and their consequences will require measures to ensure that the most vulnerable species are resilient enough to overcome the most harmful impacts of climate change. The current Natura 2000 network must therefore be adapted through initiatives and actions geared towards ensuring interconnectivity between different protected areas. Some of the main challenges which must be addressed in conservation policies for the high mountain areas of the Working Community of the Pyrenees (CTP in Spanish) are restoration of highly vulnerable habitats or those in a delicate state of balance, and protection of new spaces which can facilitate the displacement and spread of the most threatened species as their ranges change. Initiatives such as the EU Green Infrastructure Strategy provide an inspirational example. This particular strategy proposes establishing a European network of healthy ecosystems using nature-based green infrastructure.

2.2.7 Findings and recommendations

Mountain ecosystems are particularly sensitive and vulnerable to climate change and often constitute the habitat of highly specialist or endemic fauna. They also provide a multitude of highly valuable goods and services to society as a whole. The international scientific community agrees in stressing that the combined action of climate change and habitat loss caused by land use changes will be the main causes of biodiversity loss and species extinctions across the world in the coming decades. Climate change affects biodiversity in mountain regions by causing physiological and phenological changes in plants and animals and changes in the length of the growing season and in population distributions, as well as by increasing the risk of invasion, establishment and spread of non-native species.

In order to understand the responses of Pyrenean species to the effects of climate change and their different adaptation mechanisms, we must increase efforts to promote and incentivise new networks for observing high mountain biodiversity, as well as promoting the medium-to-long term maintenance of existing observation networks. Only by improving our knowledge can we better define adaptation actions to guarantee effective conservation strategies in the long term. This section provides a non-exhaustive summary of the main challenges which will have to be addressed in conservation policies for the Pyrenees from a climate change perspective. It also sets out a list of the main climate change adaptation recommendations, classified into green, grey and soft adaptation solutions.

(13) In population ecology, interspecific competition is the interaction which takes place when individuals of different species compete for the same resources in an ecosystem (such as food or living space).

Main challenges

- Protect the most representative areas of the Pyrenees in terms of conservation biology. This applies especially to unique habitats which are particularly sensitive to climatic variability or which are in a delicate state of balance with environmental conditions;

- Reduce knowledge gaps and uncertainties around the potential introduction and spread of plagues, disease vectors and non-native invasive species and develop strategies for combating these;

- Incentivise the creation of new networks for observing the effects of climate change on biodiversity, and promote the development and long term maintenance of existing high mountain observation networks;

- Promote the integration of climate change adaptation considerations in current plans, programmes and other tools for planning and protecting biodiversity in the Pyrenees;

- Limit habitat fragmentation, and as much as possible ensure gradual ecological connectivity between protected areas in the Pyrenees;

- Foster research which looks jointly at climate factors and anthropic risks;

- Promote collaboration and information exchange between competent bodies for biodiversity protection and management in the different regions. Identify and involve representatives from land use planning, from the veterinary, livestock, agriculture and forestry sectors, and from the competent bodies for the environment and protected areas management;

- Identify the areas and species which are most vulnerable to climate change and more generally global change so as to define priority conservation areas and restoration opportunities.

Soft measures [14]

- Encourage the creation of a catalogue of areas in the Pyrenees which are particularly sensitive to climate change for those parts of the mountain range housing emblematic, unique, vulnerable or particularly sensitive ecosystems, or which contain threatened or endemic species whose distribution and characteristics hinder their displacement to other areas;

- Promote forms of land use in the Pyrenees which are compatible with conservation and which can mitigate the effects of climate change;

- Harmonise adaptation policies for other sectors with goals around protecting, improving and restoring biodiversity in order to maximise positive synergies between them (principle of sustainable development);

- Strengthen and redirect current plans for monitoring and controlling vulnerable Pyrenean species and those for prevention, control and management of invasive non-native species and plagues based on potential climate-induced impacts;

- Conduct more in-depth research on the climate-induced displacement of species' ranges and the adaptation potential of different threatened species;

- Update species' red lists based on their current and potential vulnerability to climate change;

- Encourage the creation of cross-border databases, such as the Pyrenean atlases of plant and animal species;

- Promote the creation of mechanisms, methodologies and participative forums for coordinating inter-sectoral and cross-border adaptation measures to ensure the protection of Pyrenean species and habitats which are particularly vulnerable to climate change;

- Increase knowledge and monitoring of the stability and resilience of the different Pyrenean ecosystems, and define cross-border methodologies for quantitatively evaluating any change in their capacity to provide ecosystem services (e.g. define indicators);

(14) Soft measures or non structural measures to reduce or mitigate the negative effects of climate change. This category of measures is typically composed of investigative studies which goal is to deal with knowledge gaps or to add to the bases of knowledge on climate change, its impacts and the most vulnerable sectors. In this category belong as well the development of specific methodologies and systems to reduce the risks associated with climate change (ex. Development of the UN cross border early warning system for the management of heat waves in the Macizo)

• Raise public awareness of the importance of, and risks associated with, the problem of invasive non-native species and their interactions with climate change, and inform interested groups about good practices for preventing new introductions;

• Encourage the dissemination of citizen science initiatives in the Pyrenees i.e. effective collaborations between the public and researchers to enrich databases for species phenological monitoring, observations of sensitive ecosystems, gathering sample data and archives;

• Ensure proper dissemination of approved adaptation actions, the progress of these and their results to all interested parties and society in general.

Green measures [15]

• Promote the identification and subsequent protection of populations and sub- populations of species which are sensitive to climate change and those with high rates of genetic exchange, as well as habitats and ecosystems which are especially sensitive or vulnerable to the effects of climate change;

• Incentivise the design of nature-based adaptation solutions to improve the possibility of migration and of distribution changes in the protected areas of the Pyrenees by means of green corridors between them (improve ecological connectivity);

• Improve the characterisation of micro climatic changes in different populations, refuges and variable climatic gradients to a reasonable scale;

• Adjust the administrative boundaries of current and future protected areas to species' biology and to the foreseeable effects of climate change;

• Encourage the inclusion of altitudinal gradients in the current network of protected areas in the Pyrenees with a view to improving protection of those populations whose ranges are being displaced as a result of climate change.

KEY IDEAS

• Mountain ecosystems are particularly sensitive and vulnerable to climate change and often constitute the habitat of highly specialist or endemic fauna species.

• Climate change affects biodiversity in mountain regions by causing physiological and phenological changes in plants and animals and changes in the length of the growing season and in population distribution, as well as by increasing the risk of invasion, establishment and spread of non-native species.

• The observed climatic changes are altering the distribution of some species, which are forced to ascend in altitude in search of the ptimum conditions for their development. It is highly probable that this situation will increase in the future as global warming intensifies.

• The life cycle of many groups of animals has been advanced in recent decades, with advances in the laying date of some amphibians, birds and the arrival of migratory birds and insects. This trend is likely to intensify in the coming decades.

• Climate change is affecting the interaction between some species that depend on each other for survival.

• It is highly probable that the joint action of climate change and habitat loss due to changes in land use will be the main causes of biodiversity loss and species extinction in the Pyrenees during this century.

(15) The green measures or based in ecosystem services: this typology of measures includes all the measures, good practices, studies and initiatives which principle is the use of ecosystem services provided by different natural resources to mitigate the negative effects of climate change (ex. Conservatory silviculture practices to increase the capacity of Pyrenean forests to reduce hydrological risks)

2.3 Mountain biodiversity: flora

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Figure 2.3.1 : Androsace ciliata DC., endemic plant of the Pyrenees, Photo CBNPMP/C. Bergès

ABSTRACT

At the crossroads between very contrasting climatic influences: Mediterranean, Oceanic and mountainous, and with a large variety of ecological situations related in particular to the geology, relief, exposure and altitude, the Pyrenees offer great biological diversity. Their southern location, a relatively developed alpine zone and high limestone massifs are additional reasons for the great diversity of the flora and plants of great originality compared to other European mountains with a high number of endemic species (about 200 taxa, Villar et al., 1994). Thus, the Pyrenees are a hot spot of European biodiversity.

At the level of the Pyrenees, biodiversity is taken into account in European, national and local nature conservation strategies, in particular via an extensive network of protected areas. Beyond its intrinsic interest in terms of biodiversity, this great diversity is in interaction with socio-economic activities (pastoralism, forestry activities, food gathering, tourism, sports activities, etc.) some of which have played a major role in the spatial organisation of plant formations (pastures and forests) and continue to have a major effect on their evolution.

Mountain areas are known to be very sensitive to climate change (Beniston et al., 1996; Theurillat and Guisan, 2001), however, the analysis of the effects of climate change and the vulnerability of ecosystems is relatively complex owing to the different factors at play and, in particular the proportion of uses and their specific evolution, the effect of extreme events, the possible compensation between factors and, finally, the lack of medium and long term studies.

Furthermore, many studies rely on general forecasts of temperature elevations and a decrease in rainfall, but the trends concerning rainfall are not clear for the moment. The first Findings concerning climate change at the level of the Pyrenees [OPCC1 project, climate section] highlight a *"significant increase, from a statistical viewpoint, of +0.2°C per decade, more pronounced in spring and summer"* and a *"decrease in combined annual rainfall of about 2.5% per decade, more noticeable on the southern side of the Pyrenees than on the northern side and difficult to distinguish on a seasonal level".*

Trends point at a rise in temperatures by 2030, 2050 and 2090, but winter rainfall may increase on the northern side by 2030 and decrease after that (see. section 1.3), with great uncertainty with regard to rainfall in general. Another important factor to observe is atmospheric circulation (especially the foehn effect which is characteristic of the Pyrenees[16]), the effects of which on the vegetation at a local level are relatively unknown. The general organisation model of vegetation in the mountains at altitudinal levels, with variations that are dependent on exposure, masks major variations at a local level, all the more so in the Pyrenees in view of the diversity of the bioclimatic situations and the compensatory effect between different factors[17].

Finally, the response of organisms and populations will depend on phenotypic plasticity[18] and the possibility of genetic evolution. Rapid adaptations and microevolutions may occur but, currently we know very little about these processes as well as the way in which climate change may interact with other general modification parameters (Peñuelas et al., 2013). Some species and ecosystems may be more adapted to climate change than we think, but there are very few references on the subject (Martín-Vide, 2016).

2.3.1 Physiological alterations and changes in the productivity and abundance of species

We are providing a meta-analysis of bibliographic research: there is a lack of scientific proof and reference to concrete work on the alteration of productivity and abundance of the Pyrenean flora.

In general, the climate is a limiting factor for mountain species and ecosystems in view of the factors specific to mountain areas (altitudinal gradient, topographic diversity and exposure). The modification of the different climate parameters (temperature, radiation, rainfall) combined with an increase in the concentration of CO2 acts on photosynthesis with an effect on growth and development which is well-known and documented for farmed species and trees. In particular, studies on the productivity of forests indicate an altitude displacement for the growth optimum (limiting factors: drought, deficit in air vapour pressure, low temperatures) (Savva et al., 2006; Jolly et al., 2005), a phenomenon analysed for beech trees in the French western Pyrenees between 1970 and 2009 (Vitasse et al., 2010). Environmental pressures may affect plant metabolism and result in changes in the chemical composition and the concentration of nutrients in different vegetable organs. These changes may affect the soil and also the appetite of herbivores for grazing plants (see chapter 2.2) with a possible effect on trophic networks (Rivas-Ubach et al., 2012).

The adaptation of many mountain plants to extreme conditions (dryness of walls, radiation, short vegetation period, weight of snow) may put them at great risk if these conditions diminish and with the arrival of more competitive species. The CENMA has studied the potential distribution of *rhododendron* in Andorra when faced with climate change based on the potential accumulation of snow (the presence of snow in winter and spring being essential for the species). According to three climatic scenarios, the ecological niche of the species may be reduced by 37.9-70.1 km2 in relation to the current area by the end of the century and would be limited to scree and rocky grassland habitats (Komac et al., 2016).

A paradoxical effect of the general temperature increase in the mountains would be the colder temperatures experienced by chionophile biocenosis as a result of a long period of snow cover owing to the lower protection provided by the snow mantle. In the frame of the FLORAPYR programme, one of the objectives pursued is the monitoring of snowbeds in order to study changes in these very specific environments on the basis of changes in climatic parameters (temperature and duration of snow cover, Komac and Olicard, 2014, cf. infra).

2.3.2 Changes in the life cycle (phenological changes)

Works conducted on phenology in mountain areas highlights a difference in phenological cycles which vary yearly (cycle in advance with hot springs and late with cold springs). Different sources report an advance of the date of bud burst and an extension of the vegetation season (Menzel and Fabian, 1999; Menzel et al., 2006; Linderholm, 2006; Vitasse et al., 2009). Nevertheless, monitoring data in mountains still appears to be insufficient for predicting long-term trends and identifying changes attributed to general warming and the inter-annual temperature variability according to data collected in the frame of the Phénoclim scientific and educational programme initiated in 2004 and based on the participative observation of the phenology of about ten species in the Alps (see CREA, http://Phénoclim.org/fr). Thus, phenological changes may affect the precocity of flowering and fruiting, the development cycle of insects (faster transformation from larva to the next stage) with the resulting risk of a desynchronization in interactions between organisms (plants/pollinisers, plants/herbivores, see point 2.2.4). Finally, it should be noted that warming and drought have opposite effects on the phenology of the leaf senescence[19] of deciduous species and, consequently, *"the impact of climate change*

(16) Meteorological phenomenon related to altitude which has a warming and drying effect when an air mass passes over a large relief. Via the southern wind, the northern side of the Pyrenees may experience spectacular increases in temperature.

(17) Modification of the effect of an ecological factor (climatic, edaphic, topographic or biotic) through the action of another (for example for a plant adapted to a dry environment, high rainfall compensated for by filtering soil).

(18) Ability of an organism to modify the expression of its characteristics in response to environmental factors.

(19) "Photoperiod and temperature are the main cues controlling leaf senescence in winter deciduous species, with water stress imposing an additional influence. Photoperiod exerts a strict control on leaf senescence at latitudes where winters are severe and temperature gains importance in the regulation as winters become less severe. On average, climatic warming will delay and drought will advance leaf senescence, but at varying degrees depending on the species" (Estiarte and Peñuelas, 2015)

will depend on the relative importance of each factor" in a given territory (Estiarte and Peñuelas, 2015).

2.3.3. Ecological alterations and the functioning of ecosystems

The case of prairie ecosystems has been studied in particular (Grime,1973; Callaway et al., 2002; Adler et al.., 2011). It is widely recognised that the greatest specific diversity concerns formations under average grazing or cutting pressure and that interactions between plants often considered as negative (competition) may also be positive (facilitation) and explain the great diversity (Michalet et al., 2006; Grime et al., 2000). The effects of climate change will be visible in association with these pressures, such as, for example, the combination of stress of climatic origin and anthropic disturbances. Most models predict that the combined effect of these factors could alter even further the functioning of already disrupted ecosystems in the coming decades, altering their diversity to the limits of total collapse (Grime et al., 2000; Brooker, 2006).

In the case of forests, the question of the possible amplifying effects of climate variations and changes on forest stands, the specific composition of the tree stratum and/or genetic diversity of which may have been impoverished by simplified management that focused on a reduced number of species and, through certain forest management choices, especially in forests with very varied ecological niches. The effects of forest management interventions on the genetic diversity of forest trees are known although insufficiently documented (Valadon, 2004).The adaption process, including the genetic diversity creation and erosion phases, interacts with environmental conditions, climate change and also management (Lefèvre and Collin, 2009).

BOX 2.3.1. PILOT TEST TO STUDY THE IMPACT OF CLIMATE CHANGE ON THE PIRENEAN MOUNTAIN FELLS

An experience conducted in 2010-11 in summer grazing in Pierre-Saint-Martin (Pyrénées-Atlantiques) allowed to analyze the interactions between, on the one hand, the drought due to the combined effect of a climatic change and anthropic disturbances and on the other hand the moderating role of biotic interactions. This experimentation was used to modulate precipitations, simulate mowing and test different competitive situations. The results show the importance of interactions between species as a preponderant factor in diversity. These interactions can be inhibited by a high level of water hydric stress and disturbances. However, the decrease in rainfall on the northern side is not obvious and it should be noted that, according to Le Treut (2013: 230), most research work has focused *"solely on the effects of a rise in temperatures, or eventually a decrease in rainfall"*, which is not necessarily the trend observed for the moment in certain sectors of the mountain chain.

2.3.4 Changes in the composition and interaction of species in the ecological community

Changes in the distribution areas of species is one of the announced effects of climate change through the contraction, displacement or extension of areas according to the specific characteristics of the species and those of the environments they occupy. Contraction and displacement may lead to the local extinction of certain species at all altitudes, in particular through the disappearance of ecological niches at high altitude levels (Colwell et al., 2008; Bergamini et al., 2009; Thomas, 2010; McCain and Colwell, 2011), a phenomenon which furthermore probably shaped the current floristic composition according to past climate variations. The complexity of ecological factors in mountains means that compensation phenomenona may counter these forecasts (cf. for example, the effect of thermal inversions in deep valleys). Furthermore, "species" approaches are often reductive, overlooking ecological knowledge (Austin, 2002; 2007) and do not take into account interactions between species and the functioning of communities or the role played by genetic diversity. Indeed, many studies envisage possible responses such as changes in competition between species which will allow some of them to persist or even migrate downwards despite climate change, whereas others will migrate to higher altitudes (Lenoir et al., 2010). In mountain massifs where the effects of climate change on the flora and vegetation have been studied, the general trend shows an increase in the number of plant species requiring heat to the detriment of those requiring colder conditions (a phenomenon called thermophilisation, Holzapfel and Vinebrooke, 2005) but with a great variability in response according to massifs and even locally in the same massif (Gottfried et al., 2102).

Snowbed plant communities, composed of a specific flora, such as Salix herbacea (Salix herbacea L.), are particularly sensitive owing to the very selective soil conditions and the microclimate of these environments (Grabherr, 2003). Snowbeds are, without a doubt, the natural alpine habitat where microclimatic conditions may change the quickest (Grabherr, 2003; Heegaard and Vand-vik, 2004). In the case of a warming scenario with an earlier thaw season, we may see an extension of the vegetation period, desiccation, increased biological soil activity and the exposure of vegetation to colder temperatures (Baudière and Gauquelin, 2005). These effects would contribute to the evolution of the environment, it becoming occupied by other less specialist and more opportunistic species (or speices more resistant to the cold). In the opposite case, an increase in the average duration of snow cover or frost would shorten the vegetation period, which is already very limited, and modify the composition or structure of it (Braun-Blanquet, 1948 ; Eynard, 1978 ; Corriol and Mikolajczak, 2014). Alpine snowbed vegetation, which is mainly perennial and adapted to the context, is nevertheless able to integrate very large inter-annual climate variations and react to trends in the long-term. The reproduction performances of the species concerned may be affected more than their phenological cycle (Lluent et al., 2013). The monitoring of snowbeds implemented in the framework of the OPCC-1 programme has been continued through the FLORAPYR programme (14 sites in 3 countries: Spain, France and Andorra, Komac and Olicard, 2014). The plant inventories and the annual measurements of phenology and temperatures implemented since 2011-12 do not yet provide trends for inter-annual variations. The research will be completed by additional work and, in particular, the setting up of warming simulation units (setting up of Open Top Chambers at four sites).

BOX 2.3.2 GLORIA: THE INTERNATIONAL INITIATIVE FOR MONITORING ALPINE FLORA.

Currently, more studies are carried out on the fauna (birds, butterflies, dragonflies, and pollinating insects) than on the flora and vegetation (Le Treut, 2013) (more information in chapter 2.2.3). The alpine vegetation is particularly sensitive to environmental changes and may respond to climate variations. The international plan GLORIA aims to study the evolution of the alpine flora thanks to a protocol deployed throughout all alpine mountain areas around the world. This plan includes six floristic tracking sites in the Iberian Peninsula, two of which are in the Aragon Pyrenees. (Pauli et al., 2004). The first analyses between the implementation of the initial inventory (2001) and the first tracking (2008) showed an average elevation increase of 2.7 m for European alpine flora during the period considered, with major differences between the mountains under Mediterranean influence, which lost species (-1.4 on average) and northern European massifs which generally gained species (+3.9 on average) (Pauli et al., 2012). This result does not appear to contradict the thermophilisation hypothesis, and only southern mountains lost species under the effect of summer drought (Moncorps, 2015). Such a measure is designed to be monitored in the long-term in order to confirm or refute the trends. Furthermore, the measurement cannot be analysed on the level of each massif due to a lack of sufficient sampling. For the Pyrenees, it will be completed by two new sites set up in the frame of the FLORAPYR programme. Finally, the monitoring of temperatures at Gloria sites provides long-term information about the duration of the vegetation season in the alpine zone which will be interesting to compare with data collected at snowbed monitoring sites.

Currently, at the Pyrenees level, Le Treut (2013) notes that *"no analysis appears to allow quantitative estimations of the extinction risk for species faced with climate change"* and deems that *"such forecasts remain out of reach in view of current modelling capacities and the type of data available or collectable"*. A first attempt to identify species sensitive to climate change in the Pyrenees was carried out in the frame of the biodiversity section of the OPCC1 project with an initial list of about 80 plants (see executive report OPCC1). This approach needs to be reinforced. The implementation of the Red list of the Pyrenees flora in the frame of the FLORAPYR programme should introduce a sensitivity to climate change criterion (implementation 2018-2019, methodology: UICN, 2012, criteria A3, A4 or B2(b)) but this would be difficult to define in view of the uncertainties concerning climate scenarios.

It is often believed that the current upper limit of the forest will probably rise under the effect of climate change and that this may constitute a threat for pastoralism with the development of forests in summer grazing land. It should be recalled that forests have reached higher altitudes in the past in the Pyrenees: signs of forestry activities in Ariège in the Middle Ages can be found up to about 2,200 metres (Bonhote et al., 1988). The taking into account of the abandonment of pastoralism shows that it is a Key factor in the rise in attitude of these trees and the upper limit of the forest (Bodin, 2010). Furthermore, possible internal changes in the composition of forests at medium altitudes have been studied very little (for example, the conquest of fir trees in mountain beech forests in sectors where it had declined as a result of use [Galop & Jalut, 1994]). Work in the Alps has shown that the forestry dynamic produces a clear displacement of trees species upwards under the effect of the closing and maturing of medium altitude forests (Bodin et al., 2013).

At low altitude, studies on beech trees showing a rise in altitude of the optimum level for growth (Vitasse et al. 2010) ultimately point at local extinctions at low altitude at the foot of the north-western Pyrenees, as already seen in Catalonia (Grime, 1973; Jump et al., 2006). However, the rise in the optimum level for growth does not necessarily imply the extinction of populations. The case is known for beech trees that do not reach the dominant level of mixed forests in situations of pedoclimatic stress[20] without this necessarily meaning they become extinct if forest farming is sufficiently extensive. In the foothills of the French central Pyrenees, paleoecological and historical studies bear witness to the presence of fir trees in large numbers in Neolithic times in Volvestre, of their regression from Antiquity onwards under the effect of various uses (land clearance, agro-pastoral pressure, intensive farming), whereas nowadays they show a high capacity for colonisation (Gonin et al., 2014).
The development of invasive exotic plants in the mountains already occurred over the past several decades in favour of works, reforestation and displacement (human and work machinery), even the abandonment of pastoralism (as in the case of the Norway spruce), with possible effects on landscapes, the functioning of ecosystems, certain supply services (pastoralism, ski areas where a species such as the Norway spruce closes the landscape of the French central Pyrenees). It has been shown that cold environments are less subject to biological invasions than hot environments, and climate change may accentuate this phenomenon according to the parameters concerned (Pauchard et al., 2016; Gallien et al., 2016) . The CENMA has studied the evolution of potential ecological niches of Buddleja davidii and Senecio inaequidens in Andorra under the effect of climate change over the past century. The results show that depending on the scenario, between 10 and 70% of the territory may be climatically viable for both plants (10-40% for *Buddleja* and 30-70% for Senecio, according to the study).

(20) Physiological stress related to soil and climate conditions alleviated by cover by other varieties.

2.3.5 Vulnerabilities and ecosystemic services

The ecological functions of ecosystems provide support services, regulation services, supply services and cultural services. Below, we outline the services rendered by the flora and vegetation which may be affected by climatic change (Moncorps, 2014) with a focus on a few elements of vulnerability (Moncorps, 2015). The role of vegetation in support services is visible in the water cycle, biomass production, the nutrients cycle, the formation and maintenance of soil and the habitat for biodiversity.

Regulation services concern:

- The regulation of the water cycle, erosion and natural risks, as well as the maintenance of snow cover through permanent plant cover adapted to the bioclimatic context. The pressures arising from use and development, climatic pressures and even the choice of species in the restoration of certain environments may affect these services;

- The regulation of water quality;

- The regulation of air quality;

- The regulation of climate and carbon capture: apart from the recognised traditional function of forests (with a capture capacity three times greater for mountain forests than for forests in the plain), medium altitude mountain pastures and peatbogs also constitute carbon sinks;

- The pollination by pollinating insects being favoured by landscape diversity (mosaic of environments[21]).

Supply services correspond to goods that are sold and that provide a source of revenue and employment: the production of timber (relatively limited in the Pyrenees owing to the operational difficulties related to natural constraints), the pastoral value of grassy environments, the importance of the area for certain leisure activities (ski areas), the value of food gathering plants (pharmacology, cosmetics, herbal plants, liquors, etc.).

BOX 2.3.3. THE ECOVARS INITIATIVE FOR THE ECOLOGICAL RESTORATION OF HIGH MOUNTAIN MEADOWS.

In the French Pyrenees, the Ecovars ecological restoration programme in high altitude grassy environments (Malaval, 2015) (ski areas and roadsides) aims to maintain or restore these services thanks to an improvement in intervention techniques and the use of local plant material backed by a trademark (Pyrégraine de néou). Similar approaches are being developed in Andorra and Aragon.

Production of a crop of *Achillea millefolium* L., of purenean origin for an ecological catering use in the Pyrenees. Photo CBNPMP/Gérard Largier

Cultural services concern:

- Leisure and tourism: the identity and tourism attractiveness of the Pyrenees is based on the landscapes and their wild appearance, in which plants play an important role (relatively paradoxical when you realise how human activities have shaped this area) as well as its emblematic species (endemic flora in particular): beyond the general public, the Pyrenees and its diversity have also attracted scientific tourism for many years;

- Educational value and scientific knowledge; this concerns in particular the characteristics and specific floristic features of the massif;

- The identity, heritage and artistic (aesthetic) dimension in which the floristic elements also play an important role.

(21) The mosaic of environments or landscapes refers to the natural areas managed by men which vary in terms of size, form and order.

On the subject of the habitat offering for biodiversity, one question regularly recurs, namely *"how are protected species able to contribute to the preservation of biodiversity and mountain areas"* (Le Treut, 2013) in a context of climate change? The aim is to understand whether sensitive species and ecosystems will be able to survive in zones often considered to be climate refuges although they have not been defined on the basis of such a criterion and will be equally subject to climate change if it occurs. One question concerns ecological continuity between these different areas and the possibility of maintaining the flow of genes and migratory routes. Here again, research is generally based on "animal species" models, with experts not necessarily agreeing about their representativeness for the territories under consideration (lack of reference studies for mountains). Some mangers of protected areas have set up programmes on ecological continuity in the frame of "climate plans" (Pyrenees National Park, Ariege Regional Nature Park, Pibeste-Aoulhet Massif Regional Nature Reserve).

2.3.6 Findings and recommendations

In the "Mountains" chapter of the "Les impacts du changement climatique en Aquitaine – un état des lieux scientifique" report, Le Treut (2013) proposes *"some general solutions with degrees of operationality and ethical realism to be confirmed, for adaptation or mitigation adapted to mountain ecosystems and species faced with climate change"* which may apply to all the Pyrenees and which we will complete on certain aspects:

"Re-evaluate the management goals in light of the challenge of climate change and reduce local anthropic systems as far as possible which represent factors that may alter the ability of biodiversity to adapt to general changes (fragmentation, pollution, etc.). Use the diversity of local forest genetic resources to reinforce the ability of forests to adapt to climate change." However, we will stress that the revaluation of the management objectives remains complex in view of the uncertainties that weigh on climate scenarios, in particular with regard to the evolution of rainfall and snow cover. For the management of genetic resources, which also concerns open non-forest environments, we recommend an approach at a local level.

"Maintain traditional land uses where they have constituted the main form of management by ensuring original missions in harmony with the preservation of historic crops and local traditions. Protect the traditions and cultural heritage associated with the territories that are best suited to guaranteeing the preservation of specific local diversity and sensitive ecosystems (pastoralism, etc.)".

"Promote original initiatives which associate "low pressure in terms of management" and the "creation of spatial heterogeneity". For example, as in northern European countries, it appears to be essential to continue to cut grass and graze the most mesophilic grasslands in order to avoid invasion by competing species which greatly threaten the diversity of communities and landscapes." However, "low pressure" and the "creation of spatial heterogeneity" are contradictory and, furthermore, the creation of heterogeneity is not an end in itself if you consider the extensive and relatively homogeneous ecosystem which the boreal forest represents.

"As a priority, preserve the essential ecosystemic characteristics (those that determine the intrinsic structure and functioning) and protect species (in particular Keystone species) the best suited to adapt and act as a source for any form of recovery[22] [Preserve species identified as redundant ("doubles") in such a way that in the case of a local disruption at least one of them subsists. Protect variables (species resources) that are able to act as buffers with a persistence rate adapted to climate change (Baron et al., 2009)".

"Recognise and improve missions for protected areas. Preserve zones identified as "refuges", for example, development localities for populations of rare or threatened species or stations less likely to be concerned by climate change. These zones may be used as sources for repopulation or as target zones for establishing transplanted populations." They should be subject to a prior inventory of past introductions of plant material (especially forest material) in order to identity sectors free of non-native genetic sources. The preservation of these refuge zones should include measures concerning invasive exotic species.

"In the most extreme cases, for the most severely affected species, some mitigation strategies recommend 1) the maintenance and reproduction in captivity[23] of species at high risk of extinction and/or 2) the translocation (assisted migration) of populations,

(22) Resilience
(23) Or in a seed bank.

the displacement of organisms from one zone to another, separated by a barrier (urban, developed, etc.)."

"Despite the positive effects expected for biodiversity in terms of climate change mitigation as a direct result of the reduction of GHG emissions, some authors (Araújo et al., 2011) call for a change in paradigm in conservation policies and the deployment of more effective approaches than those currently implemented: requalification of existing conservation areas, creation of new zones and development of more operational integrated management mechanisms that facilitate connectivity between conservation zones and their vertical (altitudinal) and horizontal dimensions". This implies a study and an organisation at the Pyrenees level.

The Findings of the "Mountain" chapter in the Le Treut (2013) report converge with those of the "3^{e} rapport of climate change impacts and vulnerability in Catalonya" (Martín-Vide, 2016). Whilst reporting on the results of scientific works which identify impacts attributed to climate change, it presents the same type of reserves (lack of reliable scenarios or uncertainties on the impacts related to the imprecision of scenarios, research that is often preliminary, variability according to local situations) and stresses the need for research and monitoring. Whilst highlighting the interest of models, Le Treut (2013) recommends, in particular, "taking care not to generalise too quickly observations or experiments implemented in specific contexts" and "to differentiate between work which is based truly on measures and field work and that (often more abundant and at too wide a level) which is based solely on models." We will recall the classic example of the ascendance of forest varieties for which the climate motor may have appeared obvious whereas other non-climate related measures were initially actually responsible for this.

In terms of studies and monitoring of biodiversity and flora, the work of the OPCC in general and that of the FLORAPYR programme in particular should be taken into account in the long-term beyond the period of these specific projects: measures such as the monitoring of snowbeds, GLORIA, or the participative science programme Phénoclim require long implementation periods before producing analysable sets of data in relation to the climate data observed. The on-going consolidation and updating of the Atlas of the flora of the Pyrenees, also introduced in the frame of the OPCC, will allow us to benefit from an up-to-date and useable inventory for implementing a cross- analysis of data. Finally, it will be necessary to devise other measures designed to monitor the genetic evolution of plant populations in preserved sectors of exogenous incomers or, on the contrary, in sectors where non-native plant material was introduced many years ago and has developed in interaction with the local flora (as in the case of the introduction of other species of Mediterranean fir trees [complex of species] in the Bagnères-de- Luchon valley, in the Pyrenean fir plantation (introgression with Abies Alba). Such measures would be useful for explaining certain adaption choices which often lead to the introduction of species whereas the local flora and natural ecosystems may be the solution in an evolving context.

2.4 Forests

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ABSTRACT

Forest land covers 59 % of the surface area of the Pyrenees mountain range and represents a natural renewable resource, a set of ecosystems rich in biodiversity, exceptionally popular tourist zones and visitor attractions, a form of protection against natural phenomena (avalanches, large rock falls, flooding, etc.) and a large natural reserve of CO_2. The landscape, the diverse types of exposure, the Atlantic and Mediterranean climatic influences and the diversity of its geological layers combine to create a wide variety of conditions for growth (FORESPIR, 2007). Mountain forests have been undergoing significant changes for several decades already, due to a range of social, economic and environmental factors (Ameztegui et al., 2010) but the climatic, biological and social conditions in which forests are poised to develop in the future remain largely unpredictable. Local climate models predict a rise in temperatures and hardly any change in terms of annual cumulated average rainfall. However, the main models predict a sharp rise in seasonal rainfall variations leading to an overall trend of increasingly intense periods of drought, especially in winter and summer. Aside from any human intervention, these climate changes may have an impact on Pyrenean forests, in particular by increasing soil dryness during the summer (Aussenac and Guehl, 2000; Bréda et al., 2006) and by modifying the pattern of certain disturbances (pests, wildfire, storms). In parallel, the new climatic context may logically lead to an increase in the growth rate of trees due to a longer growing season and increased photosynthetic activity. In addition to the potential impacts of climatic modifications on the trees and forests themselves, it is important to take into account the foreseeable consequences on the numerous functions and ecosystemic services performed by mountain forests. Climate change can indeed have a serious impact on the diverse functions of Pyrenean forests by causing dieback in forests used for production or protection, the destruction of certain notable species and habitats and a deterioration of the forest landscape.

2.4.1 The potential impacts of climate change on the diversity of plant communities and the distribution of forest species.

Recent social and economic changes in rural areas, which have revolutionised the way land is used with unprecedented speed, combined with the reality of climate change - which no longer leaves any room for doubt - constitute the main drivers of climate change in the Pyrenees (Garcia et al., 2016). However, it is widely acknowledged that there is growing uncertainty about the climatic, biological and social environment, and it is within this context of uncertainty that our future forests are poised to develop – Pyrenean Mountain forests included.

Changes in the diversity of plant communities

Although in most European mountains, pasture abandonment has given rise to afforestation, the interaction between farming land and pasture abandonment processes, their transformation into forest landscapes or bushland and climate change (Ameztegui et al., 2016) or ecosystemic services such as biodiversity or CO_2 sequestration (Montané et al., 2007; Garcia-Pausas et al., 2017) remains largely unknown. A recent study of modifications in the vegetation cover of the Aragonese Pyrenees between 1957 and 2007 revealed a significant revegetation process characterised by the spread of bushy vegetation layers followed by forest (Lasanta and Vicente-Serrano, 2007). These authors conclude that the changes in vegetation which occurred during the past 20 years have contributed in some cases to an increased homogeneity of the vegetation cover, and in other cases have given rise to increased heterogeneity. Homogeneity occurs mainly in pre-existing forests, which become denser when farming activities cease, while increased heterogeneity is observed on abandoned land which has extremely varied types of vegetation cover depending on the period during which the land in question ceased to be farmed, the type of forest management put in place as well as natural conditions.

However, changes in natural habitat and biodiversity depend on the natural dynamics of the species found there (Garcia et al., 2016). A comparative study of the communities in the ecotone between alpine pastures and the forest's uppermost treeline between 1998 and 2009 revealed that a significant increase in tree cover of between 20% and 35% had not been sufficient in the medium term to bring about a significant change in the diversity and composition of alpine and subalpine plant species (Pardo et al., 2013 in Garcia et al., 2016). Likewise, supra- forest pastures do not yet appear to have been affected by the considerable transformations in their biodiversity, in contrast to the changes observed in certain pastures on south-facing slopes with a steep gradient, where the process is more dynamic. However, other studies, such as that conducted in the Ordesa and Monte Perdido National Park, paint a worrying picture of changes in the biodiversity of alpine communities (Pauli et al., 2012). According to the findings of this study, the pastures show a high degree of naturalness and a wealth of flora that is nonetheless conditioned by low temperatures. This makes them particularly vulnerable to global warming, with species suited to cold weather being replaced gradually by other thermophilic species (Gottfried et al., 2012). The average spread of their distribution has been estimated to be 2.7 m. on the European mountain peaks (Pauli et al., 2012 in Garcia et al., 2016).

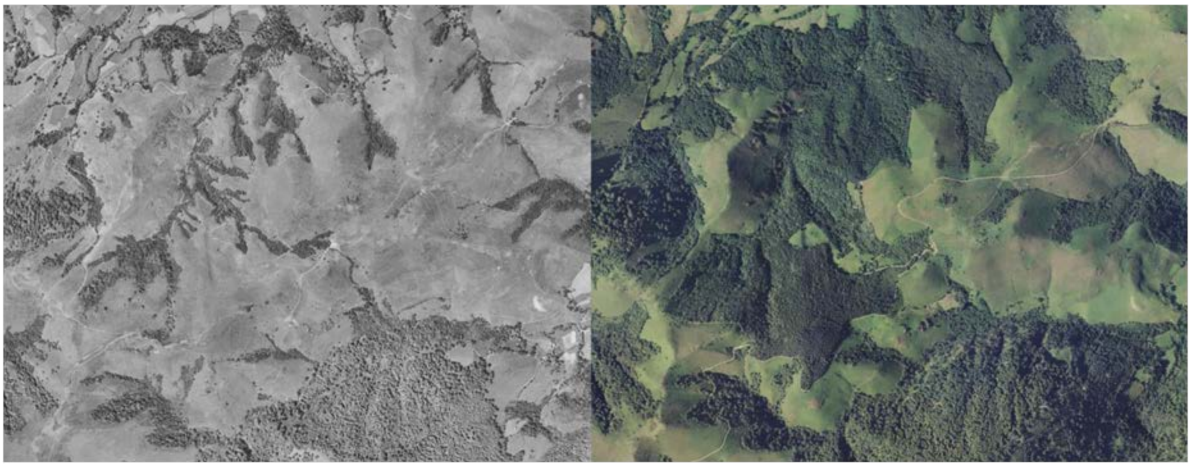

Figure 2.4.1. Example of the spread of forest cover on farming and pastoral land between 1959 and 2016 in the French Atlantic Pyrenees region (district of the Basque mountains). Source: IGN

Figure 2.4.2. Example of the spread of forest cover on farming and pastoral land between 1945 and 2017 in the Belagua valley (Navarre). Source: Navarre regional information system

Changes in the altitudinal distribution of forest species

Plant species are not generally distributed in a uniform manner. They are restricted to certain specific geographical areas in which they have been able to grow or which they have succeeded in colonising over time, helped by biotic and abiotic conditions that favour their growth and reproduction (Matias, 2012). However, significant changes in the way land is used, together with the climate changes observed at a global level (IPCC, 2007), are altering these conditions, leading to phenological changes, an increase in the populations of several species or a modification of their natural dynamics (Matias, 2012).

In Europe, the uppermost treeline and the alpine area are in the process of shifting towards higher altitudes. In the case of trees, shifts to higher altitudes must be analysed with caution, because they may be related to pasture abandonment in the uppermost regions; the lack of any cultivation in these pastures paves the way for the return of forest vegetation to these areas now left free. This in turn leads to a return to the natural upper treeline, such as it existed before human activity intervened. In a recent study conducted on the southern slopes of the Pyrenees, an average displacement of the uppermost treeline of 35 m. was observed over the past 50 years (Ameztegui et al., 2016). In addition, it was demonstrated that the majority of plant species found in the forest areas of the French Alps have shifted to higher altitudes (Lenoir et al., 2008): the beech to Spain (Penuelas and Boada, 2003) and seven tree species to Scandinavia (Kullman, 2002).

Other studies have concluded that the shift to higher altitudes of certain vegetation layers could reach 700 m. if the predicted 4°C average temperature rise occurs (Courbaud et al., 2010). However, few studies have focused on the responses to climate change demonstrated by biological communities along the entire altitudinal gradient of the mountain ranges, where one would expect ecological diversity to be on the decline (Regato, 2008). Comparison of the historical floristic inventories of the different European mountain ranges emphasises the fact that this migration to higher altitudes of the uppermost treeline is affecting alpine pastures and in particular rare or specialised species (Rixen and Wipf, 2017).

It is important to note that studies already carried out in France (Badeau et al., 2005; Piedallu et al., 2009; Cheaib et al., 2012) and Spain on the possible effects of climate change on the future distribution of varieties or their vulnerability usually concern the national or regional scale; consequently, the Pyrenees are a marginal aspect of the regions analysed, meaning that the models produced are probably less valid than in other areas, and the findings less relevant and more difficult to exploit. Modelling of the potential distribution of four forests of mountain pines (Pinus uncinata) in the Catalan and Andorran Pyrenees for the years 2020, 2050 and 2080 based on various climate change scenarios (A2 and B2) suggests that these forest formations will, by 2080, have optimal bioclimatic zones located at higher altitudes than those observed at present. Such forests would reach average altitudes of 2472 m. in the case of scenario A2 (scenario based on a probable global temperature rise of +3.4°C for 2090–2099 compared with 1980–1999) and an average altitude of 2340 m. in the case of scenario B2 (scenario based on a probable global temperature rise of +2.4°C for 2090–2099 compared with 1980–1999). This also increases the possibility of a partial shift of some bushland areas and alpine pastures to higher altitudes (Pérez et al., 2011; Martínez et al., 2012).

On the other hand, these subalpine forests might be less affected by an overall decrease in their surface area than alpine grassland and alpine and subalpine bushland areas. It has indeed been estimated that the latter may lose up to 90% of their potential distribution area in the case of scenario A2 and 70 % in the case of scenario B2. The forest stands located in areas that receive rainfall (such as fir and spruce forests for example), could be threatened with destruction due to increasingly frequent periods of drought, higher temperatures and the effects of previous forest management practices (Camarero et al., 2011).
In Aragon, in the Ordesa and Monte Perdido Natural Park, an expansion of bushland and forests has been observed, at the expense of supra-forest pastures. This phenomenon leads to the rapid colonisation of medium-altitude hay meadows by Scots pine (Pinus sylvestris). At higher altitudes the colonisation process is slower and was characterised by gradual 55"densification" throughout the last century, caused by pasture abandonment and accentuated by global warming (Camarero and Gutiérrez, 2004).

Findings

The studies available suggest that the two main drivers of change (climate and land use) have a major influence on the composition and structure of forests and their uppermost limits. They also tend to show increased densification of vegetation, due mainly to a decline in forest activity and an end to farming and pastoral activities in the pastures and hay meadows in mountainous and subalpine areas. This then leads to recolonization by bushland followed by forest. These changes could alter biodiversity. The natural habitats of rare and specialised alpine floristic and faunistic species will be most dramatically affected by the progression of habitats currently located at lower altitudes. Analysis of the scientific literature available suggests, however, a high degree of spatial and temporal variability in terms of processes and highlights the fact that the changes observed do not always follow the predictive models.

2.4.2 Changes in the productivity of forests and the role of forests as carbon sinks

The productivity of a forest stand is defined by the increase in biomass output per hectare. In order to grow and thrive, trees need light, carbon dioxide and oxygen, water and nutrients contained in soil. This productivity is also conditioned by a certain number of endogenous factors specific to the stand (structure, density, composition, etc.) and its position (soil depth, orientation, altitude). In trees' natural life cycle, productivity increases rapidly during the early development years then peaks, and starts to decline gradually in the senescence phase (Ryan et al., 1997).

During the 20th century, and particularly in the second half, we observed a considerable, widespread increase in the productivity of European forests (Spiecker et al., 1996) due to a series of favourable factors such as a rise in temperatures, increased carbon dioxide concentration and nitrogen fertilizer, caused notably by pollution of anthropogenic origin (Nellemann et al., 2001; Kahle et al., 2008 and Solberg et al., 2009; Bontemps et al., 2011; Bontemps et al., 2012). The earlier arrival of warmer temperatures and the advent of warmer autumns and winters modify trees' annual development cycle by increasing their growing period. However, excessive temperature rises combined with limited water supply and aggravated by increasingly frequent periods of severe drought can have a negative impact on tree growth. During these episodes, certain varieties adopt avoidance strategies by regulating their photosynthesis so as to reduce their evapotranspiration (closing of the stomata). In this context, Soubeyroux et al., (2012) analysed the impact of climate change on the occurrence of drought periods in France and found that "even if there is no change in meteorological drought periods, a higher frequency and intensity of extreme events related to lack of moisture in soil is to be expected as early as the first half of the 21st century." Certain studies have already shown that the occurrence of these extreme phenomena related to climate disturbances can have a significant impact on the productivity of forests (temperatures, periods of severe drought, wildfire, attacks by pathogens and diseases) (Bréda and Badeau, 2008). In areas where certain species are already at the limit of the distribution area (beech, Scots pine and fir in the Mediterranean region, for example), a decline in growth and dieback have already been observed due partly to lack of water and very high summer temperatures (Jump et al., 2006; Charru, 2012; Camarero et al., 2015).

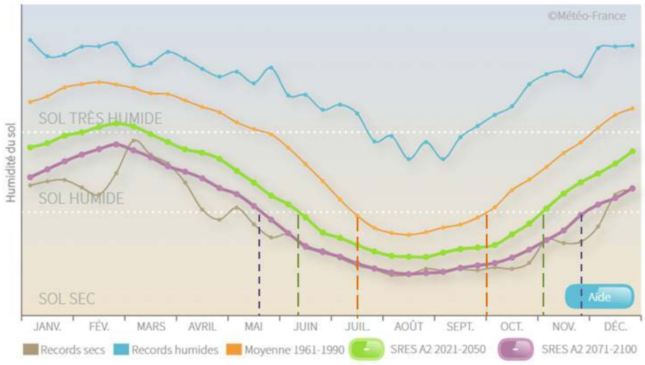

Figure 2.4.3. Annual soil moisture cycle; 1961 average, climate records and simulation for two time scales. Source: Météo France.

Given this scenario, we place hope in the ability of forest stands to adapt to changing conditions. The assumption is that if the disturbance does not exceed a given threshold, the overall forest stand will be able to "absorb a highly disturbing change without altering its fundamental state" (concept of resistance; Gunderson, 2000 in Charru, 2012) or, in the aftermath of the disturbance, it will return in the short or medium term to the state in which it was before the disturbance occurred (concept of resilience; Dobbertin, 2005). This resilience faculty depends on the duration and frequency of the disturbance, as well as the species affected (Manion, 1981; Dobbertin, 2005 in Charru, 2012).

Therefore, if the amount of CO_2 in the atmosphere remains at the current level, we can make several major assumptions regarding the productivity of forests:
In areas affected by rising temperatures but which do not suffer from any notable water shortages (since changes in rainfall are very difficult to predict), we can expect to see an increase in the productivity of forests,
In areas affected by rising temperatures and reduced rainfall (or, at the least, a change in rainfall patterns in terms of frequency), we can expect to see a reduction in the productivity of forests; this possibility must however be considered in the light of the soil's maximum Available Water Capacity (AWC[24]).

In all cases, the repetition of extreme phenomena will weaken the stands and, if the tolerance thresholds are exceeded, may lead to dieback causing a decrease in the amount of standing timber available.

In addition to climatic factors, the productivity of forests is strongly linked to the trees' ability to absorb and store carbon dioxide (CO_2). Absorbed by the stomata in leaves, the CO_2 in the atmosphere combines with water and energy from sunlight to produce cellulose, starch and other components required to form wood, bark, roots and leaves. Consequently, the more the tree develops, the more carbon it will store (we consider that 1m3 of wood consumes 1 tonne of CO_2). Storage of carbon dioxide in the French forest ecosystem – hardwood and softwood forest, dead wood and soil – represented 80 million tonnes of carbon dioxide per year in 2013, i.e. almost a fifth of the country's total greenhouse gas emissions. Forest soil plays a particularly important role, given that it accounts for 57% of CO_2 in the forest ecosystem (Dupouey et al., 2002).

Absorption and sequestration of carbon dioxide by the forest and soil are therefore essential mechanisms by which we offset the progression of climate change. Yet, there is a high degree of uncertainty regarding the phenomena caused by climate change and their potential impact on the forest and its ability to absorb and store CO_2 (storms, droughts, wildfire, diseases, etc.). Forest management and the wood industry play an important role in mitigating the effects of climate change by helping forests to adapt and by continuing to store CO_2 in forest ecosystems, while at the same time providing sustainable material that enables the long-term sequestration of this carbon dioxide in wood-derived products. Finally, this wood can be used as a substitute for other materials and energy sources that emit higher volumes of greenhouse gases. Several projects aimed at enhancing our understanding of the role played by the forest-wood industry in offsetting climate change via the storage of CO_2, and how to optimise its efficiency, have recently been conducted. To cite just one, a recent study led by the Frrench IGN (National Geographic Institute) and INRA (National Institute for Agronomic Research) (Roux et al., 2017) analysed the impact of 3 possible policy scenarios related to the removal of CO_2 from the stock contained in French forests, depending on whether the stock in question came from the forest ecosystem or energy/material substitution and sequestration of products derived from wood. The three scenarios illustrate the important role played by the forest-wood industry in offsetting greenhouse gas emissions by 2050, a role which could become even more crucial. In the three scenarios, a slight increase in carbon storage capacity was observed; only the distribution of the gas stored in the compartments of the forest carbon differed depending on the scenario. This study also takes into account the three types of disturbances related to climate change that may affect forests (rising temperatures, storms, biological invasions) and – by extension – their carbon storage capacity. Regardless of the type of disturbance, the study concludes that *"the carbon storage capacity of the forest-wood industry between now and 2050 remains positive [...]; it is by actively managing the resource that we will succeed in countering the drop in the industry's capacity to offset carbon emissions".*

(24) The maximum available water capacity (AWC) refers to the maximum amount of water that the soil can hold and make available, and depends on a range of parameters such as the texture, depth of roots, stone content and apparent density. Source: http://silvae.agroparistech.fr

2.4.3 Impact of climate change on the role of forests in mitigating natural risks

In mountain regions, the probability that a natural phenomenon will occur (influenced by the specific weather conditions in this environment) is greater than in any other natural environment. Natural phenomena that are specific to mountain areas are usually triggered by climatic events (rainfall or snowfall, rapid freezing/thawing cycles, periods of intense heat, etc.) and arise on slopes where the social and economic stakes are highest (housing, infrastructure, communication channels, etc.). The level of natural risk will be calculated by taking into consideration two factors: the natural phenomenon in question (type, intensity, return period) and the stakes under threat. As we have seen, forests and natural environments play an important role since they account for a significant percentage of land cover in the Pyrenees mountain range. In fact, if we consider the entire mountain range, forests are omnipresent at altitudes of between 600 and 2000 metres (Villiers et al., 2016). The Pyrenean forest therefore plays an important role by protecting against the natural phenomena that can affect the mountain range (snow avalanches, torrential floods, debris flows, large rock falls and landslides). Forests have the ability to limit the triggering of such phenomena (by stabilising the land through the root system, reinforcing the blanket of snow in areas where avalanches develop, limiting surface runoff, etc.) and to reduce their impact (slowing down, channelling or stopping rock falls and avalanches on slopes of average gradient, etc.).

Figure 2.4.4. Large rock fall stopped by a beech tree.
Source: S. Chauvin, FORESPIR

Analyses of the impact of climate change on the protective role of forests need to integrate two approaches: the natural dynamics of forest environments and the biotic and abiotic risks that can affect them.

Indeed, all the plant formations and tree varieties found in forests do not offer the same degree of "protection" against natural risks. Climate change can therefore have an influence on the way in which vegetation cover will evolve but can also lead to a whole series of factors which do not depend on the natural dynamics of the vegetation, thereby altering the protective role played by forests. As a result, the way in which these forest stands are managed is a Key lever for reducing the risk of natural phenomena and limiting the intensity of their impact on the socio- economic stakes of the mountain range. The characteristics of the vegetation that grows in an area potentially exposed to natural phenomena strongly influence its ability to control an unforeseen event. In this context, the two major parameters to be taken into consideration are a change in the type of vegetation and a change in the dominant tree variety within a forest stand (Villiers et al., 2016). A stable forest dynamic enables the forest stand to adapt gradually to changes while preserving the same tree varieties (based mainly on genotypic[25] diversity and natural selection). In this case, if the forest stand already plays a proven protective role (and based on the hypothesis that natural phenomena and socio-economic stakes will remain as they are), its control over unforeseen events will continue. In contrast, a regressive forest dynamic, together with a regressive herbaceous shift towards land where vegetation is scarce, will seriously modify the vegetation's ability to control an unforeseen event. However, several intermediary dynamics come into play and the predicted evolution of these environments must also incorporate the consequences of human intervention and the role of domestic and wild animal populations, in particular large ungulates, pastoral pressure and their impacts, etc.

Concerning possible changes in the dominant tree varieties as a consequence of climate change, we can make the following general assumptions about the type of successions that might occur:

(25) Genotypic diversity refers to the variety of information in the genetic makeup of a species, contained within each cell of the organism.

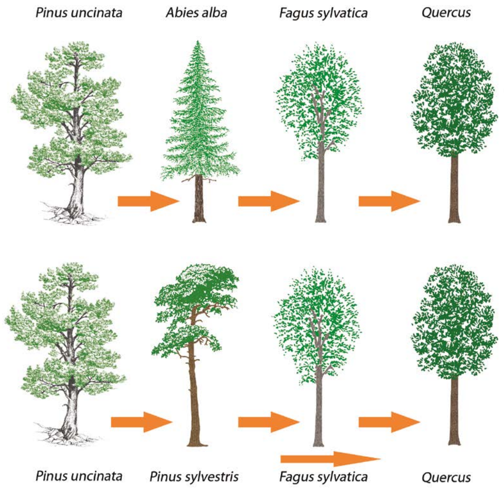

Figure 2.4.5. Possible successions of tree varieties as a consequence of climate change in the Pyrenean mountain area. Source: FORESPIR quoted in Villiers et al., 2016.

However, these potential successions in the forest dynamic are based on the assumption that the previous variety will disappear completely. Yet forests have their own adaptation strategies, both at individual, "short-term" level (via acclimatisation or phenotypic plasticity) and as a whole, in the longer term (via genetic adaptation) (Rozenberg, 2015). Consequently, the increase in terms of risk caused by changes in vegetation will depend partly on how quickly climate changes occur and the amount of time available for trees to implement their adaptation and regeneration strategies to inhabit any ecological niches freed up (Villiers et al., 2016). Beyond natural evolutions in vegetation cover, a second element needs to be taken into consideration if we hope to improve our understanding of the impacts of climate change on our protective forests: the biotic and abiotic risks affecting forest environments. Their occurrence or intensity may be related to climatic modifications (storms, wildfire, droughts, freezing, heatwaves), or biological changes (pests, pathogens, large ungulates, etc.) and have the power to alter the forest's ability to control natural phenomena (independently of the way in which these phenomena evolve in reaction to climate change). Without considering human intervention, these two elements (natural dynamics and biotic and abiotic risks), which are intricately linked to climate changes, have a very strong impact on the role played by forests to reduce natural risks. If forest cover is sufficient, the composition and structure of the stands influence the occurrence and intensity of natural phenomena: for example, since the trunks of hardwood trees are more shock-resistant, their progression at the expense of conifers in mountain areas could improve the degree of protection against large rock falls, while a shift in the habitat of softwoods beyond the subalpine level would help limit the formation of avalanches by making the blanket of snow more stable while simultaneously limiting landslides (INTERREG CLIMCHALP, 2008).

In all cases, the natural dynamics of mountain forest stands are very difficult to predict (because they depend on a multitude of factors that act over a very long period). These changes mean that forest managers have to be particularly vigilant, because they have the power to improve the protective role of forests if they act in a timely way to help those stands whose protective role starts to diminish. In a context marked by an increasingly high level of social demand regarding the protective role of forests, this protective role needs to be backed up by an appropriate diagnosis method and effective forest management recommendations.

BOX 2.4.1 GUIDE TO MANAGING PYRENEAN FORESTS WITH A PROTECTIVE ROLE

The OPCC INTERREG POCTEFA 2007-2013 project led to the creation of a "guide to managing Pyrenean forests with a protective role". The aim of this technical document is to provide forest managers with the means of identifying the forestry itineraries to be implemented if two conditions are met: presence of a proven natural risk and diminished control over unforeseen events by vegetation. This guide applies to the Andorran, Spanish and French Pyrenees and deals with the management of forests that play a protective role against natural phenomena but are not used for production. Its structure provides readers with:

1) a corpus of information about natural phenomena and the role of vegetation,

2) a means of assessing the natural risks in a given area by taking into account the probability of unforeseen events and the stakes under threat,

3) a means of assessing the degree to which the current forest stands control the risk of unforeseen events and,

4) depending on the degree of control, a means of identifying which actions need to be taken in order to guarantee that forest stands maintain a sufficient degree of control over these unforeseen events.

2.4.4 Alteration of the health of forests and possible imbalance with communities of pathogens

Since as far back as we can remember, humans have been concerned about the health of trees and forests, given that wood and forest products are essential resources for our survival (food supply, heating) and development (construction, green chemistry). Later, in the early 1980s, various biotic (attacks by pathogens, etc.) and abiotic (particularly climatic) phenomena led to a gradual deterioration of the state of health of Europe's forests. These phenomena sparked widespread concern throughout society and led foresters to investigate methods for monitoring forest ecosystems.

European network for systematic monitoring of forest ecosystems

Although several ideas were explored, in the 1980s, the idea of a structured network for monitoring the state of health of our forests began to take root. Several European countries acquired this type of network at the same time, leading to a European proposal in 1986 based on the merger of similar national schemes within each country into a European network for the systematic monitoring of forest ecosystems (Nageleisen and Taillardat, 2016).

As a result, for the past twenty years or so, we have conducted an annual survey of the health of trees in over 5000 plots in Europe. This network has two levels reflecting the complexity and completeness of the parameters monitored:

• Level I: systematic statistical monitoring of plots marked out with a square mesh of 16 km x 16 km;

• Level II: more precise monitoring of certain experimental plots concerning a set of dendrometric[26], health-related, ecological, environmental, meteorological parameters and more... in order to understand the influence of the parameters in relation to one another.

Focus on the Pyrenean mountains

These plots enable us to conduct an annual review of the health of trees within a predetermined zone and draw attention to any regional trends or trends affecting certain varieties. Several parameters are studied: defoliation, discoloration of foliage, branch mortality and tree mortality. Due to recent changes in measuring protocols, concerning discoloration of foliage and branch mortality, we only have access to comparable historical data going back to 2011, which is not sufficient to confirm any trends in the way these parameters are evolving.

The most telling parameter used as an indicator of the effects of climate change on forest stands is therefore defoliation. In stressful situations, trees lose some of their offshoots. They can recreate these offshoots (resilience) by developing latent buds[27], if exposed to more favourable climatic conditions (Drenou, 2012).

	Nivel I	Nivel II	Total
Andorra	11	3	**14**
España	98	4	**102**
Francia	45	7	**52**
Total	**154**	**14**	**168**

Table 2.4.6. Distribution of plots within the European network for monitoring forest ecosystems in the Pyrenean mountain range.
Source: Rouyer et al., 2014

(26) Dendrometric parameters refer to the measurement of the various physical and quantifiable dimensions of trees (such as their diameter, circumference, height, overall volume, age) and forest stands (such as density, average height, average volume, basal area, average growth).

We have access to a fairly large amount of historical data for this parameter, because it has been monitored since 1997 in the European network for systematic monitoring of forest ecosystems.

Use of this data has enabled us, on the one hand, to study temporal evolutions affecting species and, on the other hand, to identify potential spatial differences in the way forest ecosystems react (Rouyer et al., 2014). Several trends resulting from the analysis performed within the framework of the OPCC INTERREG POCTEFA project on the data collected from the plots that form the European network are starting to emerge (OPCC-CTP, 2013). Although the tree mortality rate remains low (less than 0.5 % / year, with the exception of 2004, in the aftermath of bark beetle (scholitids)[28] attacks which came on top of the 2003 heatwave), several signs of deterioration are starting to become apparent such as defoliation and branch mortality in the upper part of tree crowns (Goudet, 2015).

Data from the Forest Health Department does indeed indicate that defoliation is on the increase, especially in the Mediterranean area (Maaf and IGN, 2016) but also in the Mediterranean part of the Pyrenees (Rouyer et al., 2014; Goudet, 2015).

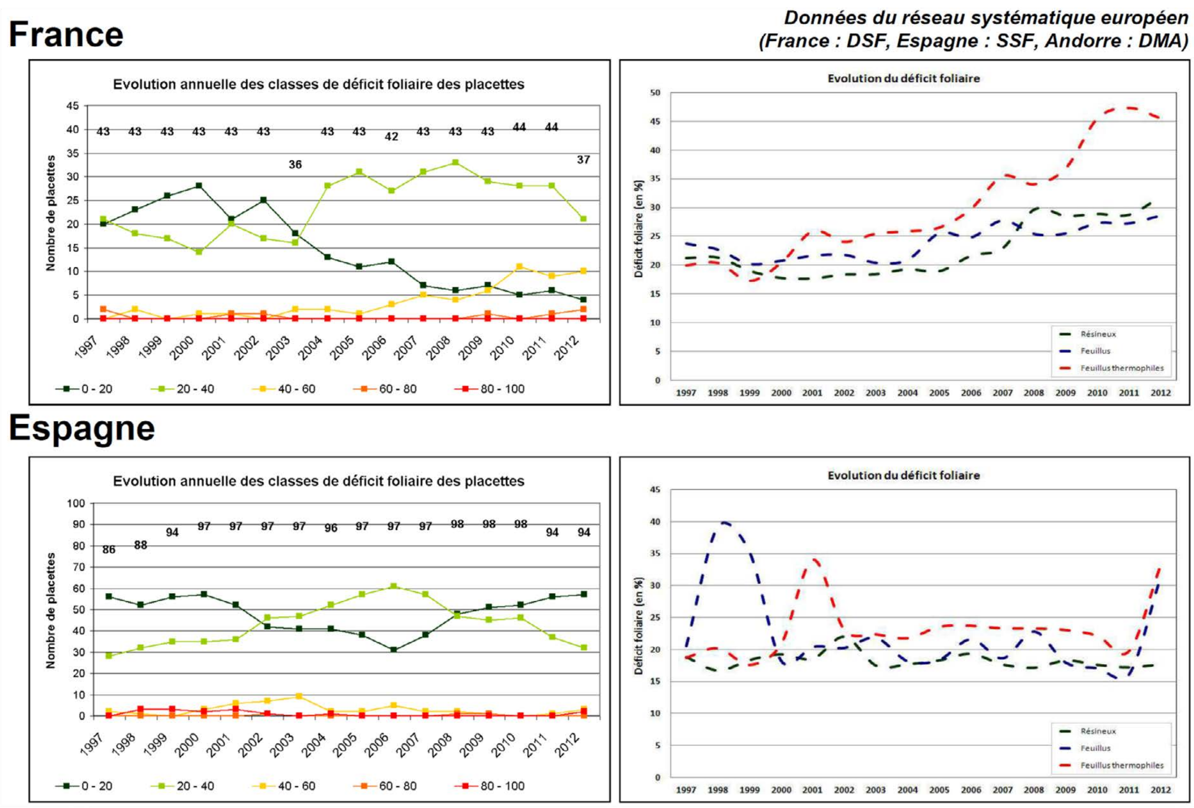

Figure 2.4.7. Changes and trends in defoliation (1997-2012 period) per country and category of tree variety, based on data from the European network database. Source: Rouyer et al., 2014.

(27) Plant bud which does not develop in the year of its formation and which may remain in a vegetative state due to a certain event.

(28) The scholitids are various species and genera of xylophagous coleoptera that participate in the decomposition of dead wood but which can also attack several species of living trees and cause significant damage that can lead to the death of the tree.

This trend has been particularly pronounced since 2000 onwards, and seems to affect hardwood trees known as thermophiles, regardless of whether they are evergreens such as the evergreen oak (*Quercus ilex*) and cork oak (*Quercus suber*) or deciduous trees such as the downy oak (*Quercus pubescens*) or even chestnuts (*Castanea sativa*). The same report shows that over the same period, defoliation levels remained constant for the sessile oak (*Quercus petraea)* and the common oak (*Quercus robur)* and increased slightly for softwoods: Norway spruce (*Picea abies*), silver fir (*Abies alba*), Douglas fir (*Pseudotsuga menziesii)* and maritimepine (*Pinus pinaster*) (*Maaf-IGN, 2016*).

In parallel, the network of correspondents in charge of observing the health of forests provides means of recording the appearance and impact of various pests. Thanks to this network, since 1989 we have been able to observe the growing impact of pathogens such as Diplodia sapinea (*Sphaeropsis sapinea*) on pine trees in the aftermath of drought periods and hailstorms.

By monitoring the life cycles of defoliating insects, we have also been able to show that defoliation peaks are sometimes exacerbated by climatic conditions (armyworms attacking pine trees). Another example is the growing presence of red band needle blight disease (*Dothistroma septospora*) on the edges of Corsican pine plantations in the western part of the Pyrenean mountain range.

Finally, we are being particularly vigilant about the arrival of exotic pests, especially nematode worms on pine trees, which are covered by a European monitoring plan.

Concerns and perspectives

The main explanatory factors that emerge are water supply variables during the current year as well as those recorded during the two preceding years: precipitation and difference between precipitation and evapotranspiration (Ferretti et al., 2014 in Maaf-IGN, 2016). This confirms the prominent role played by climate change and its presumed impact on forest ecosystems in the long term, if the pattern of rainfall and temperature variations alters. In addition to the deteriorating health of trees, an amplification of the dieback phenomenon might lead to a worryingly high mortality rate among certain species that are less well adapted to change, thereby modifying the range of flora found in the ecosystems, with a shift in habitat further northwards or to higher altitudes (Bertrand et al., 2011).

However, we must not overlook the considerable genetic variability of trees, which is an important asset in the context of climate change, or the fact that forest management can help us prepare for the expected changes by adapting forestry practices even now, and modifying our choice of tree varieties for replanting in the years to come.

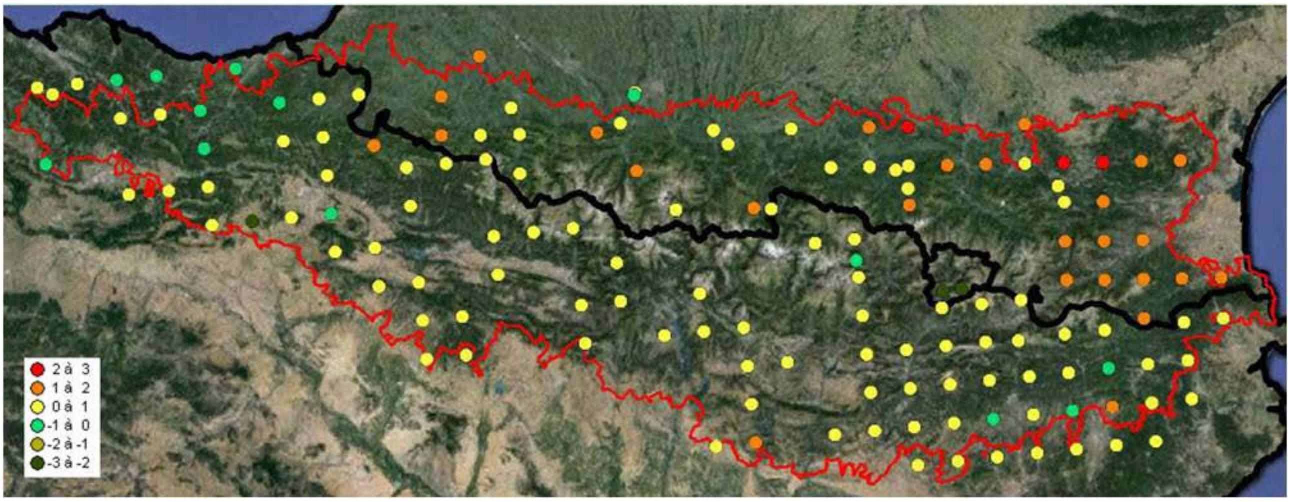

Figure 2.4.8. Slope coefficient of the linear regression of defoliation (1997-2012 period) in the plots within the European network. Source: Rouyer et al., 2014.

BOX 2.4.2. ARCHI, A NEW HEALTH DIAGNOSIS TOOL BASED ON ANALYSIS OF TREE ARCHITECTURE.

Forest dieback is not an irreversible phenomenon. Resilience strategies exist. The ARCHI method bases its diagnosis on characterisation of the process by which a return to a normal situation is achieved, combined with observation of the various physiological and architectural responses. The ARCHI method has been developed over the past few years by the Institut pour le Développement Forestier (IDF) in partnership with the CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) and the DSF (Département Santé Forêts - Forest Health Department).

Its principle is to carry out two series of observations. The first concerns the symptoms of tree crown deterioration (poorer quality of offshoots; mortality, etc.); the second 63concerns the tree crown recovery processes, in particular the development of "gourmands". By studying the balance of power between these antagonistic processes – deterioration and recovery – we are able to produce a diagnosis for the tree. In order to simplify the notion, the number of possible outcomes has been limited to five: healthy tree, stressed tree, resilient tree, tree on the decline and tree affected by irreversible dieback (Lebourgeois et al., 2015).

The ARCHI method can be applied to each tree variety. At present, several varieties already have ARCHI identification Keys (*Quercus robur, Quercus petraea, Quercus pubescens, Abies alba, Pseudotsuga menziesii, Castanea sativa*) and others will be developed and translated into Spanish as part of the INTERREG POCTEFA CANOPEE project (*Fagus sylvatica, Pinus sylvestris, Pinus uncinata, Pinus nigra subsp. salzmanii*).

2.4.5 Impact of climate change on the risk of forest fire in the Pyrenees

The outbreak and spread of wildfire depend on the presence of ignition sources, the continuity of combustible material and its degree of humidity.

Given the specific climatic conditions of mountainous regions and the humidity of combustible materials resulting from those conditions, the Pyrenees have not traditionally been affected by major wildfires. To illustrate this point, in Catalonia, the uppermost altitude above which the probability of wildfire outbreak decreases significantly is situated at 700 metres (Gonzalez et al., 2006). However, at certain times of the year, the number of fire outbreaks, the continuity and volume of combustibles in the Pyrenean region is similar (and in some cases even greater) than in the bordering Mediterranean regions, as is the number of fires started naturally by lightning strikes (González-Olabarria et al., 2015). At present, the vast majority of fires that break out in the Pyrenees are caused by activities related to pasture management operations (González- Olabarria et al., 2015). The decline in farming, which occurred mainly during the 20th century, meant that many pastoral regions in mid- and high-altitude mountainous areas became overrun with vegetation (Améztegui et al., 2010), thereby increasing the quantity and continuity of combustibles. The determining factor in terms of fire outbreak and spread is the water content (humidity) of the combustible material. In this respect, rising temperatures and longer periods of summer drought can increase the amount of combustible material available and the risk of fire, which in turn increases the frequency of so-called "high-risk years" (Moriondo et al., 2006). At present, the vast majority of forest fires in the Pyrenees occur in the winter months, when the colder temperatures have dried out the grasslands and bushlands. In this respect, then, a shift towards a more continental climate in the Pyrenees, combined with a drop in the amount of snow cover, is likely to increase the risk that major wildfires will break out and spread. Consequently, while we cannot be sure that the pattern of forest fires will follow that of the bordering regions (more Mediterranean), neither can we exclude the possibility that summer fires will be more common and severe in the future (Figure 2.4.9).

Pyrenean vegetation, compared with Mediterranean vegetation, has not evolved as a result of devastating forest fires. At present, the majority of forest fires in the Pyrenees are relatively limited in terms of ground covered and tend to spread quickly, while they have little impact on seed stocks and soil.

Although we have only limited understanding of the way Pyrenean (plant and animal) species respond to major fires, the arrival of more severe fires will have a significant impact on the structure and composition of vegetation, by increasing the erosion of catchment areas, the risk of avalanches and flooding. The probable extension of major fires could lead to a reduction in the forest's surface area and, consequently, a more homogeneous landscape. There is absolutely no doubt that this will have a negative effect on biodiversity, the degree of protection against natural risks, the beauty of landscapes and, consequently, the number of visitors to the regions affected (refer to chapter 3.1).

Another aspect to take into consideration is the perceived risk by potential tourist populations. Although the impact of forest fire risk has not been

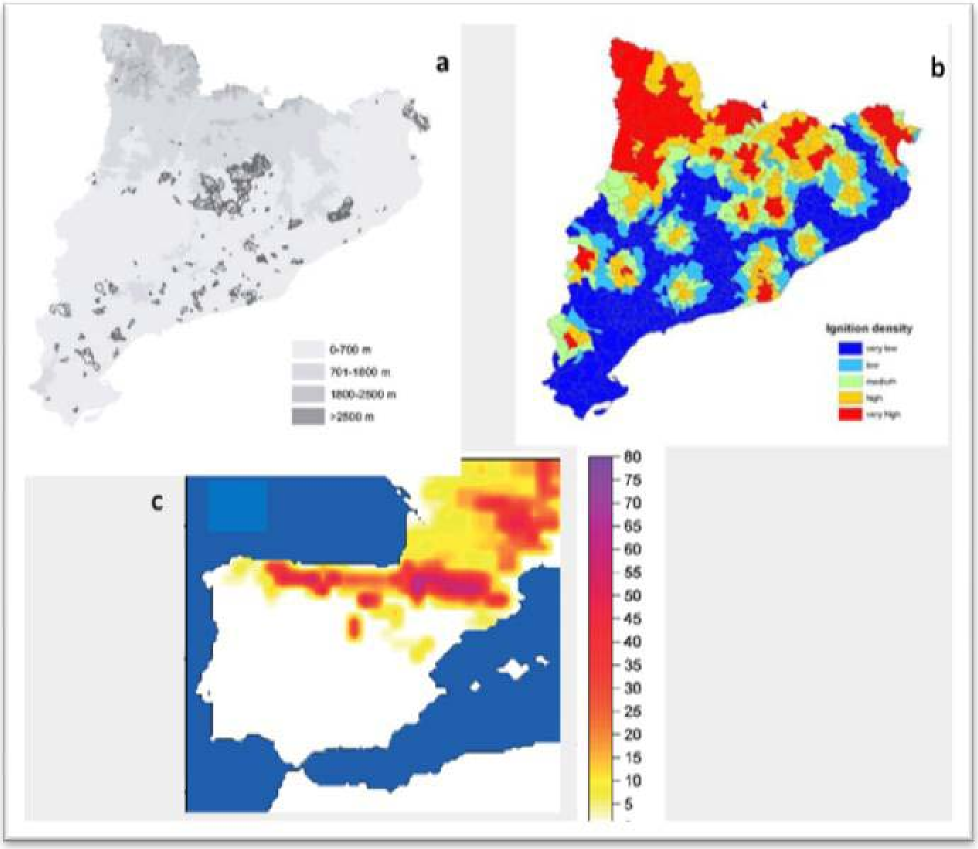

Figure 2.4.9. The pattern of forest fires in Pyrenean areas (e.g. Catalonia) is defined by precipitation patterns (a: Gonzalez et al., 2006), and agro-pastoral activities, which determine the number of winter fire outbreaks (b: density of fire outbreaks caused by stubble burning, in Gonzalez-Olabarria et al., 2015). However, these factors can be modified by the increased recurrence of "high-risk years" (c: percentage variation in the number of "high-risk years" in climate change scenario B2, according to Moriondo et al., 2006)

studied in depth in Europe, in the USA a direct cause-effect relationship has been demonstrated between an increase in the number of forest fires in a given year and a decrease in the number of tourists, combined with the associated economic downturn of the hotel sector (Thapa et al., 2004).

The battle to prevent wildfire in the Pyrenees requires better predictive models of risk levels and the behaviour of a possible fire, together with active management of combustibles in Key areas (Box 2.4.3). Weather conditions are highly variable in mountainous regions and, generally speaking, very little data is available concerning spatial variability. Consequently, it is very difficult to forecast local weather conditions with a convincing degree of reliability. Fire has always been used traditionally in the Pyrenees as a means of improving pastures and modifying the distribution and composition of vegetation (Montané et al., 2009). Farming activities in the past and pastoralism up to the present day have led to the creation of a patchwork landscape which is typical of many valleys and high mountain areas in the Pyrenees. In order to preserve the landscape and reduce the risk of forest fire, we need to provide more financial support to existing agricultural, pastoral and forestry activities in mountainous regions, mainly by promoting and emphasising the high quality of the products produced there. In addition, the battle against forest fires requires active management of Key areas to avoid the spread of fire and reduce the severity of major forest fires (Casals et al., 2009).

2.4.6 Findings and recommendations

Due to its location from East to West, the Pyrenees mountain range makes it more complicated for mountainous species to migrate, which would be their logical response to climate change (they restrict migration from the south northwards). Despite this, there are still very few general studies of the impacts of climate change on Pyrenean forests that cover its entire East-West and North-South sides. Considerable work is currently being undertaken in the framework of the Pyrenean Climate Change Observatory to make up for this knowledge gap.

The Pyrenean forest is closely related to the evolution of rural society. Numerous socio- economic stakes are directly linked to changes in the natural environment and the factors that condition those changes. Climate change, which modifies temperatures and rainfall levels, alters the pattern of disturbances, both biotic (pathogens, diseases, etc.) and abiotic (wildfire, storms, etc.) and therefore has a significant impact on the dynamics and workings of forest ecosystems. However, we should not ignore other factors which also have more short-term effects on forests, such as wildlife management and hunting (a major issue as regards regeneration), a reduction in traditional pastoral activities and, quite simply, forest management for the purposes of wood production. Changes in structure, composition, health conditions, geographical distribution areas and vulnerability to external phenomena (pathogens, climatic phenomena, etc.) all constitute effects (either positive or negative) that need to be foreseen and managed, because they will determine the way Pyrenean vegetation cover evolves and may lead to a significant modification of all the components that make up the multiple functions of our mountain forests. Predicting forests' response to climate change is a complicated, hard-to-define task requiring a vast amount of knowledge, made even more difficult by the fact we now know that the responses are neither as quick nor as linear as we once thought.

Main challenges

Forests and forest management must be considered from a long-term perspective. The decisions made today will determine the state of our forests in the future.

In order to boost the resilience of Pyrenean forests and counter the negative effects of climate change, we must therefore:

• Improve our understanding – in the specific context of the Pyrenees - of the effects and impacts of climate change on forests (particularly the most vulnerable in the short and medium term) and adaptation processes (both natural and anthropogenic);

• Maintain and develop farming, pastoral and forestry activities in mountain areas, since these activities guarantee sustainable management of the forest environment with numerous positive effects: lower volume and reduced continuity of combustibles, patchwork of more resilient housing, risk control and increased resilience of forests in the event of health or climatic hazards, etc.;

• Promote enhanced awareness of technical and scientific progress among non-specialist populations.

Pyrenean stakeholders, including first and foremost owners, scientists, forest managers and public authorities, must therefore take action right now to ensure that our forests are able to develop in the best possible conditions and are well prepared to adapt to these changes.

Recommendations

Soft measures [29]

· Try out and promote various adaptive forest management models in order to increase forests' degree of resilience in the face of repeated and/or extreme unfavourable climatic events;

• Set up a sustainable network for observing the phenological evolution of Pyrenean forests (budding periods);

• Promote synergies between the various observational and monitoring processes (remote detection, citizen science, etc.);

• Improve our knowledge of and experiments

(29) Soft measures or non structural measures to reduce or mitigate the negative effects of climate change. This category of measures is typically composed of investigative studies which goal is to deal with knowledge gaps or to add to the bases of knowledge on climate change, its impacts and the most vulnerable sectors. In this category belong as well the development of specific methodologies and systems to reduce the risks associated with climate change (ex. Development of the UN cross border early warning system for the management of heat waves in the Macizo)

regarding the genetic variability of trees in order to predict possible alterations, adapt current forestry practices accordingly and determine the choice of species for forestry practices in the years to come;

• Identify and highlight possible destructions of species and forest habitats which are particularly vulnerable to climate change, in order to assess genetic decline in mountain regions;

• Promote the development of a scheme for monitoring, alerting and triggering an operational response to the forest pests and pathogens that can affect Pyrenean forests;

• Improve our knowledge of the impacts of climate change on forest ecosystems as a whole;

• Raise awareness among the general public and local politicians, through communication campaigns, about the interactions between forests and climate change (potential impacts, usefulness, adaptation, etc.) and the role played by forest managers;

• Improve our ability to predict the risk of wildfire by developing an index adapted to the specific features of the mountain range (vegetation, meteorology, topography, etc.);

• Fine-tune our knowledge about climatic compatibility zones and the potential distribution areas of Pyrenean forests, in order to identify the most vulnerable zones and offer advice to owners and managers regarding the most appropriate forestry practices;

• Support forest land owners to encourage the selection of the best adapted varieties for a given zone, which meets their requirements in terms of nutrition, oxygen and water supply.

Green measures [30]

• Reinforce and support sustainable forest management in order to reduce the vulnerability of forests with respect to natural disturbances: encourage dynamic forestry practices to reduce the risk of accidents and optimise the resilience of forest stands.

KEY MESSAGES

• The Pyrenean forests provide a wide range of goods and services: production of wood and other non-wood products, harnessing and storage of CO2, protection against natural hazards, fertile ground for plant and animal biodiversity, hosting of visitors, and more.

• Climate change will have significant impacts on the way Pyrenean forests function, mainly as a result of rising temperatures and modified rainfall patterns (extended growing period, modified productivity, change in the way species are distributed, etc.). Climate change can also lead to consequences that affect Pyrenean forests themselves (wildfire, pests, pathogens, storms, etc.).

• In addition to the effects of climate change, other factors prompted by general changes (land use, practices, etc.) have a considerable impact on the dynamics and workings of Pyrenean forests. Forest management is the primary lever for helping forests to adapt to climate change: "by taking the right action today, forest managers will shape the way our forests look in the future."

• Promote the use of local wood (locally transformed wood) as a material: this guarantees "secure" sequestration of CO_2 and is a way of limiting the use of other materials that produce higher volumes of greenhouse gases.

• Promote the use of wood as a local energy source and as a substitute for other energy sources that produce higher volumes of greenhouse gases (the carbon impact of wood burning is fully offset by the release of the CO_2 stored by the tree throughout its development).

• Optimise management of the natural environment in areas that have only recently become exposed to fire risk, by promoting active management (especially forestry and agro-pastoral practices) to limit the volume and continuity of combustibles in high-risk areas.

(30) The green measures or based in ecosystem services: this typology of measures includes all the measures, good practices, studies and initiatives which principle is the use of ecosystem services provided by different natural resources to mitigate the negative effects of climate change (ex. Conservatory silviculture practices to increase the capacity of Pyrenean forests to reduce hydrological risks)

2.5. Sensitive high altitude ecosystems: alpine lakes and wetlands

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ABSTRACT

High altitude alpine lakes and peatlands are iconic landscape elements in the Pyrenees, greatly vulnerable to climate change and increased human activity pressure. During millennia, they have sustained a complex biodiversity and they have served as carbon storage reservoirs and provided a number of services for water availability, habitats for biodiversity, grazing pastures and meadows and more recently, tourism. Conservation of these ecosystems in the framework of more sustainable development in the mountains is a challenge but also an opportunity to educate the citizenship on the reach of global change impacts even in areas considered pristine.

2.5.1. Pyrenean Lakes and peatlands

Alpine lakes and peatlands are iconic elements of the Pyrenean landscape, greatly vulnerable to climate changes and rising human impact. There are a number of lake and peatland inventories for the Pyrenees, considering different criteria as surface area and altitude, but according to Castillo-Jurado (1992), there are around 1000 alpine lakes (>0.5 ha surface area) located in the alpine and montane vegetation belts, mostly between 2000 and 2500m asl. The 17 largest lakes (surface area > 0.3 km^2) represent about 7.87 km^2 surface area, and about 75% are smaller than 0.04 km^2 with average drainage basin around 1.67 km2 but ranging between 0.1 km^2 (Gentianes, Gave de Pau) and 32.6 km^2 (Baños de Panticosa, Gállego River). Considering depth, there are two main types: shallow (< 10-15 m maximum depth) and deep (> 15 m). In the Pyrenees we have 90 lakes deeper than 25 m, and 47 are deeper than 40 m.

Peatlands are ecosystems characterized by the accumulation of organic matter derived from terrestrial vegetation in waterlogged conditions. In the Pyrenees, most of them are of "fen" type, fed by precipitation, run-off and ground waters. Their origin and evolution depends on local topography and hydro-climate conditions. Most of the Pyrenean peatlands originated from the deglaciation of the valleys and they have accumulated organic matter since then. There is no complete inventory, although the number is smaller than in other mountains ranges with more Atlantic climates (Heras et al., 2017). Information about the small ones (<1 ha surface area) is particularly limited, although they are the most abundant, especially at higher altitudes and associated with alpine lakes. Well developed peatlands occur in Navarre (Atxuri, Belate, Gesaleta y Baltsagorrieta) and in France (Bernadouze and Col d'Ech). Only in a few sites thickness and age of the accumulation are available, so we do not have accurate estimates of carbon inventories.

Depositional dynamics of lakes, wetlands and peatlands originating from glacial-related processes are strongly influenced by cryosphere processes in the watersheds (snow accumulation and melting, ice-fields and permafrost dynamics). These high altitude ecosystems are characterized by high solar insolation and UV radiation, low temperatures and long ice-coverage periods; very dilute waters, in many cases ultraoligotrophic, due to low chemical weathering and nutrient influx (Figure 2.5.1). Because of these features, they are particularly sensitive to changes in some climate parameters as temperature and snow regimes and wind variability. They are sentinels of the changes in the Pyrenean territory as they respond to current climate and environmental variability in the watersheds. They also archive in their sediments the complex signatures of landscape, aquatic system and biotic and a-biotic processes during the last centuries and millennia.

Lakes and wetlands provide services to the territory beyond their role as global change archives. During the last decades, the economy of many mountains areas has become more dependent on tourism, both winter sports and summer hiking activities. Some of the unique elements of the Pyrenean landscape as glaciers, lakes, wetlands and alpine tundra have become significant for the local economies based on tourism and have attained status as protected natural areas. These ecosystems also play a role in the hydrological cycle and the water resources, Key for agriculture, energy and the environment. The quality of the services provided by them in the future depends directly on the response of the criosphere - hydrosphere – biosphere to climate change. High mountains are water towers, power plants and playgrounds for all Pyrenean territories, a region with increasing water and energy demands for agriculture, industry and human consumption.

2.5.2. Processes in lakes and wetlands within the context of climate change

Biochemical processes in high altitude lakes and wetlands are controlled by the extreme features of these habitats (Catalan et al., 2006). Government agencies, Water Authorities, Ministries of Spain, France and Andorre maintain a number of programs to analyze and monitor the ecological state of lakes in the Pyrenees (for example, CHE[30] and ACA[31]). As we pointed out in the introduction, these high altitude ecosystems have very diluted waters, with low dissolved solids and solutes, oligotrophic and with a high transparency.

Watershed features (topography, drainage network) and bedrock geology (mainly carbonate versus silica formations) greatly control the chemical water composition and the carbon cycle as dissolved organic carbon mainly responds to type and soil abundance. Biogeochemical cycles are also influenced by bedrock properties (as they control alkalinity and the carbon cycle, for example), and nutrients and pollutant deposition (as they exert a large control on micro and macro-biota dynamics). Particularly, water pH is a major factor on algae and macrophyte development and it is mostly controlled by alkalinity and bedrock geology (Catalan et al., 2006). A survey during the summer of 2000 (Catalan et al., 2006), showed that 70 % of the Pyrenean lakes are ultraoligotrophic (TP < 4.7 µg L-1), 22 % oligotrophic (4.7 < TP < 9.3 µg L-1) and 6 % mesotrophic (9.3 < TP < 31 µg L^{-1}). During the ice-free season, light penetrates till the bottom in more than 75 % of the lakes, so autotrophic biota may develop. UV radiation can be quite high in these ecosystems, and many studies have shown its effects on micro-organisms. Lakes and peatlands also accumulate in their sediments organic pollutans and inorganic contaminants (heavy metals and trace elements) (Catalan et al.1993; Camarero, 2003; Le Roux et al., 2016). More than 75 % of surveyed lakes in the Pyrenees (Camarero, 2003) showed heavy metal enrichment factors higher than 1.5 with a west-east pattern, with higher contamination in central and eastern Pyrenees

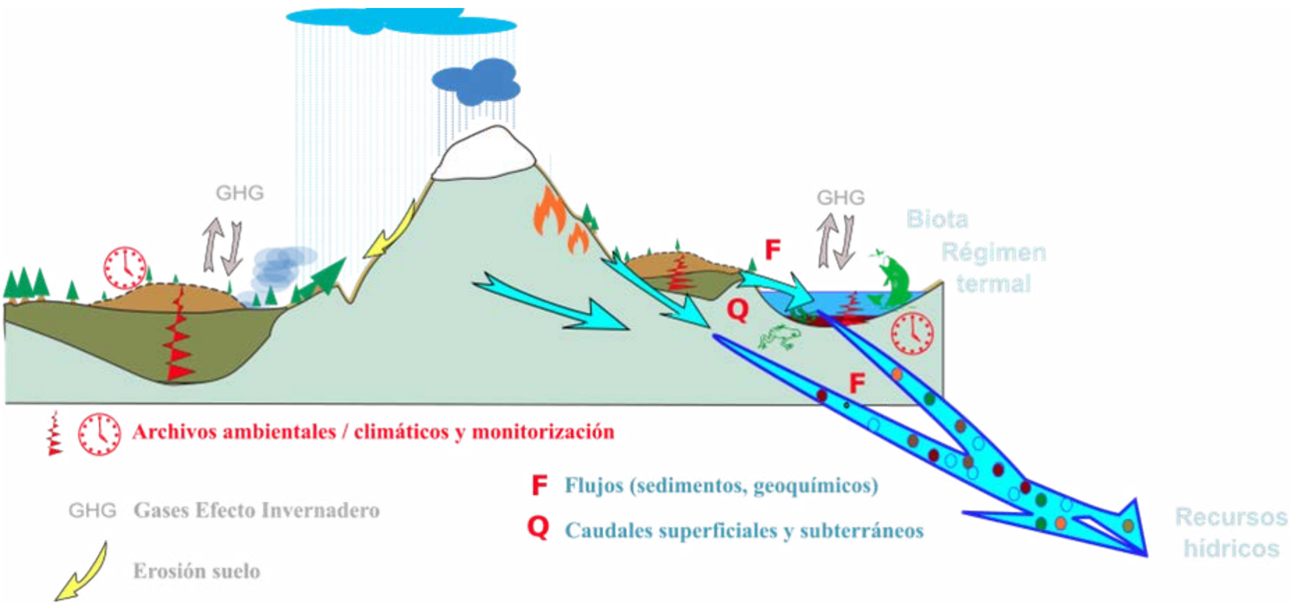

Figure 2.5.1. Biogeochemical cycles in high altitude lakes and wetlands

(31) http://www.chebro.es/

(32) http://aca-web.gencat.cat/

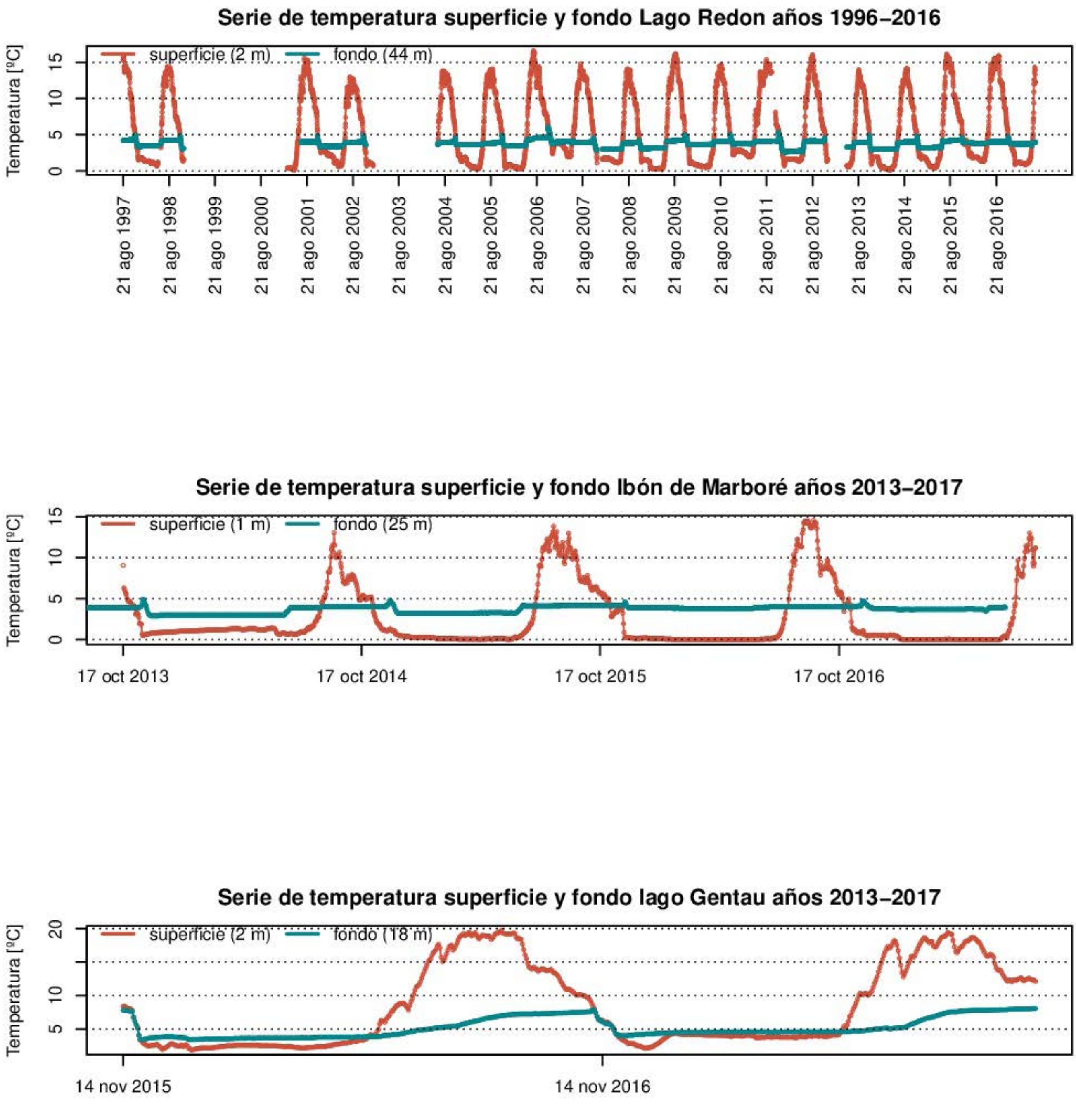

Figure 2.5.2. Temperature and background profile in Lake Redon (1969-2016), Marboré (2013-2017) and Lake Gentau (2013-2017).
Source: based on data from CLAM-IGME and REPLIM.

than in the western areas (Figure 2.5.3A). Sediments from several surveyed lakes show increased heavy metal atmospheric deposition associated to mining and smelting activities during Roman, Medieval and Industrial times, and a progressive reduction since the mid 20th century, likely due to the banning of lead gasoline (Camarero et al., 1998). Organic pollutants, however, have increased in the last decades (Arellano et al., 2015). Pyrenean lakes showed a slight acidification trend during the second half of the 20th century due to acid rain (Camarero, 2017).

Annual physical cycles in lakes and wetlands are characterized by a large seasonal variability, depending on water availability, thermal regime and length of the ice-covered period (Figure 2.5.2). Biological cycles follow the same seasonal patterns with phases of variable productivity in phytoplanckton communities (Camarero et al., 1999; Felip and Catalan, 200; Ventura et al., 2000). However, only in a few Pyrenean lakes we have relatively long time series of limnological properties (Redon, since 1996; Marboré since 2013; Sánchez et al., 2017).

Wetlands and peatlands are Key ecosystems for hydrology and carbon cycle in mountain areas (Parish et al., 2008). Peatlands are among the most important carbon storage systems as they accumulate large amounts of organic matter. They are the most efficient terrestrial carbon storage systems; temperate peatlands contain up to 7 times more organic carbon per hectare than any other ecosystem. They are also water purifiers as they filter contaminants and particulate organic and inorganic matter maintaining the high quality of the waters at the headwaters of Pyrenean rivers. The carbon cycle in Pyrenean peatlands is complex and it has not been quantified. Most Pyrenean peatlands have been accumulating carbon for millennia, but we do not know the natural accumulation rates during the Holocene (last 117000 years) and the possible changes during the Anthropocene and particularly during the last century due to global warming. At decadal to annual time scales wetlands and peatlands may potentially act as CH_4 and CO_2 net emissaries to the atmosphere and to the hydrological basins (as dissolved and particulate carbon) depending on environmental and human processes (flooding, droughts, fire,...). Finally, the microenvironments in these ecosystems support a high biodiversity. In spite of the reduced combined surface area in the Pyrenees, wetlands occur in many watersheds and they sustain a unique biodiversity. Sphagnum- peatlands in the Pyrenees are in the southern border of their geographic distribution and, consequently, very sensitive to climate and anthropic changes. To assess the resilience of wetlands and peatlands to climate change and local human impacts (deforestation, fire, grazing pressure), the dynamics of processes at annual and seasonal scale need to be identified and quantified.

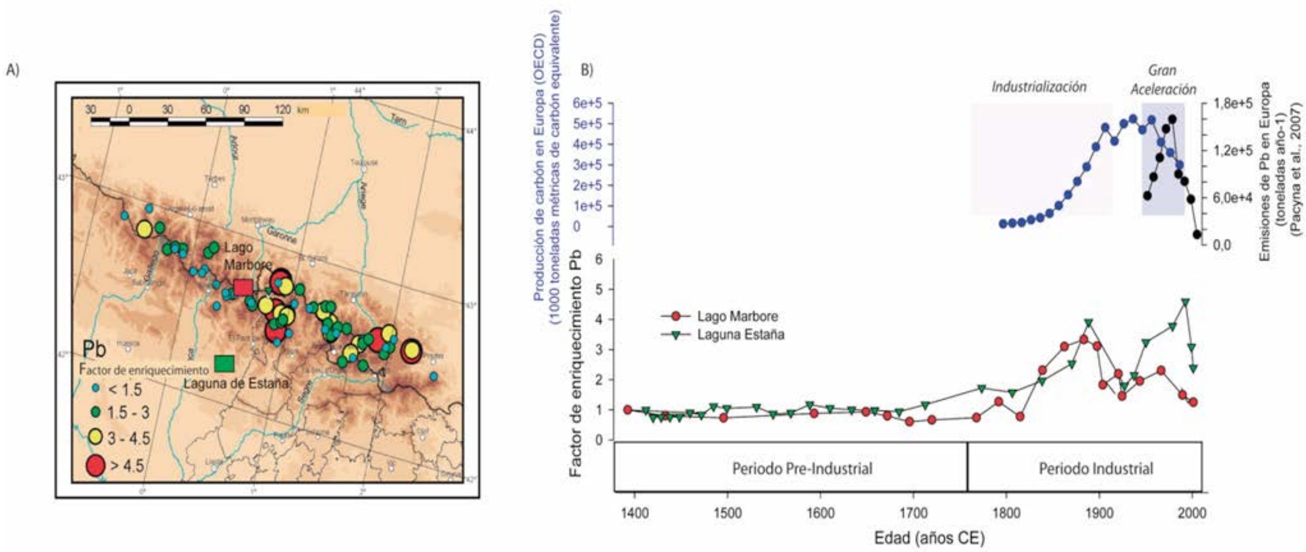

Figure 2.5.3. A. Geographic distribution of Pb enrichment factor in surface sediment in Pyrenean lakes (Camarero, 2003). B. Heavy metal enrichment factors in Marboré and Estaña Lake sediments during the last 600 years compared to global Pb emission in Europe for the last 200 years. Source: Camarero, 2003.

2.5.3. Projected impacts

High altitude areas in mountain ranges all over the world are particularly vulnerable to climate change. The main forecasted impacts on high elevation lakes and peatlands are related to changes in physical, chemical and biological properties due to water availability changes and higher temperatures. At high elevations, not only is the direct effect of climate change on water temperature important, but also the variability of the length of the ice-free season and the snow cover. Among other processes, we should expect changes in the freezing and thawing cycles, in the abundance and composition of some aquatic communities and in the chemical composition of water (mainly alkalinity). In the watersheds, snowfield degradation and disappearance of seasonally frozen soils (permafrost) will change the surface hydrology (runoff) and likely contribute to the loss of some relict plant communities. Associated to lakes and peatlands, a number of plant communities in wetlands and snowfields and many boreal - alpine species are in their distribution limit, and consequently, especially vulnerable to changes in temperature and precipitation regimes. Some of the ecosystem services they provide (quantity and quality of water, sightseeing for tourism) can also be affected by these changes.

Changes in the trophic status of high altitude lakes have been described in many mountain ranges around the world (Elser et al., 2009; Camarero and Catalan, 2012) and they have been attributed to variable thermal and wind regimes and nitrogen and phosphorous atmospheric deposition changes as a response to variability in air masses circulation. The forecasted increase in UV rations could also affect planktonic communities, as it has been shown in the Himalayas and the Alps (Sommaruga et al., 1999).

A survey in the Austrian Alps demonstrated that the combined effect of all these factors increases the sensitivity and vulnerability of the lakes located between 1500 and 2000 m asl, where changes in temperature and precipitation have the greatest impact on ice phenology and snow cover. Deeper lakes have a larger thermal inertia as it lakes longer to warm up and cool off, so it is expected they will respond more slowly to new physical (temperature and density gradients), chemical (salinity alkalinity, pH, nutrients) and biological (primary productivity, composition communities) conditions.

Impacts on lakes and wetlands due to climate change occur at the same time as those caused by human activities. From an historical point of view, Pyrenean lakes, in spite of their remote location have witnessed anthropic impacts during the last millennia, as significant heavy metal deposition started in Roman times. Lakes located at intermediate altitudes have suffered intense deforestation and variable grazing pressure in their watersheds since medieval times (González-Sampériz et al., 2016). Fish introduction has been documented since the 15th century (Miró and Ventura, 2013). During the 20th century, main affections have been damming for hydroelectric power and building of infrastructures for summer and winter tourism.

Forecasted impacts due to climate change in the Pyrenean ecosystems will be mostly related to changes in the temperature regimes. The general increasing trend (about 2ºC since the end of the Little Ice Age and 0.2ºC/decade since 1950) and the decreasing length of the ice-covered period in the lakes may introduce drastic changes in the seasonal thermal regime of some lakes. Most studies in mountains worldwide show a decrease in both snow accumulation and the length of the period with snow covered ground and both trends are likely to continue in the future. Some models and observations (Schneider et al., 2010) predict increases in the surface water temperature (epilimnion) higher than 10ºC during the 21st century. These scenarios of limnological change in hydrology, ice cover and water temperature exceed the range of change during the last 11700 years (Holocene period).

Sedimentary records from several Pyrenean lakes (e.g., Arreo, Basa de la Mora, Marboré, Montcortès, Redon) show large changes in sediment fluxes, biota assemblages (particularly diatoms but also micro and macro invertebrates) at the end of the Little Ice Age (late 19th century) and during the last decades. The causes for these changes are complex and could include climate (changes in temperature) and anthropic (higher nutrient deposition) factors. In the Pyrenees, Redon lake is the best studied and the records show a clear trend to increasing temperatures during the last century, particularly higher during the last decades (Catalan et al., 2002; III CCC report, 2016). These changes in temperature, higher in summer and autumn, have favored species of planktonic diatoms of shorter life span that bloom during the fall (Fragilaria nanana and Cyclotella pseudostelligera) and also crysophyte algae that form the cysts in spring. The length of the ice – covered period directly controls the type of planktonic crustacean communities (Catalan et al., 2009). Without long term series of past dynamics it is still an open question to ascribe the observed changes to climate variability, human impacts or the likely synergies between both types of forcings.

We also have to consider some indirect effects of climate change derived from glacier melting and permafrost thawing, as the liberation of heavy metal and persistent organic contaminants and the increasing mobility of organic matter and associated contaminants (Bacardit y Camarero, 2010). Climate change may increase remobilization of these organic and inorganic contaminants in the sediment and soil reservoirs and also increase the deposition rates (Le Roux et al., 2016).

In peatlands, the main impacts caused by climate change are ecosystem degradations, loss of flooded surface area, diminishing or reversing of the carbon sink/source effects and loss of ecosystemic services. These changes will diminish the capacity of these ecosystems to act as carbon sinks, their ability to regulate the quantity and quality of waters and safeguard biodiversity.

Increasing precipitation variability in high altitudes is likely to increase the frequency and intensity of droughts and floods, which will alter the flooded surface area in wetlands. Higher temperatures will lengthen the growth period and the primary productivity will increase. On the other hand, organic matter decay rates will be higher and, consequently, CH_4 and CO_2 emissions wll rise. Permafrost thawing will also increase CH_4 emissions and decrease Dissolved Organic Carbon in headwaters and rivers. Hydrological changes will also affect organic matter accumulation and decay rates in peatlands and the greenhouse gasses emissions as dried surface areas emit less CH4 and more N_2O y CO_2 than flooded areas. The altitudinal shift of the timberline as a consequence of higher summer temperatures could lead to forest expansion and colonization of some wetlands and peatlands, reducing albedo and providing a positive feedback to global warming. Higher freauency of storms and more torrential hydrological regimes could increase peatland erosion, and have a positive feedback with changes in the internal drainage of the basin and overgrazing. Longer and/or more intense drought periods could increase the intensity and frequency of fires, although human activities will continue to be the main cause for wildfires in the Pyrenees. Combined effects of global climate changes and local hydrological features will likely alter the distribution and ecology of plants and animals living or using peatlands and wetlands. On the other hand, human activities greatly increase vulnerability to climate change. Among them, drainage, burning and overgrazing may have strong local effects and also global implicatons (increase in carbon emissions).

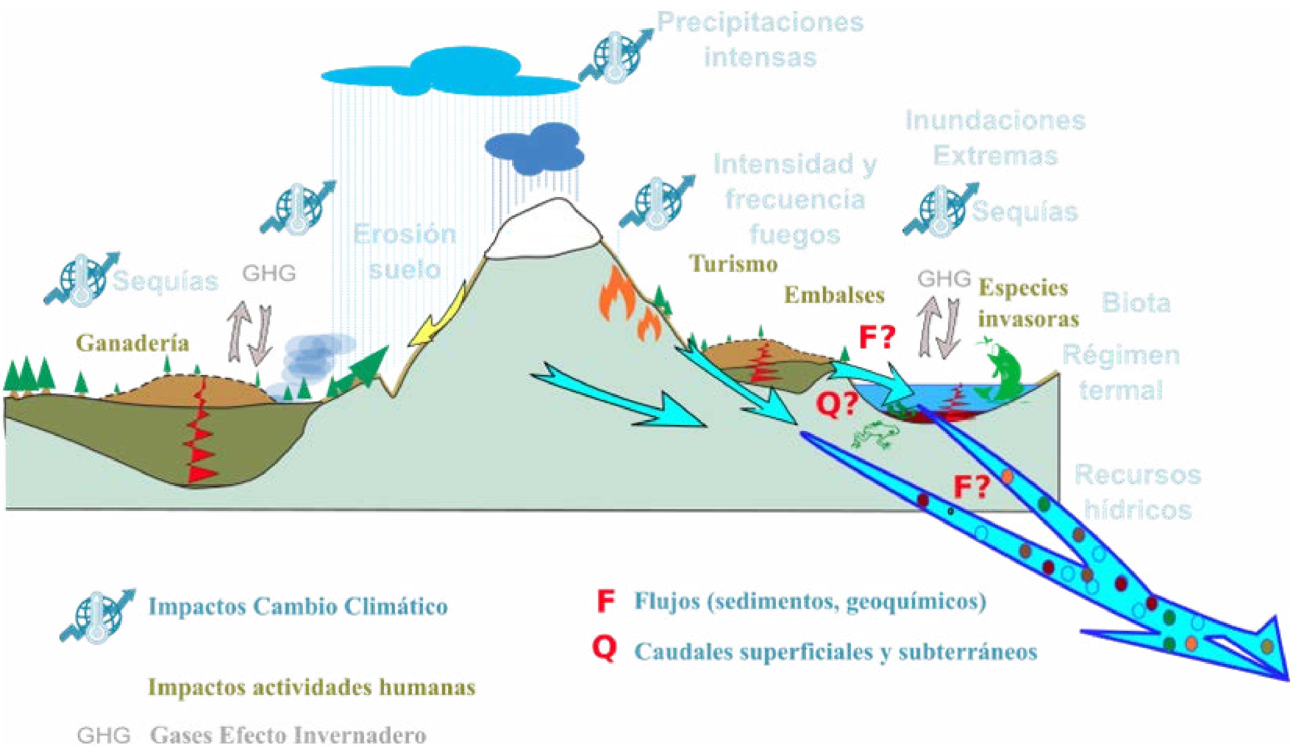

Figure 2.5.4. Espected impacts in lakes and peatlands in the Pyrenean mountains caused by climate change and human activities

2.5.4. Main Challenges

Main challenges to understand and evaluate the effects of climate change in high altitude Pyrenean lakes and peatlands are related to the complexity of the biotic and abiotic processes, the uncertainty of the models explaining the involved processes and the scarcity of long time series of natural variability in these ecosystem. Also, our capacity as society to implement effective conservation and management practices at local and global scale. As one of the main challenges, we would highlight the ascription of the observed changes and trends to either climate change or anthropic pressure. On the other hand, we have to reduce the uncertainties of our models about risks, impacts and future forcings and drivers in mountains areas. The lack of detailed information to characterize these ecosystems and their internal processes (from detailed inventories of biodiversity to quantification of biogeochemical processes) hampers our ability to understand their resilience against climate and global change. Finally, they have to be included in a more integral management of the territory to warrant their preservation and also a more sustainable use of the mountains resources.

2.5.5. Findings and recommendations

In spite of their relative remote location from main human activity centers, the impact of climate change in high altitude lakes and peatlands is not easy to detangle from the effects of the increasing human pressure in the territory (tourism, nutrient deposition, water resources...). Although in most cases, human impact may be determinant, higher temperatures may increase ecological risks for some mountain ecosystems as their communities will be exposed to higher stress. Phenotype plasticity of lake and peatland communities may help them to adapt to new climate and environmental fluctuations.

It is of paramount importance to analyze the impacts within a holistic framework, including climate and antrophic forcings, global (nutrient deposition, pollution) and local (tourism) scales. Adaptation and mitigation measures to climate change in lakes and peatlands need first to understand the effect associated to human pressures, so adequate measures could be implemented. Lakes and peatlands are unique elements of the Pyrenean landscape, well known and valued by citizens and that could serve to motivate citizen participation in monitoring and conservation programs and help to understand better the impacts of global change in mountain areas.

A few general measures for a more sustainable management of lakes and peatlands are proposed, taking into account their adaptation to the forecasted negative effects of global change:

Soft measures [33]

- To develop stable multidisciplinary, trans-boundary working groups, including members of all interest groups and stake holders (city halls, tourism entrepreneurs, hydropower companies, regional and local authorities, scientists, ecologist organizations, NGOs, ...). These groups would lead the debate on the climate and human impacts on these ecosystems following participation models of observation and decision making;

- To establish and maintain monitoring and observation networks for these ecosystems and to promote integrated projects with the participation of all stakeholders;

- To include in all management plans for the territory, at local and regional scales, the risks associated to climate change.

Green measures [34]

- To facilitate ecological tourism with a minimum impact on the protected areas and seeking the participation of citizens in their conservation;

- To develop education programs at local, regional and trans-national levels to explain the services provided by these ecosystems and their capacity to act as carbon sinks and water reservoirs, to protect biodiversity and soils and to diminish erosion

Grey measures [35]

- To offer incentives to mountain tourism companies to adequate their activities to conservation goals and more sustainable management.

KEY MESSAGES

• High altitude lakes and peatlands are iconic ecosystems in the Pyrenees but highly vulnerable. Their conservation provides an opportunity for citizenship to better understand the challenges of climate change and increasing human pressure in the mountains.

• To manage the effects of climate change in high altitude lakes and peatlands we need observation and monitoring strategies to identify the complex processes occurring in these ecosystems, to reduce the model uncertainties and to be able to improve our capacity to implement management policies based on more sustainable objectives agreed upon with all stakeholders.

(33) Soft measures or non structural measures to reduce or mitigate the negative effects of climate change. This category of measures is typically composed of investigative studies which goal is to deal with knowledge gaps or to add to the bases of knowledge on climate change, its impacts and the most vulnerable sectors. In this category belong as well the development of specific methodologies and systems to reduce the risks associated with climate change (ex. Development of the UN cross border early warning system for the management of heat waves in the Macizo)
(34) Green measures are based on ecosystem services: these include all measures, good practices, studies and initiatives around the use of the ecosystem services obtained from natural resources, and which seek to alleviate the negative effects of climate change (e.g. forestry practices which conserve the capacity of forests in the Pyrenees to reduce hydrogeological risks).
(35) Grey or structural measures are all those involving the construction or implementation of specific infrastructure to alleviate the effects of climate change (e.g. building dykes in inhabited areas at risk of flash floods).

2.6 Hydrological cycle and water resources

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ABSTRACT

The Pyrenees play a fundamental role in providing water resources to the territories located on both sides of the hydrological boundary, and this influence goes well beyond the strict limits of the mountain range, since its headwaters generate a very important share of the surface and sub-surface resources of important river basins such as the Ebro, Adour, Garonne, etc.

The analysis of time series of streamflow data shows a global trend towards reduced annual river flows in the last decades. This reduction of streamflow can be attributed in part to climate change, but an important contribution to this trend can be attributed to changes in land use and in vegetation cover, most notably in the southern part of the mountain range. There have been changes also in the monthly regime of streamflow, related to a change in the ratio snow / rainfall in winter that led to reduced snow accumulation and earlier snowmelt. This has translated into changes in the river regimes, which have now a more pluvial character with higher streamflow in winter, earlier and reduced snowmelt-related high flows in spring, and longer and more pronounced summer lows. No clear sign has been found, on the other hand, about statistically significant changes in the frequency of extreme flows. Most future climate simulations indicate that the Pyrenean region will experience a trend towards higher temperatures and reduced precipitation during the 21st century. These changes will represent increased stress to the vegetation and will enhance evapotranspiration, which in turn will affect the other components of the water balance (surface runoff, base streamflow and groundwater recharge). The overall consequence will be less water in the soils and less frequent soil saturation conditions, which will be limited to shorter periods in winter and spring. In addition to changes in the climatic forcing, the water balance of the Pyrenees will be affected by changes in the vegetation cover, driven by a continuation of re-vegetation processes already observed since the middle of the 20th century as a consequence of the abandonment of agricultural activities and as a response to global warming that implies an upward movement of the vegetation altitudinal belts. Human activity, in the meantime, will concentrate on a few places such as ski resorts and touristic villages. The observed and foreseen changes in the annual and seasonal streamflow levels may imply a reduction in water quality, due to the dilution effect of contaminants.

The most agreed scenario, therefore, is towards a continuation of the trends already observed in the last decades, which lead towards reduced water resources. On the demand side, despite foreseen improvements in distribution and use of water resources, there are also predictions of increasing water demand, most notably due to the planned expansion of irrigated agriculture thanks to the development of new infrastructures. Considering that irrigated agriculture is a major water consumer in the region, this may lead to increased competition for water resources across sectors and regions.

Like many other mountain areas, the Pyrenees are a water tower for the territories that surround it, since it hosts the headwaters that generate a large share of the water resources (surficial and subterranean) that are used downstream in the basins of the Ebro, Bidasoa, Adour, Garonne, internal Catalan catchments (Norht and Central systems), and Aude. For instance, the Pyrenean rivers represent 70% of the total streamflow to the Ebro River, which is one of the most important river basins of the Iberian Peninsula (Confederación Hidrográfica del Ebro). The water resources generated in the Pyrenees are, thus, fundamental for the irrigated agriculture and food production, hydro-power generation, industry and domestic water use not only within the Pyrenees, but in a much larger territory that includes millions of inhabitants and some of the largest urban concentrations in the south of Europe. Any changes in the water balance of the Pyrenees are therefore susceptible to have an impact over a very large territory and population.

Adequate managememt of water resources in the Pyrenees should start from a deep understanding of the details of its hydrological system. This implies understanding and quantifying the mechanisms that allocate the precipitation water (snow and rain) into evapotranspiration (water returned to the atmosphere

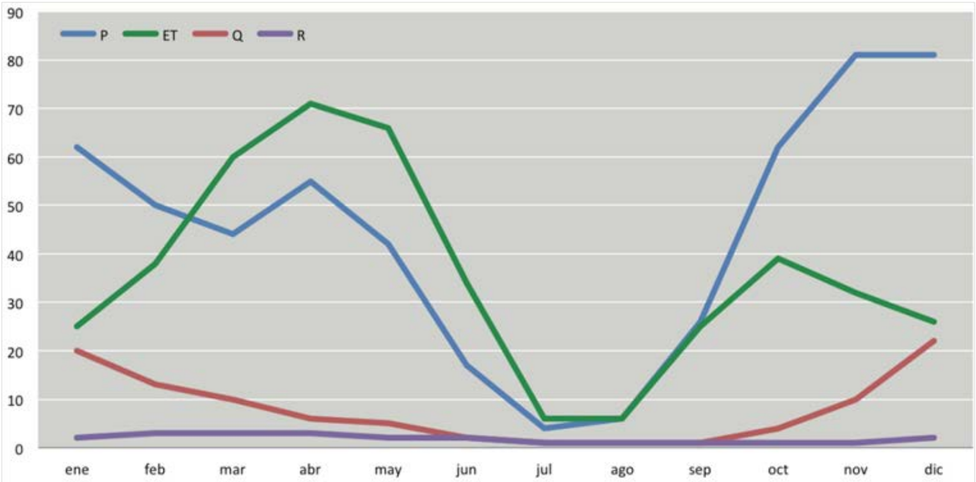

FigurE 2.6.1. Monthly water climate: input flows by precipitation (P), and outputs by evapotranspiration (ET), streamflow (Q) and aquifer recharge (R). Units: l m-2. Source: Balance in a forest catchment under Mediterranean: adapted from Beguería et al., 2015.

as vapour, either directly from the soil or through plant transpiration), streamflow generation (either from surface runoff and from shallow aquifer return), and deep aquifer recharge. These processes together determine the volume of water in the different surface (rivers, lakes) and subsurface (aquifers) water bodies, as well as in other temporal water storages such as glaciers and the snowpack, in the soil, in peat lands and other temporally flooded areas, or in the vegetation. Figure 1 shows the monthly values of different components of the water balance of a forest catchment on a typical Mediterranean climate. Precipitation water (input) is distributed across different output fluxes, with time lags due to temporal storage in the soil. Evapotranspiration may represent between 40% (Guipuzcoa, río Garona) and up to 80% (Mediterranean catchments) of the output flows. The remaining water (precipitation minus evapotranspiration) is allocated between surface streamflow and sub-surface recharge. The time lag between the different flows (which causes, for instance, that evapotranspiration is higher than precipitation during certain months) is due to internal water storages in the catchment such as in the soil, but in the long run input and output flows in the annual water balance cancel out. In mountain catchments, as it is the case of the Pyrenees, the annual cycle of formation and melting of the snowpack is a very important water storage that produces a temporal delay between the timing of precipitation and the other components of the water balance.

Most future climate simulations indicate that the Pyrenean region will experience a trend towards higher temperatures and reduced precipitation during the 21st century. These changes will represent increased stress to the vegetation and will enhance evapotranspiration, which in turn will affect the other components of the water balance (surface runoff, base streamflow and groundwater recharge). The contribution of precipitation in the form of snow will also decrease, and snowmelt will occur earlier in the season. The overall consequence will be less water in the soils and less frequent soil saturation conditions, which will be limited to shorter periods in winter and spring. A number of studies highlight the impact that these processes may have on the water balance and on the water resources (ACA, 2009; García-Ruiz et al., 2011). In addition to changes in the climatic forcing, the water balance of the Pyrenees will be affected by changes in the vegetation cover, driven by a continuation of re-vegetation processes already observed since the middle of the 20th century as a consequence of the abandonment of agricultural activities and as a response to global warming that implies an upward movement of the altitudinal belts. Human activity, in the meantime, will concentrate on a few places such as ski resorts and touristic villages.

Future scenarios for water resources in the region foresee a progressive decrease in the available resources, most notably in the form of streamflow, which vary in magnitude depending on the study. Moreover, all the studies agree that there will be important changes in the monthly regimes, with increasing winter and decreasing spring streamflow due to an earlier snowmelt, as well as longer and stronger summer low flows. On the other hand, the projected evolution of water demand for the mid 21st century predict stationary or even decreasing urban and industrial demand due to the progressive improvement in distribution systems and consumption, but at the same time there are plans of expanding irrigated agriculture, for instance in the Ebro basin (465.000 new has are planned for the period 2016-2021, to be added to the current 900.000 has, according to the Plan Hidrológico del Ebro 2015-2021). All these changes in the availability of water resources and the evolution of water demand will likely imply larger uncertainties in water supply, both in the Pyrenees and in the regions downstream, stressing the need for an adaptation strategy. In this chapter we will address the following issues:

- What are the observed trends in the volume of water resources (surficial and subterranean) in the Pyrenees in the last decades?

- What are the expected trends in water resources during the 21st century, according to current model simulations?

- What are the consequences of the observed and expected trends in the hydrological balance of the Pyrenees on water quality, biological cycles and aquatic ecosystems?

- What adaptation measures can be suggested to overcome any negative effects?

To answer these questions, we can rely on two methodological approaches:

- Statistical approach: the analysis of the longest time series available of indicator variables of water balance (such as precipitation records, river gauges or reservoir levels) allows determining the existence of time trends. This is a retrospective method because it is based on the observations of different components of the water balance during the past decades, and in addition to determining the existence of time trends it should allow discriminating the causal chain of the observed changes. In particular, a crucial question is to allow discriminating between climatic forcing and other causes such as the changes in land use.

- Modelling approach: the use of numeric simulation models of the hydrological system calibrated against observations during the observation period it is possible to simulate future scenarios with different climatic, land use and other characteristics. This is, therefore, a prospective method, which should allow estimating the most likely effects of different scenarios on the components of the water budget and on the availability of water resources.

2.6.1 Changes in the annual streamflow of surface waters

The empirical evidence, through the study of observational data from gauging stations across the Pyrenees, shows evidence of changes in the average annual streamflow of the Pyrenean rivers over the past decades. García-Ruiz et al. (2001) found a statistically significant downward trend in the mean annual streamflow in 28 out of 31 gauging stations of the Central Spanish Pyrenees, in the period 1964-1994. In a more recent study, Vicente-Serrano et al. (2015) found significant downward trends in the main rivers of the Spanish Pyrenees. López-Moreno et al. (2010) analysed streamflow data on natural rivers in the whole Ebro basin over the period 1950- 2010, and found significant downward trends in 55 out of 88 locations. In the French Pyrenees, the Acclimaterra report (Le Treut, 2013) shows a decrease of between 25 and 30% in the annual streamflow of the Garonne River at its outlet, for the period 1959-2010. At this scale and location, however, it is difficult to discriminate the influence of any changes in the consumption of water in the basin from other causes (climate, land use change), and studies in more natural river catchments are lacking. A recent study comprising the western part of the Pyrenees at both sides of the Spain-French border (Zabaleta et al., 2017; IHOBE, 2017) analysed daily streamflow data from 18 stations for the 1955-2015 period, and 43 stations for the 1975-2015, and found similar downward trends. For a shorter period (1995-2015), and using 117 stations, the same study found contrasting results, since some of the stations showed an increase of the annual streamflow. In the eastern extreme (Pyrenean sub-catchments of the Têt and Tech Rivers), Lespinas et al. (2009; 2014) also found decreasing annual streamflows.

The attribution of these changes in the annual streamflow, that is the identification of their cause and the discrimination between climatic and non-climatic causes, have been dealt with in these and other studies. In general, all the studies stress that the climatic forcing (that is, the changes in temperature and precipitation) does not completely explain the observed changes in streamflow. Once the influence of the climate variables is accounted for, the streamflow data still shows a downward trend (Figure 2.6.2). Apart from the climatic forcing, there is a consensus between the studies consulted in that an increase in the average evapotranspiration due to changes in land use and in the vegetation cover are the most plausible explanation for this trend in the streamflow. It is important to note that relatively small relative changes in evapotranspiration of around 2 o 3% have very large consequences on the water balance because evapotranspiration, as we saw earlier, accounts for a very significant share of the water budget. Beguería et al. (2003) estimated a decrease of around 25% of the annual streamflow in the rivers of the Central Spanish Pyrenees over the period 1945-1995 due to non-climatic reasons (Figura 2.6.2). Gallart and Llorens (2003, 2004) estimated, for the whole Ebro basin, a decrease in streamflow of about 0.63% per year, and they attributed 30% of this change to increasing evapotranspiration due to re-vegetation of the headwater areas. In the Noguera-Pallaresa and Ribera Salada rivers, Buendía et al. (2016) described a significant decrease of the annual streamflow which they attributed to the combined effect of climate change and reforestation of the headwater areas. In the French side of the Pyrenees, the study at the European scale by Stahl et al. (2010) detected decreasing trends in the two catchments analysed, for the periods 1952-2004 and 1962-2004. The use of numeric simulation models may shed some light about the attribution of the observed changes in the annual streamflow in many river catchments of the Pyrenees, and permits simulating the response of future annual streamflow in different climate change scenarios. Following this approach López-Moreno et al. (2014) estimated, for the southern side of the Pyrenees and with a 2050 time-horizon, that the availability of surface water resources could decrease between 10 and 20% with respect to the reference period 1970-2000, depending on the catchment. As a comparison, the Ebro River basin authority estimated this reduction to 5% on average for the whole Ebro basin, for the 2027 time-horizon (CHE, 2015). Quintana-Seguí et al. (2010), analysing the Pyrenean rivers of the Rhône-Alps region, estimated a decrease of the annual streamflow of between 10 and 20% for the 2035-2065 period with respect to the 1970-2000 reference period. Pascual et al. (2014) estimated this decrease by 25 and 34% in the Catalan internal catchments for the last quarter of the 21st century, and Manzano (2009) estimated this reduction to 10% for 2040. Candela et al. (2012) estimated for the 2050 horizon a reduction of around 20% of the stramflow asociated to downward trends in precipitation, and a 18% decrease in aquifer recharge. Caballero et al. (2007) estimated, for the Ariége River, a decrease of about 20% in the annual streamflow for the period 2055-2065, with respect to the reference period 1985-1995. Simulations performed in the headwaters of the Zadorra Reservoir point towards a decrease of about 8 and 15 % of the annual inflow for the year 2060, with respect to the reference period 1961-2000 (IHOBE, 2017; Meaurio, 2017).

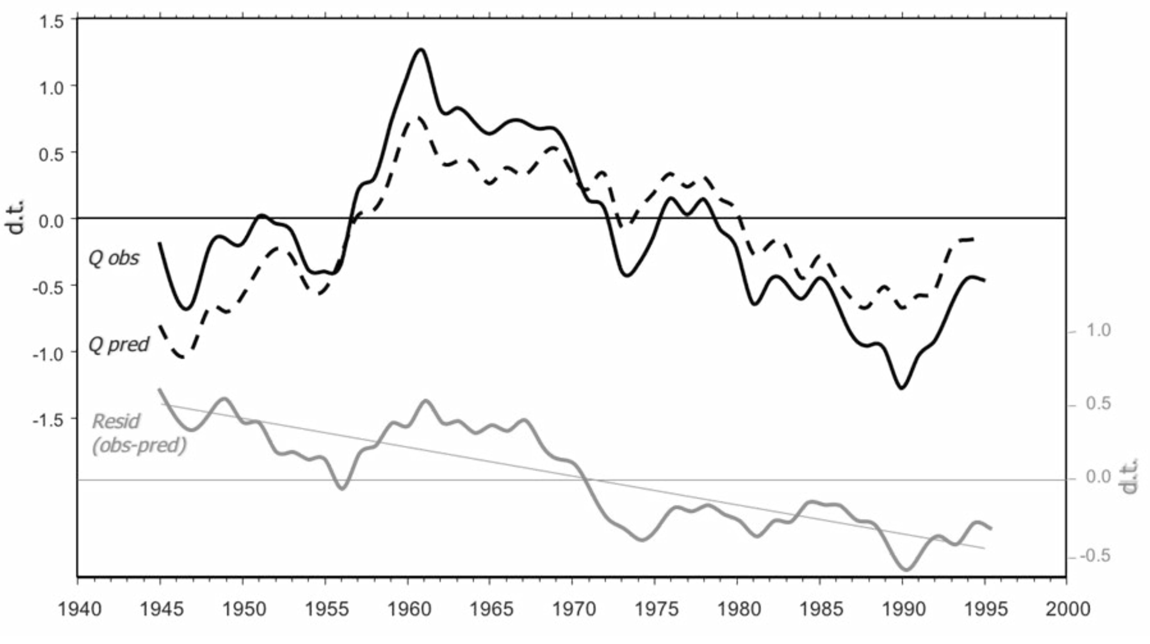

Figure 2.6.2. Time evolution of the observed annual streamflow on natural catchments of the Central Spanish Pyrenes (Q obs), and of the expected streamflow according to a calibrated model considering only annual variations in the climatic forcing (Q pred). The residual, or difference between the expected and the observed streamflow (Resid), exhibits a decreasing trend in the streamflow that is not accounted for by the climatic variability, and which is attributed to the increasing evapotranspiration over the period due to revegetation

2.6.2 Changes in the monthly regime of surface waters

Changes in the monthly regime of streamflows have also been studied. An increase in average temperatures, in principle, should favour the occurrence of rain rather than snow. As a consequence, increasing temperatures imply an increase of liquid precipitation in winter and a decrease in snowfall, a trend that has been reported in the last decades in several studies. For instance, López-Moreno (2005) described a decrease in snow accumulation in the Spanish Pyrenees for the period 1950-1999. A major consequence of this for the hydrological system is an increase in the winter streamflow, together with an earlier start of the snowmelt period. On the contrary, the summer streamflow has been found to show important decreasing trends, as demonstrated for instance by García-Ruiz et al. (2001) or by Stahl et al. (2010). In the Biscay Bay, Zabaleta et al. (2017) documented a trend towards diminishing streamflows in autumn at least since 1955, a trend that can be interpreted as a lengthening of the summer low flow period.

The analysis of streamflow data in the French Pyrenees focused in the study of summer low flows. The study by Giuntoli and Renard (2010) found generalized negative trends (decreasing streamflows) in summer for the period 1968-2008, and the Acclimaterra report (Le Treut, 2013) describes similar trends in the Adour River. All the studies that used simulation models together with future climate scenarios showed an increase in the above mentioned trends. The reduction of the snow accumulation may reach - 78% below 1500 m in the last quarter of the 21st century (López-Moreno et al., 2009). The consequences on river regimes could be especially important during the spring, when strong reductions in streamflow and an earlier occurrence of snowmelt high flows may occur. This is also the case of the summer low flows, which will be longer and more pronounced, while the winter flow will maintain similar values to the present (Figure 2.6.3). The combined effect of climate and land use change accentuates these patterns.

On the French side of the Pyrenees, Boé et al. (2009) used an ensemble of climate change scenarios and a simulation model and projected a similar evolution of the monthly streamflow regime in the Ariège and Garonne Rivers (Figure 2.6.4). Comparing the period 2046–2065 with the reference period 1970–1999, they found a generalized reduction in streamflow, which was stronger in spring and early summer due to the combined effects of reduced rainfall, enhanced evapotranspiration and reduced snowpack. The winter period, on the contrary, showed little variation with the reference period (Garonne), or even had increasing streamflows (Ariège), due to a higher frequency of rainfall episodes with respect to snow episodes. A similar simulation by Caballero et al. (2007) quantified a reduction of around 50% of snow precipitation in the Adour- Garonne catchment for the 2050–2060 horizon, with respect to the reference period 1985– 1995. The consequences of this change would be an increase of the winter streamflow and earlier spring snowmelt flows, together with a reduction of the summer flows of around 11%.

2.6.3 Changes in groundwater and springs

The impacts of climate change on groundwater resources and their future evolution are more difficult to evaluate than surface waters, due to the large variability of the geological characteristics of aquifers (MartínVide, 2016). Thus, groundwater's response to climate forcing is tightly controlled by the characteristics of the geological formations (aquifers) where it is stored. Groundwater will flow more easily in unconfined than in confined aquifers, where low- permeable layers keep it under pressure. The hydraulic interactions between aquifers, such as is the case of coastal aquifers, where an interaction with seawater can occur, is also very important. Finally, the intensity of use (water extraction by pumping) also plays an important role in controlling the response of the underground water bodies (Green et al., 2011).

Aquifer dynamics in mountain regions are very sensitive to small changes in the components of the water balance. There are a number of factors that influence groundwater flows in mountain regions and this need to be accounted for in order to understand their temporal dynamics. In addition to strong altitudinal gradients and contrasting climate, vegetation and soil characteristics, mountain areas usually contain a high density of groundwater springs at different altitudes. Groundwater water recharges, but also discharge, are heavily controlled by snow dynamics. Regarding the availability of information and knowledge about mountain groundwater systems, a characteristic of mountain areas of crucial importance is that they are not easily accessible, which hinders data acquisition.

In a global warming scenario, the reduction of snow precipitation is expected and the snow cover duration will decrease as the snowmelt starts earlier in the season. The peak of groundwater recharge associated to snowmelt will also likely occur earlier in the year. This may lead to water scarcity in areas with limited reservoir storage capacity (Barnett et al., 2005). In snow-dominated regions, the presence of a snowpack reduces dramatically the infiltration of water into the

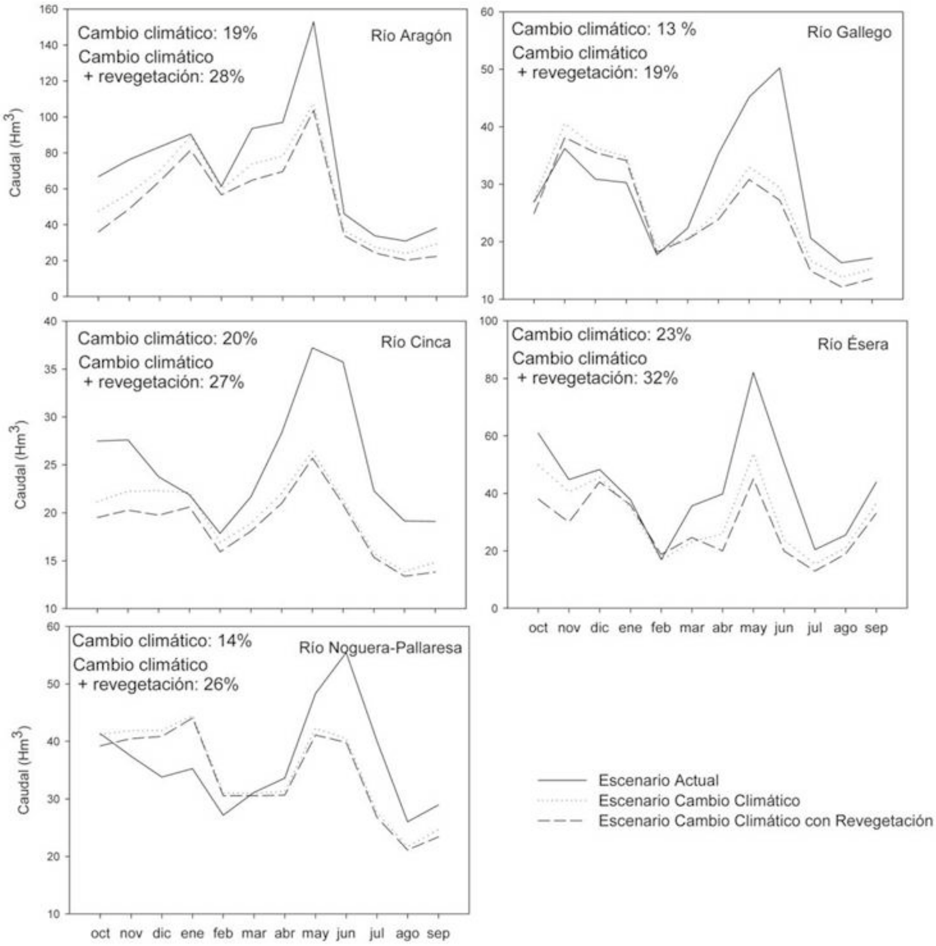

Figure 2.6.3. Variation in the monthly river regime of some Pyrenean rivers in 2050 with respect to the mean regime in the period 1970-2000, for climate change scenarios and climate change plus revegetation scenarios. Source: adapted from López-Moreno et al., 2014.

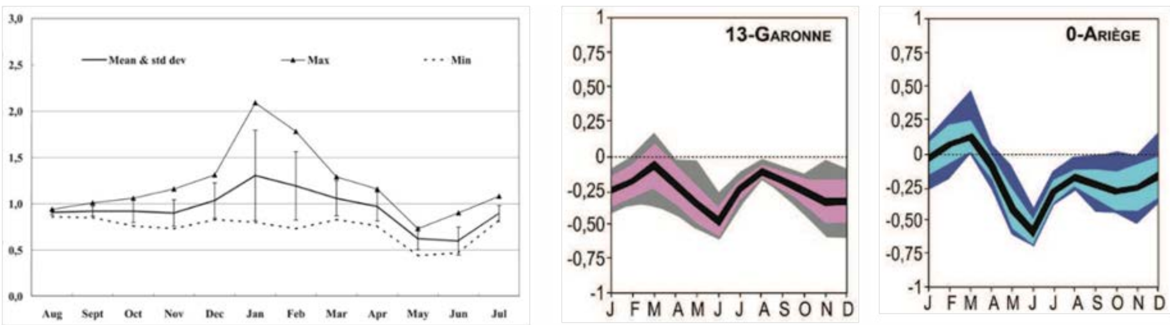

Figure 2.6.4. Relative variation of the monthly regime of the Garonne River in Foix (2055–2065 with respect to 1985–1995); Garonne in Lamagistére and Ariège in Foix (2046–2065 with respect to 1970– 1999). Source: Caballero et al., 2007; Boé et al., 2009.

soil, and hence the groundwater recharge (Kuusisto 1984; Rutulis 1989, Van der Kamp y Maathuis 1991). Due to the direct contact between the subsurface water and the soil, the aquifers, most notably the surficial ones, are especially sensitive to changes in climatic conditions (Winter 1999; Healy and Cook 2002; Sophocleus 2002; Dingman 2002; Lee et al. 2006). It is expected that, in snow-dominated regions, warmer winters would lead to changes in snowmelt and in groundwater recharge (Jyrkama y Sykes 2007; Sutinen et al. 2007). Moreover, the surface runoff due to snowmelt might occur earlier in the year (Veijalainen, 2008). These changes will likely affect the recharge and discharge dynamics of the aquifers, and therefore affect the interaction between groundwaters and surface waters.

Generally speaking, groundwater stored in an alluvial system (in strong interaction with the surface water) or in carbonated (karst) systems tends to show a very fast response to the climatic forcing, while in sedimentary aquifers (combination of sandy and clay formations, more or less consolidated) or in crystalline rocks (granites and schists) it has a slower response. The response of groundwater bodies to climate change can be boosted, or else be mitigated, by the effects of changes in land use and by modifications in the intensity of water extraction. For instance, Kim and Jackson (2012) showed that reforestation leads in general to a reduction of groundwater recharge, possibly enhancing the effects of a warmer and drier climate. This complexity helps understanding the difficulties involved in providing reliable estimations of the volume of water stored in a particular aquifer, or even more to quantify the effects of climate and other changes.

A reliable estimation of the recent evolution of the groundwater stored in the Pyrenean aquifers is not an easy task. This is due in part to the coarse spatial resolution of the existing piezometric network and to the short time span of the existent records (less than 15 years, in general). The Acclimaterra report (Le Treut, 2013) stresses the lack of information about the impacts of climate change on the groundwater resources of the Adour-Garone basin. In a similar way, in the case of the French Pyrenees, it has not been possible to confirm or reject the existence of temporal trends in the hydrogeological systems (AEAG, 2011).

Due to this lack of reliable observational data, most studies used simulation models in order to explore the consequences of climate change on aquifer recharge. A possible reduction of rainfall, seasonal changes and the evolving relationship between liquid and solid precipitation, may have a large influence on the recharge. Additionally, changes in evapotranspiration due to the increase in atmospheric water demand or to changes in land use, may also have an important impact on the recharge. This is especially true in the case of the unconfined aquifers, which are especially sensitive to changes in the water balance. Any future changes in precipitation intensity may also have an impact on the recharge, although this effect is yet to be explored in depth.

In the case of France, the RExHyss project estimated a reduction of 30% in the recharge of hydrogeological systems in the Seine and Somme basins at the end of the XXIst century, due most notably to the reduction of winter precipitation of 12% in average. In the French Pyrenees, Le Cointe et al. (2018) estimated the impact of future climate scenarios on the aquifer recharge in the Adour-Garonne basin. They used climate projections for the RCP 2.6 y 8.2 emission scenarios, using a set of five downscaled General Climatic Models (GCMs), and two alternative water balance models. According to the results, the recharge in the region may experience a -10% decrease by 2050 (on average).

In Spain, Candela et al. (2012) analysed the consequences of climate change on the aquifer recharge in the Siurana basin, a tributary of the Ebro River. They used the hydrogeological model Visual Balan (Samper et al., 2005), together with an ensemble of climate projections from various RCMs under the SRES A2 y B1 emission scenarios. They estimated a decrease of the aquifer recharge of between 5 and 15% by 2050. This trend could be higher if the effects of future land use change were added to those of climate change, for instance a reduction of cultivated areas linked to higher forest cover. Ortuño et al. (2009), using the same model and climate change scenarios, analysed different basins in Catalonia. They stressed the difficulties involved in quantifying the present and future rates of aquifer recharge and also stressed the variability found between different aquifers and across different climate scenarios. Despite this variability, they evaluated the average change in recharge for 2070-2100 to a 25% decrease for the A2 scenario, and 19% for B2. Another prospective study from the Ebro basin water authority (Confederación Hidrográfica del Ebro, CHE, 2005) estimated, for the time horizons 2010-2040, 2040-2070 and 2070-2100, average reductions of 12%, 21% and 19% for the total streamflow in the basin; b) 17%, 25% and 19% for surface runoff; c) 9%, 18% and -8% for the hipodermic flow; and d) 13%, 23% and 20% for the subterranean flow. These results were based on the use of the GIS-BALAN model, created with climatic data from the CGCM3 model and the A1B, A2 and B1 scenarios as well as the Commit scenario from the CCCma. The calibration of the hydrological model was performed against streamflow and piezometric data, for the 1970-2000 period.

Finally, changes in hydrogeological systems may have an impact on the numerous water springs on both sides of the Pyrenees, be them in karst, crystalline, sedimentary or even alluvial aquifers. The mean spring discharge, as well as its seasonal variability, depends largely on the behaviour of the aquifer. Therefore, springs that are linked to unconfined aquifers will most likely be affected by changes in the water balance of their recharge areas. The springs that will be most affected by climate change will be those that already have a strong seasonal behaviour, with strong fluctuations between high and low discharge periods within the year. Some springs, as noted in many cases in the Pyrenees, may even have persisting dry periods during droughts. These episodes may become more frequent in the future in this type of systems, which have a low storage capacity and short resident times.

2.6.4 Changes in the physical and chemical characteristics of water bodies

Water quality, i.e. the concentration of natural and artificial compounds–such as pollutants–in the water, depends on the relationship between the water bodies and the contamination sources, but also on the amount of flowing water. There may be diffuse sources for contaminants (e.g. runoff from agricultural fields) or point sources (e.g. from deficient waste water treatment devices). However, the amount of streamflow is the major driver of changes in the metabolic parameters of the biologic communities and physical and chemical water parameters, especially at small spatial and temporal scales such as those characteristic of small mountain streams (Hunt et al., 2012; Marcarelli et al., 2010). At these small scales, the presence of contaminants has a predominant importance for water quality.

As seen in previous sections, climate and land use change (mostly re-vegetation) have affected the surface streamflow, and they will continue to do so in the future, which will in turn have an effect on water quality. Longer and more intense summer low flows, and stronger droughts, lead to a rise in the contaminant concentration, and therefore imply a reduction of water quality. High flows, on the other hand, although initially promote contaminant dilution and have a positive effect on the water quality, are also responsible for re-mobilizing sediments and associated contaminants which are often stored close to diffuse sources (Petrovic et al., 2011). Other factors that influence the contaminant dynamics are closely linked to human activities (infrastructures such as reservoirs, water diversions, power plants, water extraction points, etc), and all these factors are present in the Pyrenean rivers. In addition, extreme events also have an impact on the thermal transfer between air and water (Val et al., 2017). Changes associated to climate change in this energy transfer process may lead to changes in the chemical and biological processes that play a role in water quality dynamics.

A reduction of the streamflow implies in most cases a deterioration of water quality due to the increasing concentration of contaminants of human origin (Petrovic et al., 2011). The combination of lower flows and the presence of toxic substances that affect the aquatic communities may cause structural and functional problems in fluvial ecosystems (Val et al., 2016a, 2016b). The close relationship between water level and quality (chemical and biological) has been long recognized and it is integrated in the Water Framework Directive (DMA). For instance, the recommendations for water monitoring stress the importance of covering "the volume and level or rate of flow to the extent relevant for ecological and chemical status" (DMA, art. 8).

The lack of streamflow in some fluvial sections can be especially problematic when these streams receive the effluent of water treatment plants (EDAR). In this cases (as it the case, for instance, of the Llobregat River), the effluents may represent up to 100% of the streamflow, which causes very important water quality issues downstream. Another risk factor is precisely the opposite situation: the absence of EDAR in many small and medium-sized populations in the Pyrenees. The inadequate sizing of treatment plants and the selection of technologies, which was caused in part by the economic crisis, has stopped the development of EDAR in many locations, and there are many municipalities in the Pyrenees that still lack adequate waste water treatment.

In a context of diminishing streamflow and higher frequency of low periods, it is to be expected that many headwater areas in the Pyrenees will see a deterioration of the water quality due to the processes described above. As a consequence, the rise of the water temperature to air temperature will be an additional factor of stress (Pérez-Zanon et al., 2017). There is evidence of this deterioration in some Pyrenean Rivers. A recent study of historical data on the Gállego River at Jabarrella (Huesca) show a strong impact on the metabolism of the biological community associated to a decrease of the streamflow, that caused an increase of contaminant concentration (Val et al., 2016b).
In the same area, another study (Val et al., 2015c) showed that the increase in water temperature due to a rising air temperature caused a higher sensitivity of the biological community (algae) to the presence of contaminants, and more specifically to mercury contamination. The study also demonstrated that other factors, such as the presence of particulate or

dissolved matter from diffuse sources in the catchment that may also change in the future, may not only modify the water composition but may also have a role in increasing (or decreasing) the toxicity of other contaminants (Val et al., 2015c). For instance, while an increase in the concentration of suspended sediment during high flows may reduce the toxicity of heavy metals, the changes in the quality of the dissolved matter (such as organic carbon) may increase it.

All these predictions are reinforced by the results of previous studies based on diatoms indices (Gomà et al., 2005). These indices give higher value to the presence of species that have a low tolerance to contamination. Therefore, high values of the index are a sign of a better chemical status of the water. In a study performed in 1998 it was found that in the rivers of the eastern part of the Spanish Pyrenees the high streamflow period (due to the snow melt) had the best water quality, while the lowest values were obtained at the end of the summer, during the low streamflow period (Gomà et al., 2005).

2.6.5 Changes in the biological composition of water bodies

Climate change, land use changes and pollution act as stress factors to mountain aquatic ecosystems, threatening their functioning and health. Steep gradients of abiotic conditions in the mountains favor the existence of a variety of micro-habitats that support a rich biodiversity. Organisms inhabiting those habitats are frequently adapted to narrow ranges of abiotic conditions, making them especially sensitive to climatic change (Elsen and Tingley, 2015) (Nogués-Bravo et al., 2007). Certain species can be used as sentinels for environmental degradation. With their presence or absence and their state of health, they can inform us about the health of the aquatic ecosystem.

Amphibians, as semi-aquatic organisms, are affected by changing conditions of their habitat in water and on land. Due to their sensitivity, they are often seen as indicator species for the quality of aquatic ecosystems. Mass extinctions of amphibians on a global scale seem to be related to a complex combination of interactions between habitat loss and environmental degradation as well as emerging diseases (Blaustein and Kiesecker, 2002). The alarming spread of a fungal pathogen, *Batrachochytrium dendrobatidis* (Bd.), has been held responsible for many of the recent declines (Wake and Vredenburg 2008). Bd. epidemics have been observed in various bioclimatic settings and mountain regions are especially affected. Bd. spreads by aquatic zoospores, infecting the skin of its amphibian host. Infection can eventually lead to the disease chytridiomycosis, and cause the death of the host. Bd. is also present in the Pyrenees and has led to local extinctions of amphibian populations. The observed intensification of infections of amphibians with Bd. vary spatially (Figure 2.6.5), with a hotspot of occurrence in the western central part, within or in proximity of the Parc National des Pyrénées.

For species conservation efforts as well as for the surveillance of ecosystems' health it is important to understand which environmental conditions govern pathogen spread. Temperature and water presence are among the most crucial factors controlling pathogen growth and survival. Bd. optimal growth in culture has been observed to be between 17 and 25 °C, and zoospores do not tolerate desiccation (Piotrowski, Annis, and Longcore 2004). Temperatures above this range represent a physiological limitation for the pathogen. Low temperatures, on the other hand, have been linked to triggering disease outbreaks. This can be explained by a changing strategy of Bd., which produces more zoospores in a colder environment (Woodhams et al. 2008). Moist environments favor fungal growth. Higher infection rates have been related to humid climatic conditions (Berger et al., 2004) Murray et al., 2011). Amphibians inhabiting seasonally drying ponds were shown to be less afflicted by the disease (Scheele et al., 2015). Changes in hydro-climatic conditions are superimposed to land-use and land cover changes in the mountain landscape. Those alterations are likely to define Bd. occurrence patterns in the Pyrenees. To explore the pathogen abiotic habitat, data on climate and hydrology as well as physicochemical habitat properties have to be analyzed. The P3 project - People, Pollution and Pathogens – aims at investigating the health of aquatic ecosystems in the Pyrenees and three other mountain ranges (USA, China, Oman). Within the project, samples of water quality, microbiome and sediment of mountain lakes along altitude gradients are taken and analyzed. Hydrological modelling with the Soil and Water Assessment Tool (SWAT) model is used in order to characterize the dynamics of abiotic conditions of aquatic ecosystems in a changing climate. Pathogen distribution will respond to changing conditions in the Pyrenees with possible impacts on ecosystem health.

A general redistribution of continental aquatic species towards higher altitudes as a consequence of climate change has been documented globally (Hari et al., 2006). As the waters of streams get warmer, more tolerant fish species replace cold water species (Matthew, 2016). In mountain streams of the USE, for instance, an early starting of the migration period of salmonid populations has been described as an effect of the rise of water temperature (Kovach, 2012).
The physical characteristics of the water of mountain

lakes are also changing as a consequence of climate change (Thompson et al., 2009). For instance, if the frozen lake duration period reduces, then the photosynthesis period increases. This interacts positively with the higher temperature of the water during a longer period, with the combined effect of boosting the lake's productivity (Mendoza, 2013). A recent PhD Thesis (Mendoza, 2013) describes how the macro-invertebrate populations in the lakes of the Pyrenees will likely respond to global change, with differential responses to its various components: climate change, habitat loss and fragmentation and invasive species. These factors may also interact with each other, resulting in stronger effects. The displacement of the species upstream represents a reduction of the potential habitat, which will likely cause local extinctions.

2.6.6 Findings and adaptation recommendations

The term Integrated Water Resources Management (IWRM) denotes "a coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare" (Agarwall et al., 2000). Despite the relative success of this concept within the scientific community, few examples exist of its practical implementation in the context of water resources management. However, it is clear that in order to cope with the challenges posed by climate change in regards to water resources an integrative approach is required that re-thinks the regional allocation of water uses. Headwater areas generate most of the water resources that are used in-situ and downstream in the water-deficit and highly populated plains and coastal regions. Thus, actions on headwater land uses may represent an effective adaptation option on water-scarce environments. For instance, forest operations such as thinning can enhance groundwater infiltration and surface runoff, hence increasing the production of blue-water[36] at the catchment scale while optimizing the green water[37] productivity at the stand scale. Actions of this kind, also, may have a direct and measurable effect on the societies of the Pyrenees, since they generate labour and economic activity.

Water resources management in the Pyrenees is also faced by knowledge challenges. There are a number of actors (basin authorities and others) with responsibilities in monitoring and managing water

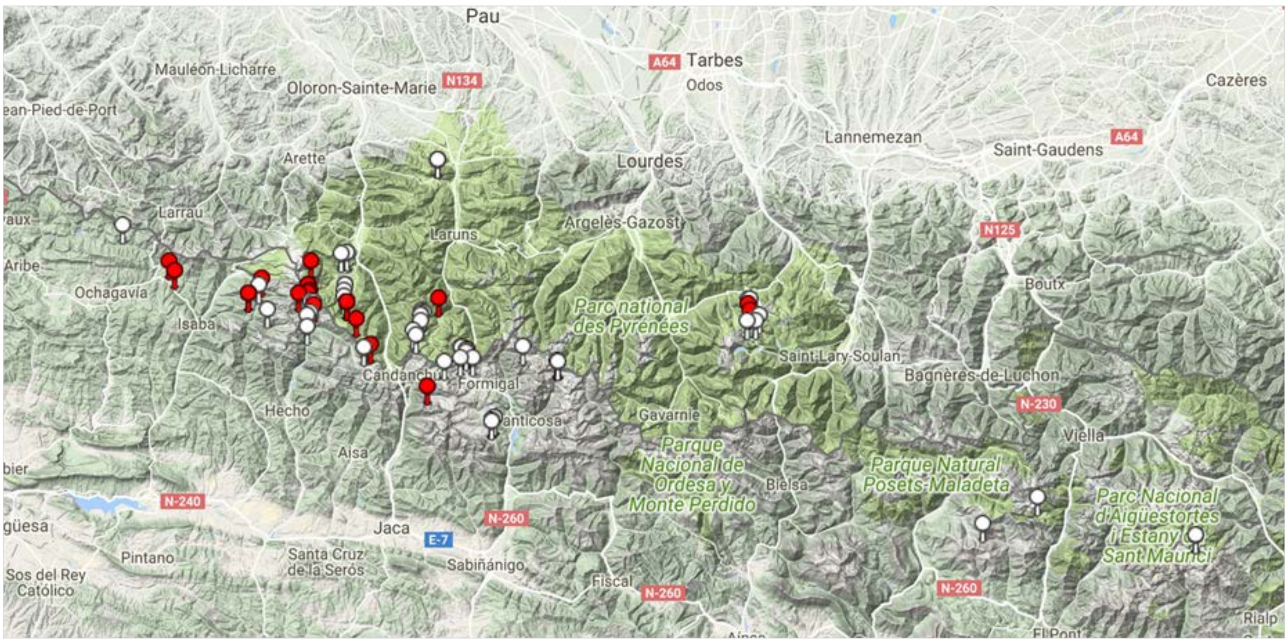

Figure 2.6.5: Prevalence of Batrachochytrium dendrobatidis in the central Pyrenees: locations with confirmed presence (red markers) and absence (white markers) of the fungi. Source: www.bd-maps.net.

resources, and there are monitoring networks and a good number of prospective studies, as we have reviewed in this chapter. However, there are no evaluations of the water resources that include the whole territory of the Pyrenees. The absence of trans-boundary studies is especially lacking, because the mountain range is a Key element in their interaction with the atmospheric dynamic, so any study on future water resources needs to take into account the mountain range as a whole. The importance of this issue is patent, for instance, when future climate simulations performed on either side of the Pyrenees are compared. A modification of the trajectories of the extra tropical cyclones that are responsible for a significant part of the precipitation in the region is frequently predicted by thess simulations, but often with an opposing sign, consequently this pattern of change on the hydrological system on both sides of the mountain range is also opposing. There is, therefore, a need for prospective studies that consider the Pyrenees in an integrated way.

(36) Blue water refers to the surface water resources (water in rivers, lakes and reservoirs) and the groundwater resources (water in the aquifers), and represents the fraction of the water resources that can be distributed and used elsewhere.

(37) Green water refers to the water resources stored in situ after precipitation occurs, most notably in the soil, which is directly evaporated to the atmosphere or used by plants (either natural vegetation or crops) through transpiration in order to satisfy their physiological demand. The green water is, therefore, part of the water resources of a given territory.

BOX 2.6.1 NATIONAL AND REGIONAL CLIMATE CHANGE ADAPTATION STRATEGIES RELATED WITH WATER RESOURCES

At the national level, France and Spain were the first countries in the EU to develop their own Climate Change Adaptation Strategies. The Spanish National Plan for Climate Change Adaptation, launched in 2007, recognizes mountain areas as the most vulnerable to climate change. This same plan establishes a series of goals for the evaluation of climate change impacts and the development of measures of adaptation in mountain areas:

1) Introduction of sectorial or territorial evaluations in the field of mountains, including the cartography of the impacts of climate change;

2) Development of climate change monitoring networks, including indicators;

3) Monitoring and characterization of the impacts of climate change on the hydrological balance.

The French National Plan for Climate Change Adaptation, launched in 2006, presents as a primary goal the presentation of concrete operative measures for tackling and making the most of the new climatic conditions, and identifies some of these, such as the rise in temperatures, heat waves and more frequent and intense droughts, etc. The document presents territorial adaptation measures as indispensable and complementary to actions for the mitigation of climate change such as policies for the reduction of greenhouse gas emissions.

There are relevant initiatives at the regional level, such as the 2013 Catalonian Strategy for Climate Change Adaptation. It evaluates the observed and forecasted effects of climate change in different socio-economic and environmental sectors, identifying and promoting concrete measures for adaptation. Likewise, the Aragonese Climate Change Adaptation and Clean Energy Strategy plans for climate change mitigation and adaptation strategies, complementary to the Spanish strategy. The Bask Country Fighting Against Climate Change aims for 2020 at the consolidation of a new carbon-free socio-economic model and minimizing vulnerability to climate change. The Navarran Strategy Against Climate Change also identifies concrete goals and actions to improve the Navarran society's adaptation potential to climate change within the same 2020 horizon. The 2009 Climate Plan of the Languedoc-Roussillon region also proposes adaptation measures mobilizing all the competencies of the region. The Midi-Pyrénees region developed as well a Regional Plan for Climate, Air and Energy, adapting the national strategy to the particularities of the region. The Aquitaine Regional Plan for Climate, Air and Energy launched in 2012 establishes a framework for adaptation in the region, including through the creation of a committee of experts to combine public policies with scientific knowledge, especially to adapt to the needs of the region.

Concerning the management of water resources, the European Union has widely recognized the necessity to guarantee a sufficient supply in quantity and quality. The Water Framework Directive (2000/60/EC) is the central document in terms of management of water resources and protection of hydrological systems. This directive has been translated for instance in the Basin Management Plans realized by the different basin organizations, in agreement with and developing the principles of the Water Framework Directive.

Another European document (COM/2007/414) tackles the challenges linked to water scarcity and droughts in the European Union, emphasizing the importance of promoting efficient measures of water resources management. The Directive related to environmental quality in the field of hydrological management (2008/105/EC) defines the concentration thresholds for different polluting substances in water bodies. At the national level, the different water management organizations have adapted the general framework of the European Directive to their respective basins, launching management plans for hydrological resources for different future scenarios.

3. Impacts of climate change on socio economic sectors

3.1 Tourism

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ABSTRACT

Tourism is an economic driver in the territories of the Pyrenees. Snow sports in Aragon comprise 7% of the GDP, with skiers spending around 170 million euros each season (ATUDEM (Tourism Association for Ski and Mountain Resorts in Spain)2016). In Andorra, snow sports comprise an estimated 15% of the GDP, with a direct, indirect and induced impact of around 450 million euros each season (OBSA (Sustainability Observatory of Andorra), 2014, UNWTO data search on the economic strength of tourism on both sides of the Pyrenees). Climate plays a Key role in mountain tourism. Climatic factors and weather conditions are decisive in the perceived touristic appeal of different destinations and thus determine tourists' choices (Eurostat, 2015). There are two specific and important aspects of the effect of climate change on the choice of tourism destinations. Firstly, it can trigger direct effects in tourists linked to changes in thermal comfort. Secondly, climate change may also be decisive in determining the necessary conditions for certain activities (e.g. sufficient snow cover and thickness for skiing), and may cause environmental changes which have negative contextual effects. Specifically, aspects such as the presence or lack of certain emblematic fauna and flora, ecosystem quality, the state of iconographic natural formations and that of the environment in general could be affected by climate change (Perels et al., 2015) and lead to a loss of touristic interest.

For many tourists, climate conditions may determine how they plan their trip, orienting it towards a location with the ideal conditions for their chosen activity. It is therefore highly likely that the increase in climate variability forecasted for the upcoming decades, together with average temperature increases, will trigger changes in current choices of tourism destinations, with both positive and negative repercussions on the dynamic of tourism flows on both sides of the mountain range.

3.1.1 Reduction of winter tourism appeal of ski resorts

Current situation: Winter tourism is the main source of income and the driving force of local development in many areas of the Pyrenees (UNWTO, 2015). However, in recent years this tourism industry sector has been identified as being extremely vulnerable to the effects of climate change (Pons et al., 2015; EEA, 2017). The significant increase in average, maximum and minimum winter temperatures recorded on both sides of the mountain range during the last century (OPCC, 2013) and the high sensitivity of snow to temperature increases have led to a reduction in the proportion of winter snow precipitation, and an increase in the amount of energy available for snowmelt (Rood et al., 2008). Consequently, the number of days with sufficient accumulation of snow for the normal practice of the various types of alpine skiing are decreasing, and the snow line is migrating towards higher altitudes (Minder, 2010; López-Moreno et al., 2013). A recent study on the evolution of the snow cover and the number of skiable days in ski resorts of the Pyrenees found a significant reduction in the number of days per year with a snow thickness of 0 to 30 cm and from 30 cm to 100 cm in all ski resorts during the period between 1960 and 2010, particularly in low-altitude resorts (5-70% and 42-100% respectively) and mid-altitude resorts (4-20% and 20-65% respectively) (Gilaberte-Búrdalo et al., 2017). The season start date is also arriving gradually later (based on the availability of natural snow), with delays of between 5 and 55 days in low altitude resorts and between 5 and 30 days in mid-altitude resorts. This delay has economic implications and generally leads to a reduction in annual income: the national holiday in early December, the last few weeks of December and the start of January are particularly busy times for winter sports tourism. If the delay in the start of the snow season coincides with the period of greatest tourism demand, ski resorts are systematically forced to use artificial snow as a means of remaining operational. This has significant impacts on energy expenditure, not to mention the huge outlay in maintaining artificial snow machinery (Steiger and Stötter, 2013). Related studies in other Mediterranean mountain areas (Goyette et al., 2011; Lopez-Moreno and Vicente-Serrano et al., 2011; Franch et al ., 2016) and in the Alps (Endler and Matzarakis, 2011; Beniston et al., 2013) show similar data to those obtained for the Pyrenees.

In terms of other socio-economic factors, the water demand for snowmaking could lead to conflicts between intensive water-demand sectors in a context of reduced water availability caused by climate change and changes in land use, especially in some subbasins of the Pyrenees. This is the case in the Adour and Garona subbasins, where for some years the water demand for snowmaking has been practically on a par with that for hydroelectric and industrial uses (Clarimont et al., 2008). Large-scale artificial snowmaking, not only threatening the profitability of ski resorts, also entails a series of environmental externalities which must be considered, particularly against the backdrop of a future with scarcer water resources (Steiger and Abegg, 2013). Furthermore, the increase in winter temperatures will also affect the ability to efficiently produce artificial snow, and lead not only to an increase in production costs but also to a reduction in the number of suitable days for snowmaking (Steiger and Abegg, 2013; Pons et al., 2015). In parallel to the resulting socio-economic effects, a significant increase in snowmaking would also lead to several large-scale serious environmental externalities. Mass- snowmaking could have negative effects on vegetation and lead to more hillside erosion, as well as increasing the risk of water pollution, owing to the potential presence of additives.

Future projections: The main climate models concur in predicting a worsening of the current situation towards the middle and end of this century. With average temperature increases in the Pyrenees of up to 2ºC by 2070 and up to 4ºC by 2100 (Lopez-Moreno et al. 2008; ENSEMBLES, 2012; EURO- CORDEX, 2014) it is highly likely that both the thickness and surface cover of snow will continue to decrease over the coming decades, with a subsequent reduction in the skiable surface area and in the number of skiable days each season. If these predictions come to pass, not only will there be significant changes in the hydrological cycles and in the ecosystems of the Pyrenees, but the winter tourism sector will be up against serious challenges (SCAMPEI, 2012; Steger et al., 2013; Kovats et al., 2014; Pons et al., 2014; EEA, 2017).

A study by Pons et al. (2015) estimated the impact of climate change on (and therefore the vulnerability of) the future operating capability of ski resorts on both sides of the mountain range (Figure 3.1.1).

The study assessed the future operating capability of the main ski resorts in the Pyrenees under two scenarios for average temperature increases (+2ºC, average winter temperature increase predicted for 2051-2070, and +4ºC predicted for 2071-2100), and based on the use or not of snow cannons and piste grooming. The proposed scenarios are linked solely to the predicted temperature variations, since temperature is the variable with more influence in snow cover projection models (Pons et al., 2015). Based on the criteria used in this study, 93% of ski resorts in the Pyrenees are currently able to operate normally during an average ski season length, without the use of artificial snow. This percentage would rise to 98% with the use of snow cannons. However, this percentage would reduce to 44% in a +2ºC scenario, and for increases in average temperatures of 4ºC the total percentage of ski resorts with full operating capability would drop dramatically to just 7%. Technical adaptation measures would have a positive impact on the first scenario (from 44% to 85%), but snowmaking in the +4ºC scenario would have merely residual effects and would not generate any significant increase in the percentage of fully-operational ski resorts, owing to the reduction in the number of suitable days for snowmaking.

Climate change impact studies are not very encouraging for the sector, but there may be substantial differences in the level of sensitivity and vulnerability to climate change of ski resorts in the Pyrenees, based on their geographical, topographical and managerial characteristics (Campos Rodrigues et al., 2016; Navarro-Serrano and López-Moreno, 2016; Gilberte-Búrdalo et al., 2017). In fact, there are significant variations in the degree of vulnerability of ski resorts which are relatively close to one another -even within the same valley- based on their diversity, their geographical, climatic and managerial differences, and socio-economic and touristic factors. This difference in vulnerability enables us to classify ski resorts into three different groups. For the high vulnerability group, both the medium and high climate change scenarios would affect their activity, and technical adaptation measures would not be sufficient. For the medium vulnerability group, technical adaptation measures may be sufficient under a medium climate change scenario. With more intense changes however, these resorts will be forced to use more structural measures and to adjust to continuous operations as mountain tourism resorts, rather than seasonal skiing facilities. Lastly, the

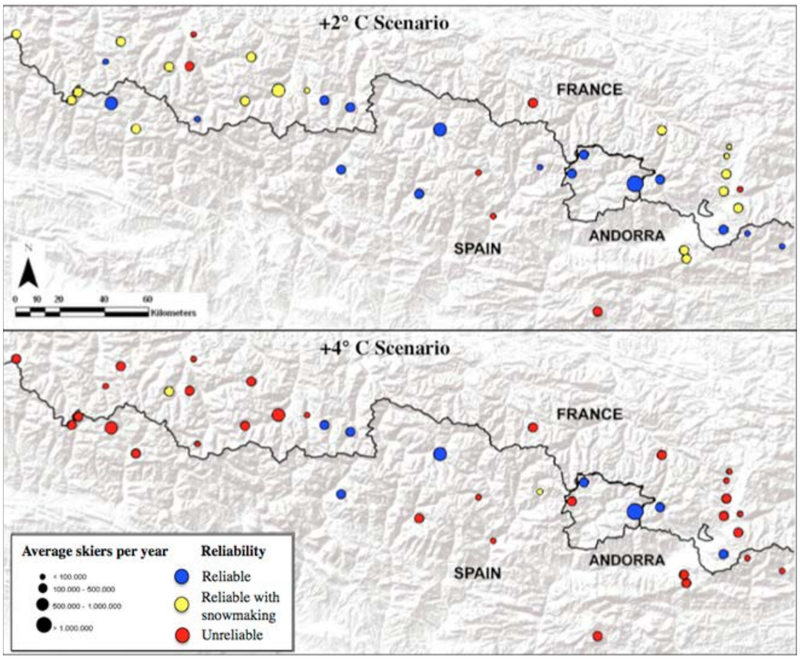

Figure 3.1.1. Evolution of the operating capability of ski resorts in the Pyrenees with and without artificial snow production for two different periods and scenarios (+2ºC for 2051-2070, and +4ºC for 2071-2100). The colours of the dots refer to predictions on the operating capability of ski resorts based on the scenarios. The blue dots represent ski resorts which are predicted to remain operational, yellow are those which will remain operational provided they produce artificial snow, and the red resorts will have difficulty operating some years, even using artificial snow as an adaptation measure. The size of the dots is proportional to the number of skiers received each year by each of the resorts studied. Source: Pons et al., 2015.

geographical and socio-economic characteristics of the most resilient ski resorts mean they have a competitive advantage over others. Contrary to the findings of other studies (Campos Rodrigues et al.,2016), said resorts will not suffer a reduction in skier numbers but may attract skiers from more vulnerable resorts (Pons et al., 2014). This hypothesis concurs with data on the skier intake in certain ski resorts in the Pyrenees, whereby intake improves or variability is lower during seasons with marginal conditions compared to seasons with good snow conditions. During the closure of a resort or when snow conditions are marginal, only an estimated 5% of skiers refrain or would refrain from skiing. The rest look for an alternative location or skiing more intensively once conditions at the resort improve (Rutty et al., 2015). Hence, rather than a shrinking of the entire ski sector, there is likely to be a redistribution of the market between more vulnerable ski resorts in the Pyrenees and those which are more resilient. Good adaptation to climate change should therefore be based on tailored actions in each resort, based on their degree of local vulnerability and the expected magnitude of the impact (Pons et al., 2014).

BOX 3.2.1 ESTIMATED ADAPTATION COSTS FOR SKI RESORTS: AN ECONOMIC ASSESSMENT

Economic assessments of estimated adaptation costs can be highly useful in decision-making around adaptation. Although economic assessments and estimations in this field should be interpreted with caution given the inherent uncertainties about the future (evolution of the economy, global emissions and future climate variability), these studies facilitate a clear analysis of the hypothetical costs and benefits of possible adaptation measures. Said studies enable adaptation measures to be optimised by weighing up the cost and potential benefits, and enable decision-makers to make an objective assessment of the feasibility of these options (Howden et al., 2007).

A recent study by Campos Rodrigues et al. (2016) analysed the impacts of climate change on winter sports areas in Spain, focussing on a description of potential adaptation measures. The researchers performed a cost-benefit analysis based on various climate scenarios and two adaptation measures: increasing artificial snow production, and lengthening the hours of activity (night skiing). Table 3.1.2 compiles the estimated future loss of income (without adaptation measures) under three different scenarios involving a reduction in the number of skiable days (low scenario: -10 days, medium scenario: -20 days, high scenario: -30).

Sistema montañoso	Estación	Escenario bajo		Escenario medio		Escenario elevado	
		Forfaits diurnos vendidos	Pérdida de ingresos (€)	Forfaits diurnos vendidos	Pérdida de ingresos (€)	Forfaits diurnos vendidos	Pérdida de ingresos (€)
PC	Baqueira Beret	731 805	–1 360 040	669 787	–2 720 081	545 753	–5 440 161
	Boí Taüll	101 608	–198 952	92 536	–397 904	74 391	–795 807
	Espot Esquí	58 072	–112 701	52 933	–225 401	42 655	–450 802
	La Molina	244 188	–473 898	222 579	–947 797	179 360	–1 895 594
	Masella	340 906	–602 908	313 413	–1 205 816	258 428	–2 411 632
	Port Ainé	96 735	–187 735	88 175	–375 470	71 053	–750 940
	Port del Comte[1]	47 357	–101 818	42 714	–203 636	33 429	–407 271
	Vall de Núria	41 729	–88 846	37 677	–177 691	29 575	–355 382
	Vallter 2000	55 470	–105 780	50 647	–211 560	41 000	–423 119
PA	Astún	179 735	–394 160	161 762	–788 320	125 815	–1 576 639
	Candanchú	173 333	–365 500	156 667	–731 000	123 333	–1 462 000
	Cerler	226 073	–438 743	206 067	–877 485	166 054	–1 754 971
	Formigal	475 928	–940 279	433 051	–1 880 557	347 299	–3 761 115
	Panticosa	75 552	–149 267	68 746	–298 534	55 133	–597 069

Figure 3.1.2. Estimation of the number of daytime ski passes sold and loss of income (in euros) associated with the climate scenarios, for ski resorts in the south-eastern Pyrenees (PC) and the southwestern Pyrenees (PA). Source: Campos Rodrigues et al., 2016.

The authors of the study concluded that based on the different climate scenarios, adopting the two tested adaptation measures would entail a significant increase in total costs in any case, and could jeopardise the future economic viability of some ski resorts. Said costs could be compensated by increasing the number of ski passes sold. In this case, the percentage of passes necessary to cover the costs of artificial snow production could exceed 10% for some resorts, and may even exceed 25% based on the scenarios considered. In any case, the overall estimated financial balance according to this study (result of the loss caused by the reduction in skiable days, the costs of increasing opening hours and the income from selling night ski passes) is negative for all ski resorts. The results suggest an aggregated negative balance of between 7 and 33.1 million euros. The authors conclude that some resorts in the Pyrenees may need to rethink their financial model and invest in other mountain activities more suited to future climate scenarios. Furthermore, when adopting structural or 'grey' adaptation measures, it is important to consider possible emerging challenges such as the need to involve regional economic agents in the debate, the possible need to exploit the physical capital invested in ski resorts, or an analysis of the labour market in each resort to assess its ability to adapt to a possible diversification of the sector.

3.1.2 Alteration of iconic elements of the Pyrenean landscape

Current situation: another possible impact of climate change on tourism in the Pyrenees is linked to landscape changes and particularly to the accelerated degradation of certain iconic features of the alpine landscape, such as peat bogs, glaciers and lakes (Stewart et al., 2016). Furthermore, the effects of global warming on biodiversity in the mountain range - such as physiological changes to forests, shift to higher altitudes of some plant community's distribution area, or a reduction in biodiversity - could, together with the degradation of the aforementioned iconic features, contribute to a reduction in the visual appeal of the landscapes of the Pyrenees. The use of forests for recreational purposes could also be affected by an increased risk of forest fires (Barrio et al., 2007; Hystad and Keller, 2008), and by the possibility of some rivers and streams drying up or water quality being affected by reduced precipitation during some seasons of the year (Moreno et al., 2010).

The accelerated retreat of the Pyrenean glaciers not only implies a series of indirect ecological impacts but represents an irreversible loss of cultural and environmental heritage (Houghton et al., 2001). From 1984 to 2016 an estimated 20 of the 39 glaciers recorded in 1984 disappeared, which equates to a glacier surface area loss of 516 ha. In other words, just over half of the glaciers in the Pyrenees have disappeared in just 32 years (Lopez-Moreno et al., 2016; Rico et al., 2016).

If climate projections were confirmed, it is highly likely that most European glaciers will disappear by the end of this century, which would mean the disappearance of almost all glaciers in the Pyrenees, given that they are the southernmost in Europe (Radić et al., 2014; Marti et al., 2016).

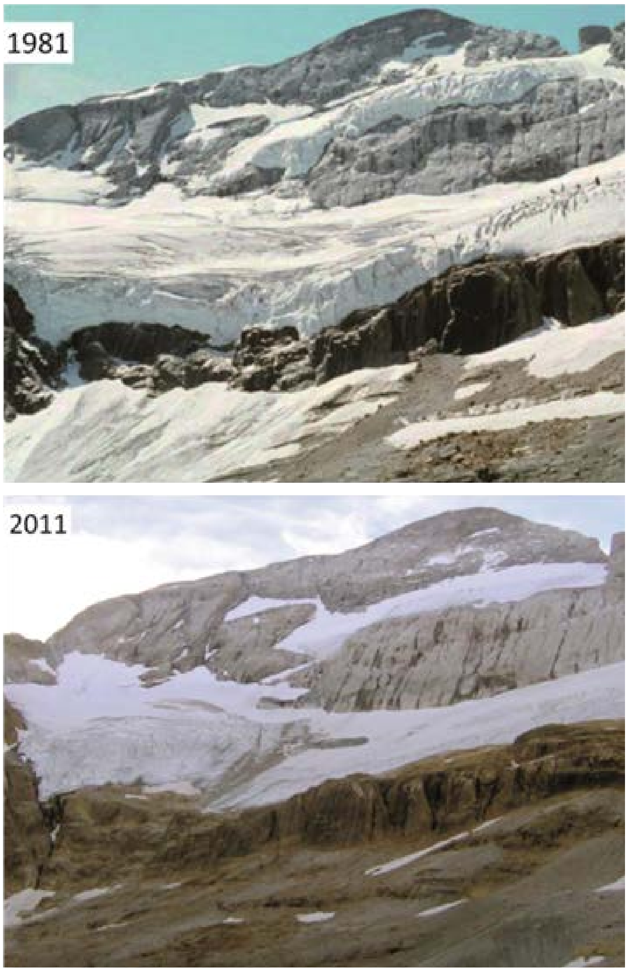

Figure 3.1.3. Monte Perdido glacier in summer 1981 (left) and summer 2011 (right). Source: Lopez- Moreno et al., 2016.

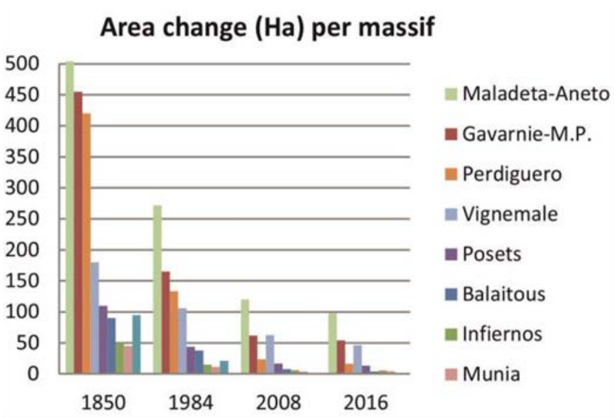

Figure 3.1.4. Estimated evolution of the area of the main glaciers in the Pyrenees. Source: Rico et al., 2017

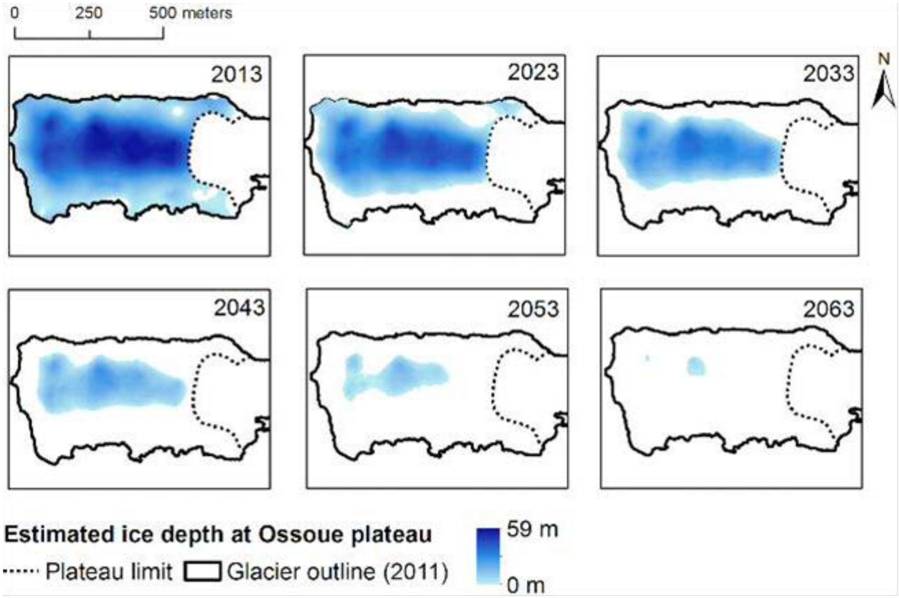

Figure 3.1.5. Estimations of the glacier ice depth on the d'Ossoue plateau in the coming decades. Source: Marti et al., 2016.

3.1.3 Increased vulnerability of tourism infrastructure to hydrological and geological phenomena and to extreme weather events

The influence of climate change on water resources and the risks derived from extreme weather events is an element of instability capable of causing serious damage to infrastructure which is directly and indirectly related to tourism in the Pyrenees (hotel complexes and rural apartments, shelters, telecommunication networks, mountain roads and tourism trails), and in some cases may jeopardise the integrity of local populations (Nogués-Bravo et al., 2007). The potential implications of the hydrological and meteorological risks in the tourism sector include direct harm to people as well as damage to accommodation and tourism infrastructure. The potentially catastrophic hydrological and geological phenomena which are most susceptible to climate- induced variations include sudden floods or those caused by more frequent intense precipitation, avalanches, and landslides caused by more frequent freeze-thaw cycles induced by greater climate variability (Keiler et al., 2010; Raia et al. 2012). Another aspect to consider is the possible affections to the security of mountain users due to glacial risks intensified by climate change. In particular, degradation of permafrost can lead to an increase in rock falls among other gravitational events (Rico et al., 2017) in addition to morphological changes in iconic mountains such as Vignemale or Aneto (more information in Chapter 3.4. Natural hazards).

3.1.4 Lengthening of the mountain tourism season

Climate change could also have positive effects on mountain tourism. The longer summer season and progressively milder temperatures in spring and autumn, together with the rise in minimum temperatures, could result in tourists opting for mountain destinations in place of others which are less comfortable owing to high temperatures (Isoard et al., 2008). This could give the Pyrenees a competitive advantage over beach holiday areas. Tourists may gradually start choosing to go on holiday in the mountains instead of on the coast, where the higher average and maximum temperatures could significantly reduce the appeal of climate conditions at lower altitudes (Scott et al., 2007).

BOX 3.1.2. CLIMATE SUITABILITY MODELS FOR TOURISM

There are various approaches to assessing the impact of climate change on tourism. The models of climate suitability for tourism (Becker, 1998; Mieczkowski, 1985; Moreno and Amelung, 2009) incorporate several meteorological parameters including temperature, precipitation and wind to try to summarise, in one value, the climate suitability of different destinations for different tourism activities. Whilst these models are not free from limitations (there is little empirical evidence on tourist behaviour) and should therefore be interpreted cautiously, they are nonetheless one of the most useful tools for assessing the effects of climate change on tourism. The climate variables utilised in these models are generally available, and they can incorporate seasonal changes in climate factors. Tourism climate indices (TCI)[38] are used to study the relationship between weather and environmental conditions and the physical wellbeing of people. They facilitate an assessment of different locations in relation to the level of comfort offered to tourists, the activities carried out by tourists in each zone of a territory, and the season of the year. A TCI for summer tourism in coastal areas will therefore yield different results than a TCI for mountain tourism. Through the European project PESETA, Amelung and Moreno (2009) have shown that there is a high level of correlation between this index and tourism flows in Europe.

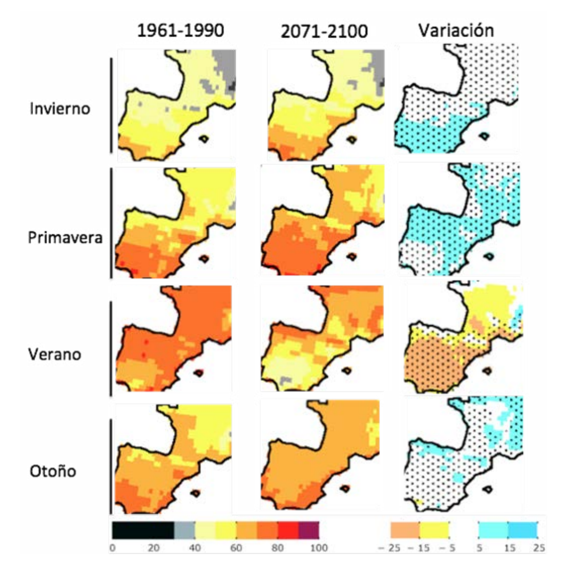

Figure 3.1.6. TCI values calculated for the reference period (1961-1990, left column), future TCI projections (2071-2100, central column) and the variation in the TCI between these periods (right column). Future climate conditions are based on the SRES A2 emissions scenario and use the mean of 5 models of climate projections from the European project PRUDENCE. Source: Perch-Nielsen et al., 2010.

Comparing the current TCI against future projections (Figure 3.1.6) suggests in general terms that the ideal conditions are to be found at higher altitudes and latitudes. Climate change is likely to push the 'favourable climate' zone towards the north and towards higher altitudes, which would improve the tourism appeal of the Pyrenees, particularly in Spring and Autumn. The situation during the summer period tends to remain stable or with only a slight increase in suitability, but this is significant when compared with the situation in coastal areas. Forecasts point to a worsening of thermal comfort in coastal zones in both France and Spain, which could open up new opportunities in nature and
mountain tourism sectors (Perrels et al.,2015).

(38) The TCI proposed by the geographer Z. Mieczkowski is considered the benchmark index for assessing the impact of climate change on tourism, and incorporates meteorological variables considered decisive in full tourist satisfaction.

3.1.5 Findings and recommendations

Tourism in the Pyrenees - an important economic driver of the regions situated along the mountain range - is particularly vulnerable to the impacts of climate change. The size of the predicted impacts will depend largely on the adaptation strategies adopted by the various parties in the sector (tourists, tour operators and management authorities) and on their capacity to implement adaptive management. This section summarises the main challenges facing the Pyrenees tourism sector and outlines the main recommendations for climate change adaptation in this regard. The Findings are set out as a list of the main climate challenges in the sector, and the adaptation recommendations are provided based on three types of intervention or adaptation measure: *green, grey* and *soft*.

Main challenges

- Rethinking tourism models to strengthen the resilience of the sector against a future reduction in the number of skiable days and greater environmental pressure caused by its activities, whilst capitalising on emerging opportunities for nature and mountain tourism (mountain resort concept);

- Reducing the vulnerability of tourism infrastructure to the possible increase in extreme and catastrophic hydrological, geological and climatic events, and safeguarding the physical integrity of tourists;

- Strengthening environmental management strategies and plans to reduce the vulnerability of the ecosystems and biodiversity of the Pyrenees, with a focus on sensitive alpine ecosystems (tarns, glaciers, peat bogs, etc.);

- Ensuring balanced management of water resources in the tourism sector, particularly basins supplied by rainwater.

Recommendations

This section compiles a set of general measures geared towards establishing mechanisms for increasing resilience of the tourism sector to the future climate and its variability. There is no one effective pre-established combination of measures for all tourist destinations in the Pyrenees. Rather, each local area must carry out a detailed study of its particular vulnerability and establish its own priorities before formulating and implementing a set of climate change adaptation measures which are optimal in terms of effectiveness and efficiency (cost/benefits).

Soft measures[39]

- Decentralising and diversifying the tourism offer by developing mountain and nature tourism, thus ensuring the economic sustainability of the sector as the climate changes (deseasonalising mountain tourism). All local parties should be involved in the process.

- Putting specific management plans and regulations in place for conserving or reestablishing the natural features of tourism areas and ensuring their good conservation status, even under future climate conditions.

- Utilising short-term seasonal forecasts for planning short-term marketing activities (UNWTO et al., 2008).

- Guaranteeing the availability of data on tourism-related demand for, and consumption of, natural resources, to ensure environmental sustainability in the sector.

- Developing research into the repercussions of the physical impacts of climate change in the Pyrenean tourism sector (e.g. development and monitoring of socio-economic impact indicators, research into perception of risk by local socio-economic agents).

- Adjusting the ski season start and end dates.

- Introducing technical and managerial measures which may increase the tourism appeal of ski resorts (e.g. night skiing).

- Developing systems for the integrated management of tourism resources within the mountain range to help create the conditions for longer stays across the entire Pyrenees region throughout the year.

(39) Soft or non-structural measures reduce or alleviate the negative effects of climate change. This category of measures typically comprises research to bridge knowledge gaps or to enrich the knowledge base on climate change, its impacts and the most vulnerable sectors. It also includes the development of specific methodologies and systems for reducing the risks associated with climate change (e.g. developing a cross-border early warning system for managing heat waves in the mountain range).

Green measures [40]

- Ensuring the good conservation status of natural corridors and their adaptation to future climate conditions, thus strengthening the gradual interconnectedness of natural spaces in the Pyrenees to guarantee the good health status of mountain ecosystems.

- Where possible, increasing tree cover on the areas between pistes to increase the area of shaded piste and lengthen the duration of snow cover.

- Incentivising green adaptation measures to encourage the natural maintenance of snow cover (e.g. ensuring the grass cover on slopes is in a good state).

Grey measures [41]

- Developing artificial snow production and methods for maintaining it (construction of accumulation barriers and wind protection barriers) in resorts and on hillsides, where feasible in the medium term from a climate perspective, and where economically viable and sustainable from an environmental perspective (e.g. good water availability). Efforts and resources related to these types of measures should be focussed solely on potentially profitable resorts and areas.

- Developing specific projects for efficient water management and self-sufficient energy production in tourist infrastructure which is planned or undergoing refurbishment, and providing tourist routes which exploit the eco-tourism potential of the area and which educate tourists on these matters.

- Implementing safety measures on mountain tourism routes and trails which are on the edge of zones at risk of flooding and landslides.

KEY MESSAGES

- Climate change is reducing the number of days with sufficient snow cover to carry out normally the different kinds of alpine skiing, as well as resulting in a migration to higher altitudes of the snow accumulation limit.

- The reudction of the snow cover forecasted during this century will affect diversely the different ski stations in the Pyrenees, following their localisation, altitude or management characteristics.

- The intensification of natural risks provoked by global warming could specifically impact some high mountain destinations or touristic infrastructures

- Climate change could alter some icnonic elements of the Pyrenean landscape, affecting negatively its touristic attraction and interest.

- The extension of the summer season and the tendency towards warmer temperatures in spring and autumn, in conjunction with the drop in minimla temperatures, could entail an increase in the selection of pyrenean destinations over other destinations, less comfortable due to higher temperatures.

(40) Green measures are based on ecosystem services: these include all measures, good practices, studies and initiatives around the use of the ecosystem services obtained from natural resources, and which seek to alleviate the negative effects of climate change (e.g. forestry practices which conserve the capacity of forests in the Pyrenees to reduce hydrogeological risks).
(41) Grey or structural measures are all those involving the construction or implementation of specific infrastructure to alleviate the effects of climate change (e.g. building dykes in inhabited areas at risk of flash floods).

3.2 Crops and mountain agro-pastoralism

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Coauthors: Rosa M. Canals (UNAV, Dpto. Producción Agraria. Grupo Ecología y Medio Ambiente) María Durán (UNAV, Dpto. Producción Agraria. Grupo Ecología y Medio Ambiente), Jordi Puig (Espigall).

ABSTRACT

Agriculture and livestock are Key socio-economic sectors owing to their high strategic, economic and territorial value on both sides of the Pyrenees. The sectors are distributed unevenly across the mountain chain. On the French side, agriculture employs 8.4% of the active population and constitutes a turnover of more than 500 million euros, principally from agriculture and livestock (ACAP, 2017). On the other hand, this sector employs 0.4% of the active population in Andorra and represents a total of 12.8 million euros of the country's gross domestic product (IEA, 2016). In the coming decades, climate change could have a significant influence on the production capacity of Pyrenean agricultural areas, both due to the direct effects of the increase in the concentration of CO_2 in the atmosphere (positive) and due to the change in climatic and environmental conditions (basically negative). The main impacts of climate change on the Pyrenean agroecosystems are associated with decreases in production due to increased water and thermal stress on crops, loss of agricultural land due to increased hydrological risks, and increased risk of pest spread.

On the other hand, the new agro-climatic conditions could propitiate the expansion of some crops, of Mediterranean type, not usual in the Pyrenees so far.

Mountain pastures are fundamental to this sector and generate several ecosystem services for society (including provisioning services, maintenance of biodiversity, landscape resources, quality water resources and carbon storage). The increase in the concentration of atmospheric CO_2, the consequent increase in air temperature, as well as changes in seasonal precipitation patterns and the greater frequency and intensity of extreme climate events will affect agriculture, pastures and the livestock sector in the Pyrenees, g enerating changes of varying magnitude and type depending on the area considered.

3.2.1. Impacts and vulnerabilities in the agricultural sector

The shortening of the frost period and the increase in average temperatures could favour the expansion of somo crops unusual in the Pyrenees bioregion, such as Mediterranean or subtropical crops. On the other hand, rain-fed crops could suffer restriction on their potential distribution due to a greater variability in the rainfall regime and an increase in temperature.

A. Displacement of the areas of climatic compatibility of certain crops

Changes in climate conditions will likely cause the displacement of potentially suitable areas for the proper cultivation of some crops (Mereu et al., 2008). Whilst the potential distribution area[42] of some crops such as maize may become smaller (Iglesias and Rosenzweig., 2009; Donatelli et al., 2012), others such as grapes and olives may benefit (Ponti et al., 2014). The increase in average temperatures and the reduction in the number of days with freezing conditions means that crops which are particularly sensitive to cold - such as grapevines and olives - could expand their potential distribution areas towards higher latitudes and altitudes (Arblaster., 2007; Donatelli et al., 2012; Tanasijevic et al., 2014) where they have been limited by climate conditions to date.

Research suggests that the area of land not suitable for olives tree cultivation in the Pyrenees will decrease considerably, whilst the area of potentially suitable and acceptable areas will expand (Moriondo et al. 2008;

(42) The potential distribution of a species is a factor used in predictive models. It refers to the locations where a certain species may be found because the climate and environmental conditions in said locations are suitable.

Tanasijevic et al., 2014). Specifically, areas which are currently not suitable will become so in the future. However, more frequent extreme climate events such as late frosts could reverse some of the aforementioned

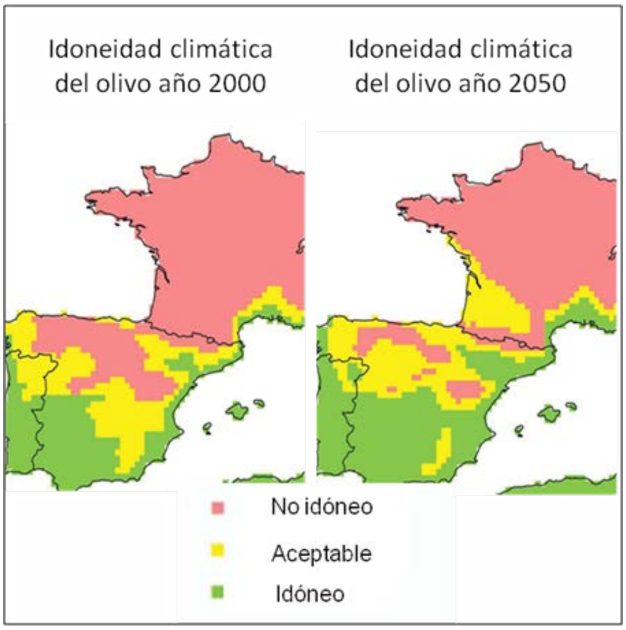

Figure 3.2.1.Estimated evolution of the climate suitability for growing olives in the period 2000-2050, using the ECHAM5 model and the A1B emissions scenario. Source: Tanasijevic et al., 2014.

positive effects, since plants would be more developed and therefore more vulnerable to these conditions (Trnka et al., 2015). For this reason the new Mediterranean crops would have to be located in very favourable areas and using short and late cycle varieties.

B. Changes in crops productivity

Climate change can have both positive and negative effects on crop yields. The most significant positive impacts are the fertilizing effect of atmospheric CO_2 and the extension of the growing season. The most relevant negative impacts (observed and expected) are changes in crop phenology, increased water deficits and increased risk of damage from extreme weather events. The productivity of crops and pastures is highly dependent on two factors: temperature and the amount of water available in the soil. Climate change has a direct influence over both these variables and may negatively affect the amount and quality of agricultural production. In addition to the gradual changes caused by the slow increase in temperatures and more variable precipitation, extreme climate events (heat waves, droughts and intense precipitation) may cause occasional yet highly significant impacts on crops. In Europe, climate change has been considered one of the main factors in the stagnated performance of some Key cereal crops, despite continual advances in agronomy (Brisson et al., 2010; Olesen et al., 2011; EEA, 2016).

Among the observed impacts, it is worth mentioning the agro-phenological changes[43] in crops. The increase in average temperatures is mooving much of the agricultural calendar forward, and in particular has advanced the flowering and harvest dates of many crops (figure 3.2.2). Whilst phenological changes may be partially countered in the short term by implementing agronomy management measures (e.g. bringing forward the sowing date or choosing later varieties), these may not be sufficient to maintain current production levels of many crops in the medium to long term (Trnka et al., 2014).

A recent conducted by the Joint Research Centre (JRC) of the European Commission found in the geographical area of the Pyrenees the wheat flowering date was brought forward by an average of 0.35 ± 0.15 days per year between 1985 and 2014, with significant differences observed depending on the considered subarea. Similarly, the maturation or grain filling processes - and therefore the harvest date -have been brought forward considerably during the last thirty years, which constitutes a considerable acceleration in the crop growing season. This generally leads to poorer crop performance, since it involves a less efficient use of thermal energy, the sun's radiation and the water resources available.

In the winemaking sector, earlier flowering and harvesting could result in a significant drop in productivity in some areas (Ponti et al., 2015). Fraga et al. (2016) have found that the grape flowering and harvesting dates on both sides of the Pre-Pyrenees could come forward by 30 ± 10 days and 40 ± 10 respectively in 2040-70 with respect to 1980-2005. One negative effect observed during recent decades is caused by early ripening coinciding with the greater

(43) Agrophenology is the study of changes in the annual crop cycle and how these are influenced by climatic factors.

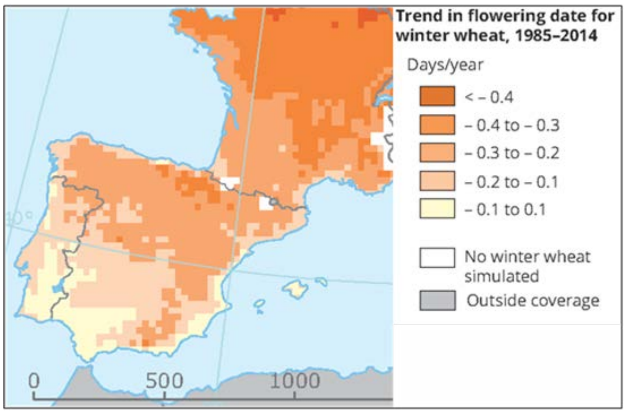

Figure 3.2.2. Estimation of the rate of change of the winter wheat flowering date during the period 1985-2014, expressed as the number of days brought forward per year. Source: EEA 2016 from MARS/STAT database.

frequency of extreme climate events, such as summer heat waves and intense rainfall. Grapes under these conditions absorb and lose a large quantity of water over a short period and can end up damaged as a result. This continuous process of hydration and drying caused by an intermittent excess of heat and water often results in the skin of the fruit breaking and the ripe grape rotting before it is harvested (Lareboullet et al., 2013). Grapevine productivity could increase under moderate temperature increases, although the quality of the harvest and the properties of the final product could also be altered (greater alcohol content in the wine). As the effects of climate change become more intense, the sector will have to gradually modify its production techniques and even substitute grape varieties with others more suited to the new agro-climatic conditions. This could raise issues for winemaking which has a protected designation of origin status linked to locations and varieties specific to the Pyrenees.

The relationship between water availability and demand is crucial to proper crop cultivation. The water demand of a crop is defined as the water necessary during the growing season for the crop to develop properly. It varies significantly between different crops and different points of the growing season. The increasing variability in precipitation patterns and the greater frequency and intensity of droughts are causing imbalances between the increasing crop water demand and the gradually decreasing amount of water in the soil, causing what agronomists call a crop water deficit (Felten et al., 2011).

Extreme climate events can cause significant damage to crops and lead to considerable productivity losses. It is estimated that the summer heat waves of 2003 and 2010 in Europe caused a loss of 20% of the total cereal harvest in the regions affected. The hottest periods in many cases coincide with periods of drought, causing a cumulative negative effect. Cereal production on the Iberian Peninsula during the 2004/2005 crop season fell by an estimated 40% on average compared to the average for other years (IPCC, 2014).

Although there are no specific specific agrophenological projections for the Pyrenees, it is highly likely that the growing season of many crops will gradually increase as temperatures rise (Savé et al., 2012; Ponti et al 2015), which will negatively affect their performance and the final quality of the fruit or grain (Olesen et al., 2012; Ferrise et al., 2013; Funes et al., 2015; Fraga et al., 2016). In terms of the projected evolution of the crop water deficit, it is likely that the expected changes in seasonal precipitation patterns, the greater frequency and intensity of droughts and heat waves, and the potential rise in evapotranspiration rates (García-Ruiz., 2011) will lead to greater interannual variations in water availability, and in turn a greater number of water deficit events in certain areas and for certain crops in the Pyrenees (figure 3.2.3).

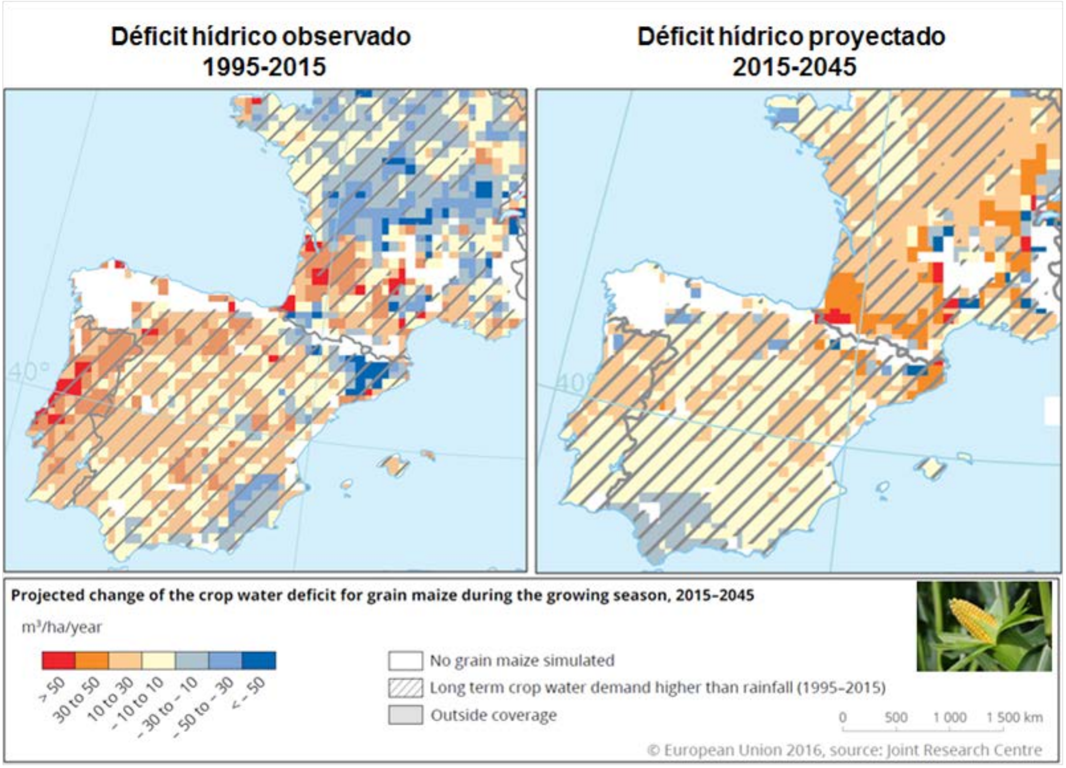

Figure 3.2.3. Estimation of the observed (left) and predicted (right) water deficit for maize based on the MIROC general circulation model. Simulations were carried out using the WOFOST agro-climate model for the RCP8.5 emissions scenario. Red indicates an increase in the water deficit and blue a decrease. Areas where crop water demand regularly exceeds water availability are marked with diagonal lines. Source: JRC, 2016.

The growing water deficit will have a direct impact on the productivity and quality of rain-fed crops, and an indirect impact on irrigated crops owing to increased irrigation needs (Ciscar et al. 2013). The imbalance between water availability and demand during certain periods of the year could increase the risk of conflicts between water-intensive sectors. According to the models used by the JRC, the water deficit for maize will be particularly high in the extreme north-east and the south-west of the mountain range. The value of said increase will vary significantly between crops, regions and hillsides across the Pyrenees, and more detailed and thorough research will be required to facilitate the design and implementation of more suitable adaptation measures in each case. Lastly, the possible increase in natural disasters induced or intensified by climate change (cave-ins, landslides, floods, etc.) may have a negative impact on agricultural land in mid- mountain areas owing to an intensification of erosion and agricultural soil loss. Furthermore, the more frequent and widespread forest fires predicted for the coming decades (Giannakopoulos, et al. 2009) could temporarily increase the amount of bare soil and thus increase the risk of water erosion of surface soil. A warmer environment could also accelerate the mineralisation of organic matter in the soil[44] and further aggravate soil loss. It is highly likely that more frequent torrential rainfall will increase soil loss, especially on arable land with little vegetation and lacking in soil organic matter, and which is therefore vulnerable to water erosion (Olesen et al., 2007; Jones et al., 2012; Panagos et al., 2015).

(44) Mineralisation is the process whereby soil organic matter (SOM) is turned into inorganic matter. A soil rich in organic matter is better structured and, amongst other advantages, is more resistant to erosion. A soil with depleted organic matter is generally more susceptible to erosion.

The thermal growing season is an agro-ecological indicator which reflects where and when different crops can be cultivated, assuming they have access to suitable soil and enough water and solar radiation. The length of the growing season is the period during which the temperature exceeds a certain threshold above which the crops can grow properly. The frost-free season is the most favourable for the growth of most plants and crops, and its calendar defines Key moments — such as flowering or grain filling — in the crop life cycle. Over recent decades the period between the last frosts of spring and the first in autumn has grown, resulting in an increase in frost-free days across Europe (Brázdil, et al., 2011). In the Pyrenees, the number of frosty days reduced by around 0.4 ± 0.2 days per decade from 1985 to 2014 (ESPON project, 2013; EEA, 2016). In the crop regions of the Pyrenees — where low temperatures and thermal fluctuations are the greatest limiting factor — the increase in minimum temperatures during winter and early spring could generate increased productivity of crops which are more sensitive to the cold. However, the elevated minimum temperatures could block the development of natural plant protection mechanisms against the cold, thus damaging some crops (Maracchi., 2004). Without these natural tools, occasional — but increasingly more frequent — late frosts could cause important losses, particularly in crops which have developed early.

Experiments have shown that an increased concentration of atmospheric CO_2 stimulates crop growth and production and also allows a more efficient water use due to the decrease in the stomatal conductance [45]. The higher the concentration of CO_2, the higher the rate of photosynthesis and the greater the capacity for plant growth and carbon fixation (Ainsworth and Long., 2005). This increase would not be linear, however, nor would all crops react in the same way, instead varying their behaviour based on their type of metabolism. C3 crops[46] (wheat, rice, alfalfa, soy and most fruit plants) respond better to the increased concentration of CO_2 than C4 plants[47] (maize, millet, sorghum, etc.), because the latter's already highly efficient photosynthesis means they respond less markedly to this increase (Long et al. 2006; Yano et al., 2007).

Some authors have estimated that in the absence of biotic and abiotic stress factors, crop productivity could increase on average by 10-20% for C3 plants and by 0-10% for C4 plants for atmospheric CO_2 concentrations of 550 ppm (403.64 ppm in November 2017) (Gifford, 2004; Long et al., 2004). Others suggest that for wheat, the fertilising effect of the increase in atmospheric CO2 concentration could even counteract the negative effects of water stress in the future (Manderscheid and Weigel, 2007). In fact, irrespective of the plant type (C3 or C4), the increased atmospheric CO_2 concentration causes partial closure of leaf stomata and thus reduces the water consumed through transpiration, without affecting photosynthesis or the productivity rate (Bernacchi et al., 2007; Kruijt et al., 2018; Arellano et al., 2012). That said, the potential fertilising effect of the increase in CO_2 concentration will be significantly limited and determined not only by less availability of water but by other limiting factors directly related to climate change. These include less availability of organic carbon in the soil, more frequent and intense extreme climate events, and greater spread of parasites and other harmful organisms.

Furthermore, the assimilation of high concentrations of CO_2 by most crops will cause changes in their composition by modifying the carbon/nitrogen ratio of the grain, resulting in mostly negative effects on productivity and quality (Bassus et al., 2014). In view of the multiple factors at play and the complexity of the potential interactions between them, research will need to focus on the design and implementation of dynamic simulations to obtain a more exhaustive assessment of the potential positive effects of greater CO_2 concentration on the different crops grown in the Pyrenees..

(45) Stomatal conductance is a proportionality parameter that relates the flow of transpired water through stomata to their motor force.
(46) C3 plants only perform efficient photosynthesis at moderate temperatures (maximum efficiency occurs at 20°C). Given their stomata are open during daylight hours, extreme temperatures increase plant transpiration through their leaves. They are called C3 plants because the first organic compound produced by photosynthesis is a compound with three carbon atoms: 3-phosphoglyceric acid, or glycerate 3-phosphate.
(47) C4 plants use the C4 carbon fixation pathway to increase their photosynthetic efficiency by reducing or suppressing photorespiration, which mainly occurs under low atmospheric CO2 concentration, high light, high temperature, drought, and salinity.

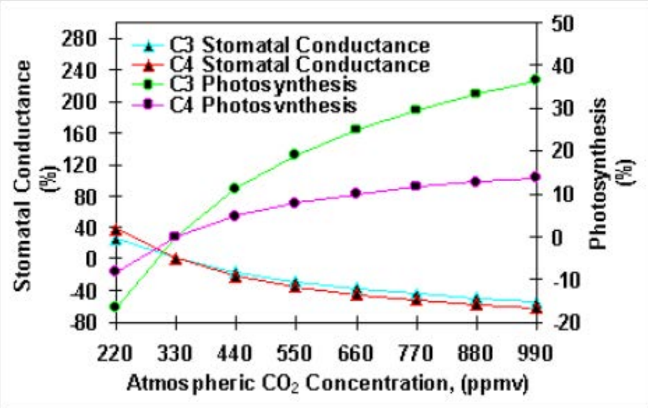

Figure 3.2.4. Curve showing the increase in photosynthetic efficiency and the reduction in stomatal conductance in C3 and C4 plants, as a function of the concentration of atmospheric CO2. Source: AVEMAC project

C. Risk of spread of crop's pests and deseases

The interactions between plants and their natural enemies are influenced by environmental conditions and temperatures. The possible modification of the distribution areas of some crops, in line with the predicted changes in humidity and soil conditions and average temperatures, could lead to variations in the distribution and spread of current plant diseases in the main crops of the Pyrenees, as well as an increased risk of spread of emerging plant diseases (Diodato and Bellocchi et al., 2010; Luck et al., 2011).

There are three main mechanisms by which climate change influences the spread and emergence of new plagues. Firstly, new climate and environmental conditions could favour the development of some harmful organisms during certain times of the year, when their development was previously limited by low temperatures. The increasingly higher minimum temperatures could mean that some crop plague organisms complete more reproductive cycles and become more prevalent (Coakley et al., 1995).

More specifically, insects are ectothermical beings[48], which respond rapidly to changes to the environment's temperature. As a consequence, the distribution, development and reproduction of different species of insects are closely linked to temperatures. In boreal and apline regions of Europe, phenomena of multivolitnism[49] of insects related to climate change have been reorted, which affects the productivity of crops and causes severe defoliation in forestial masses (Dalin et al., 2012; Stoeckli et al., 2012; Klapwijk et al., 2013). In the case of pathogenic microorganisms, the conditions of change can favour some species in periods of the year during which their development was previously limited by low temperatures.

A characteristic example of this is Colletotrichum coccodes, a fungus which seriously affects potato cultivation (anthracnose). In many parts of Europe, including southern France and northern Spain, this disease is becoming more significant than Rhizoctonia solani (another fungus which causes potatoes to rot) owing to the severity of its effects (Manici and Caputo., 2009; Garibaldi and Guillino, 2010).

(48) Ectothermic organisms are organisms which temperature is controlled principally by an external source of heat and of which the capacity to generate heat metabolically is insignificant. Typical examples of ectothermic animals are amphibians, the majority of fish and invertebrates.
(49) The multivoltinism phenomenon refers to species completing more tan one life cycle in the course of a year.

BOX 3.2.1 STUDY ON CLIMATE CHANGE ADAPTATION IN THE AGRICULTURAL SECTOR OF THE HIGH PYRÉNÉES AND ARAN: AN ECONOMIC ASSESSMENT

The study titled Climate Change Adaptation in the Agricultural Sector of the Hautes Pyrénées and Aran: Risks and Opportunities uses a climate-based model of crop cultivation to compare the current situation against a future scenario (2030-2050).

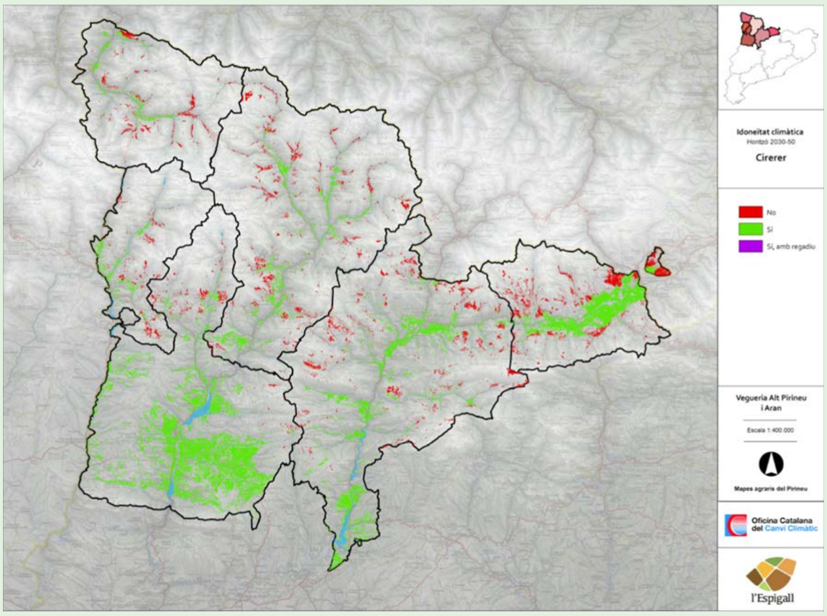

Figura 3.2.5. Map of climatic aptitude projected for the cultivation of cherry trees in the High Pyrenees and Arán for the period 2030- 50. Source. OCCC, 2017

The study concludes that climate change will bring the dry Mediterranean climate into the now cool valleys of this area of the Pyrenees. Winters will be less harsh and with fewer frosty days, whilst summers will be longer, hotter and drier. Consequently, typically Mediterranean crops (grapes, olives, cereals, etc.) and some fruits which are not water-intensive will do well, whilst some crops traditionally grown in the rain-fed Pyrenees, such as potatoes, will be grown significantly less. New crops such as apples and pears — and/or other products which may have greater added value — will take their place in irrigated areas and compete with fodder crops and other fruit and vegetables.

The research estimates that gross revenue in the agricultural sector of this area of the Pyrenees — currently €84.3M per year — could drop by 8.9% in the period 2030-50. The authors argue that strategies to limit these impacts should focus on rain-fed areas, which are much less resilient against drought than irrigated crops. They also propose a change in priority, moving away from the currently agricultural model geared towards producing animal feed, and towards another where producing human food is the objective. Specifically, their proposed main course of action is to increase the area of extensive pastureland in alpine meadows and of non-agricultural valley areas. This would reduce the current pressure on agricultural soil and, in turn, reverse the current trend towards tree invasion of pastureland and the associated loss of biodiversity. Expanding extensive pastureland in this manner would free up 26,103 ha of agricultural land which could be used for growing crops for human consumption, chosen based on maximum economic benefit and minimal water consumption. The researchers propose the integration of 10 crops for human consumption in these areas. These should be sown in locations which meet present and future requirements around suitable climate conditions (apple, pear, cherry, common bean, grapevine, olive, rye, spelt, potato and beans). With this solution in place, the authors estimate future gross revenue in the agricultural sector of €181.1M annually against the current €84.3M or the €76.7M predicted for the same period under a no-action scenario. Ths study was published by the Catalan Office for Climate Change, in the framework of the Life MEDACC project with the collaboration of the company l'Espigall.

Secondly, new climate conditions could create ideal areas for the expansion of new harmful organisms introduced by accident from warmer zones, and which could spread rapidly owing to a lack of competition and natural predators. This is the case with Sclerotium rolfsii (or Athelia rolfsii), a fungus typical of tropical areas and introduced to Spain a few years ago, where it is impacting significantly on many potato and maize crops (Tanmoy et al., 2016). Lastly, the greater frequency and intensity of abiotic stressors induced by extreme climate events could increase crop sensitivity to attacks from pathogenic organisms. For example, the M. phaseolina fungus affects the main fruit and vegetable crops, and its negative effects on strawberry cultivation have been increasing in the south of the peninsula in recent decades (Garibaldi et al., 2009; Husaini et al., 2016; de los Santos et al., 2016). Recent research suggests that climate change, together with other factors such as global trade and current agronomic soil management techniques, could cause considerable expansion of this fungus in fruit and vegetable crops, particularly on the southern slopes of the central Pyrenees (figure 3.2.6). However, other pathogens such as powdery mildew could be limited by the increase in temperatures (IPCC, 2014).

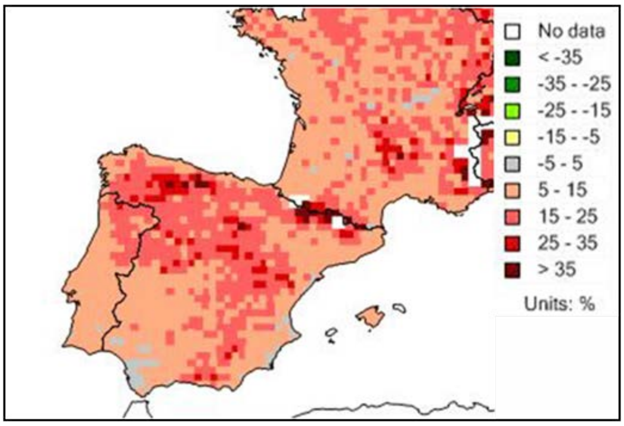

Figure 3.2.6. Estimated difference in relative growth (%) of M. phaseolina in 2030 with respect to the climate conditions in 2012. Dark red indicates the maximum increase in relative growth. Source: Manigi et al., 2012.

3.2.2. Alpine natural pastures: impacts and vulnerabilities

In addition to being a fundamental resource for the livestock sector, mountain pastures are ecosystems with a high biodiversity, landscape and cultural value (Leip et al., 2015). Climate change and especially the average increase in temperatures and more frequent and intense extreme events are influencing both productivity and the composition of natural mountain pastures in the Pyrenees.

A. Changes in the productivity and quality of pastures

Productivity in pastures in the Pyrenees is somewhat limited by low temperatures and scarcity of water (Sebastia., 2007). The increase in average temperatures, together with the fertilising effect of the greater concentration of atmospheric CO_2[50] and higher rates of mineralization of edaphic organic N[51] (Anderson., 2008), will likely increase the productivity of mountain pastures, barring severe droughts in spring and summer (Nettier et al., 2010; Climfourel., 2011). If the concentration of CO_2 in the atmosphere doubled, the productivity of mountain pastures could be increased by roughly 20-30%, provided there is no limit on the amount of nitrogen and water available (EEA, 2016).

However, it is highly likely that the greater frequency and intensity of droughts and other extreme climate events projected for the coming decade — such as intense rainfall and heat waves — will impact negatively on pastures, as far as to cancel out the fertilising effect of the greater concentration of CO_2 and of the mean temperature increase (Dumont et al., 2015). It has been shown that after very intense droughts during the summer season, recovery of autumn regrowth is very difficult (Zwicke et al., 2013), suggesting that autumn pasture production will largely depend on the intensity and frequency of summer droughts. Nevertheless, the size and even the nature of these effects could present significant geographical and temporal variability in the mountain range. It is highly likely that negative effects will dominate in pasture growth during the summer period and in mountain areas influenced by the Mediterranean sea, whilst positive effects will be more significant during autumn

(50) Under laboratory conditions, the increase in the concentration of atmospheric CO_2 increases the rate of photosynthesis in many plants and therefore the rate at which they absorb CO_2. This is known as the carbon fertilisation effect.
(51) The available N for plant growth is restricting in mountain soils, even though the edaphic contents of organic N are high. Higer temperature favours higher rates of N mineralization thanks to and higher activity of the microbian fauna of the soil.

and spring, and in areas influenced by the Atlantic ocean (Climfourel, 2011). At the same time, the increase in average temperatures, climatic extremes and hoagh atmospheric concentration of CO_2 are generating physical and chemical changes in pastures (Willerslev et al., 2014; Dumont et al., 2015), which may in turn alter the performance and end quality of livestock and their by-products (e.g. meat, dairy, etc.).

In particular, it has been shown that increased concentrations of atmospheric CO_2 have negative effects on nitrogen contents, and therefore protein contents, in plants (Dumont et al., 2015). However, at community level, the decrease in nitrogen and protein may be compensated, at least in part, by an increased presence of leguminous plants in multi- species pastures as this botanical family rich in nitrogen could be favoured by new climatic conditions (Dumont et al., 2015). On the other hand, the probable rapid depletion of pasture vegetation due to high temperatures and lack of rainfall during certain seassons would cause a loss of palatability that would lead to a lower appetite and intake of fodder by livestock.

B. Alterations in the foloristic composition and diversity of alpine pastures

In addition to affecting pasture productivity, climate and environmental changes could modify the current distribution of various species (Cantarel et al., 2013), thus changing the typical species composition of mountain fodder communities or accelerating scrub invasion on pastures (García et al., 2015).

In addition to the bush expansion process (expansion of shrubs such as Buxus sempervirens boxwood in the central Pyrenees), the effects of the natural forestation process (expansion of trees above the supra-forestry floor) are very evident throughout the Massif and could also have potential implications in terms of fire risk, changes in the albedos, duration of the snow cover or in microclimatic conditions (for more information see chapter 2.4. Forests). The expansion of some autochthonous herbaceous species is also taking place, mainly perennial grasses, which are very competitive in the face of new environmental conditions, such as Brachypodium pinnatum in the western Pyrenees (Canals et al., 2014; 2017), which degrade pastures through the loss of floristic diversity induced by their expansion.

Less floristic diversity implies less resistance (resilience) of the plant community, and therefore less capacity to adapt to the new climatic and environmental conditions.

Climate change is an added stress factor which can act in synergy with land use changes, current trends in agroecosystem degradation and the gradual abandonment of extensive alpine farming (Busqué et al., 2016). The relationships between climate, land uses and pasture management are therefore hugely relevant. Simple changes in pasture management such as changing the grazing or fodder harvest calendars could mitigate (at least in the short term) some of the potential negative effects of the observed climate change impacts.

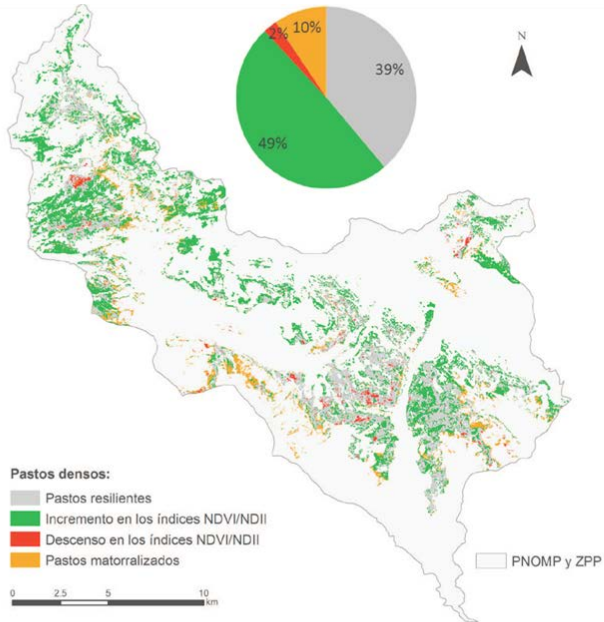

Figure 3.2.7. Estimated scrub invasion in the Ordesa y Monte Perdido National Park between 1980 and 2000. An increase in the indices (green) represents an increase in a pasture's biomass and verdure. A decrease (red) represents pasture degradation. Source: García et al., 2015.

3.2.3. Impacts and vulnerabilities in the extensive livestock sector

Livestock production will also be directly and indirectly affected by climate change. Changes in temperature and humidity have a direct influence on animal health and performance, and high temperatures and climatic extremes can indirectly affect animal production owing to fewer and poorer-quality grazing areas. Furthermore, the new climate conditions could encourage greater spread and prevalence of livestock diseases (Heffernan et al., 2012; Gauly et al., 2013), including those transmitted by vectors (Estrada-Peña et al., 2012).

A. Reduction of livestock productivity and welfare

Livestock health depends directly on the climate characteristics of the environment (Lacetera et al., 2013). Each species has an optimal temperature range, called the thermal neutral zone[52]. When the temperature of their environment exceeds the neutral zone, animals react with a series of physiological mechanisms which lead to an increase in respiratory rate, sweat rate and water consumption to counteract the increase in body temperature (Fregley, 1996; Bernabucci et al. 2010). When subjected to thermal stress, animals also reduce their food intake and metabolic activity, which directly impacts their nutritional condition and reproductive performance (Roy and Prakash, 2007; Mader, 2007), and their health and wellbeing more generally. The risk of death increases if thermal stress is prolonged (Nardone et al., 2010). The THI52 (*Temperature Humidity Index*) is a thermal stress indicator which combines air temperature and humidity values.

The value of this index has increased throughout Europe in recent decades and generated negative impacts on livestock (Vitali et al., 2008). It is highly likely that thermal stress in livestock will be more common and intense in the future, including in the Pyrenees (Segnalini et al., 2012). In the absence of proper adaptation measures, climate change could negatively impact the profitability of livestock operations in the Pyrenees, especially intensive operations in mid-mountain valleys and during the summer months (Beltrano et al., 2009).

B. New zoonoses and spread of livestock diseases

Climate change is also one of the factors involved in the greater spread of disease-causing organisms and disease vectors, in tandem with greater movement of goods and people (Patz and Olson, 2006). In fact, most insect disease vectors — especially arthropods — are

ENCUADRE 3.2.2. "ALPAGES SENTINELLES ALPINS": RED DE ACTORES PARA PRESERVAR LA BIODIVERSIDAD Y SALUD DE LOS PASTOS DE ALTA MONTAÑA FRENTE A LOS DESAFÍOS DEL CALENTAMINETO GLOBAL

A raíz de las sucesivas olas de calor y de la preocupación creciente sobre los impactos del cambio climático en los pastos de alta montaña, el Parc National des Écrins ubicado en los Alpes franceses, decidió reunir a su Comisión de Agricultura para abordar la problemática. Conscientes de la multifuncionalidad de estos ecosistemas de alto valor paisajístico, ecológico y cultural, así como del interés común de limitar los efectos negativos del cambio climático sobre los mismos, se creó un grupo de trabajo transversal en el que se implicó a los ganaderos locales, los gestores de espacios protegidos, los gestores de explotaciones ganaderas, las autoridades de los municipios interesados y a la comunidad científica.

Atendiendo a la posición privilegiada del Parc National des Écrins para el desarrollo y posterior seguimiento de iniciativas de diseño e implantación de acciones para la adaptación, los actores implicados crearon de manera colectiva la red de "Pastos centinela de montaña-" .El programa, cofinanciado con fondos FEDER, tiene como finalidad mejorar la comprensión sobre la dinámica futura de los espacios agro-pastorales de alta montaña en el contexto del cambio climático y anticipar así los posibles efectos negativos. Entre las acciones específicas promovidas por la iniciativa están:

- la creación de una red de observación de la evolución climática en las diferentes parcelas de estudio
- la definición de protocolos robustos y comunes para valorar los efectos del cambio climático en los pastos de alta montaña
- la creación y dinamización de un espacio de diálogo continuo entre los actores implicados

El programa, que fue lanzado en el 2011, se ha extendido a otras áreas protegidas (Parque Nacional de Vanoise y Mercantour, Vercors, Charteruse, Lubéron y Ventoux). Hoy en día la red cuenta con una treintena de pastos centinela, que forman parte de 37 explotaciones ganaderas incluidas en 7 territorios alpinos. La iniciativa está coordinada por IRSTEA e involucra a socios científicos, gerentes de áreas protegidas, pastores y representantes del sector agrícola. En el 2018 y gracias a la cooperación entre actores y territorios, se publicará una guía metodológica para evaluar la exposición y la sensibilidad de los pastos de montaña a los riesgos climáticos, así como un conjunto de fichas técnicas para la "gestión a prueba de clima" de los agroecosistemas de alta montaña.

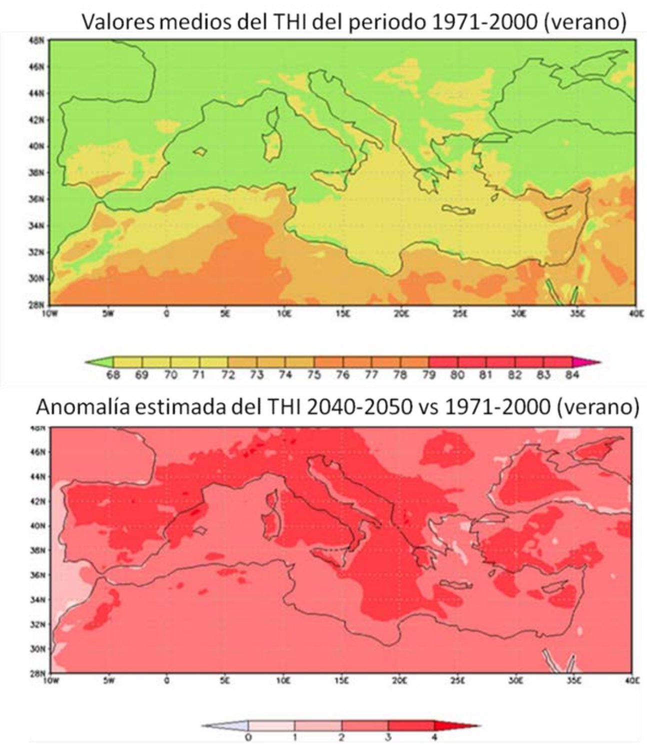

Figure 3.2.8. Average THI values for the period 1971-2000 (upper) and estimated change in the THI for the decade 2040-2050. Source: Segnalini et al., 2012.

highly sensitive to climate factors like temperature and humidity which are decisive in determining the presence, density and behaviour of these organisms. As a result, it is highly likely that the predicted increase in average temperatures will also extend the potential distribution area of some disease vectors which are already present in areas of the mountain range where the climate conditions have become suited to their biological cycles, whilst enabling the arrival, establishment and expansion of new pathogenic organisms (Iriso et al., 2017). There could also be a reduction in the life cycle duration of native vectors and an extension of the period when conditions are ideal for transmitting pathogens. An obvious example is the spread towards higher latitudes of the livestock disease bluetongue[54]. This viral disease is transmitted by an insect vector from the genus Culicoides (a species of midge considered the main vector of this disease). Europe was free of this virus until relatively recently, but in 1998 an epidemic brought the virus from Africa to Europe (FAO, 2006). The virus has been progressively spreading towards higher latitudes by means of this vector. Cases of infection by this virus are increasingly more frequent on the northern side of the mountain range (Jacquet et al., 2016), and it is likely to spread further in the future (Bonizzoni et al., 2013). Climate factors influence its spread, and the midge vector's survival rate has increased owing to milder winters and changes in the patterns of the winds which transport them (Jacquet et al., 2016), partly induced by climate change (Mardulyn et al., 2013).

Ticks in livestock are another significant example. Ticks are vectors which transmit bacteria, protozoa and viruses that cause diseases including Lyme disease, Boutonneuse fever, Crimean-Congo haemorrhagic fever and encephalitis. Ticks spend most of their life cycle in the environment, meaning their development, survival and population dynamic depends on a number of factors. These include climate change-induced variations in average and minimum temperatures and in the water cycle (Randoph et al., 2008), as well as changes in the distribution of their main hosts (Léger et al., 2013; Williams et al., 2015). It is therefore highly likely that climate change will alter the distribution and density of the population of insect vectors such as ticks, as well as the risk of transmission of the pathogens that the ticks carry. The response of these arthropods will not depend exclusively on the evolution of climate factors. It will also be conditioned to a large extent by other non-climate factors, such as changes in the populations of their main hosts in the Pyrenees (mainly large vertebrates) and by alteration or fragmentation of the landscape, amongst others.

(52) The thermal neutral zone is the temperature range within which an animal does not fight against cold or heat, meaning they have the maximum possible energy available for growth.
(53) The THI has been used since the early 1990s to measure the combined effect of air temperature and humidity on livestock health. It allows for a simple and intuitive calculation of the risk of thermal stress in livestock based on changes in environmental conditions. When the THI exceeds 72 units, ovine livestock start experiencing heat-induced stress, and their productivity rate changes. Milk production is seriously affected for a THI greater than 78. Above 82 poses a risk of serious productivity losses, and livestock show signs of extreme stress and may even die.
(54) Bluetongue virus (BTV) is an acute viral disease of sheep, goats and cattle. It causes severe physical deterioration and requires a long recovery period, leading to significant economic impacts owing to huge productivity losses and prevention and control expenditure. The disease is feared, despite being harmless to humans and having a median survival rate.

In light of the main research in this area and despite the uncertainties inherent in climate projections, the vulnerability of the livestock sector to climate change should be taken into account in investment planning and by current funding instruments (e.g. the European Agricultural Fund for Rural Development), in order to increase livestock resilience to climate challenges and prevent these from adding pressure to the diverse socio-economic challenges already facing the sector. Although climate change is presented as the biggest challenge, it is highly likely that the socio- economic factors and barriers facing farming and grazing in the Pyrenees (globalisation, price fluctuations, abandonment of the agropastoral activity, lack of generational renewal, dependence on subsidies, higher production and investment costs, etc.) will continue to be the main source of vulnerability in the future (Leclère et al., 2013; Busqué et al., 2016; Canals. 2018). Hence, to ensure that adaptation measures for farming and grazing in the Pyrenees are effective and efficient, these must be conceived and designed through the prism of future overall change scenarios in which climate change is an added stress capable of exacerbating current challenges.

3.2.4. Findings and recommendations

Productivity of agricultural systems is critically dependent on a range of factors, including climate conditions. The overall effects of climate change on agricultural productivity can be summarised as the outcome of the interactions between the increased concentration of atmospheric CO_2, the variation in the length of the growing season, change in water availability and the spread or proliferation of plagues and diseases. Although there have been few specific studies on the effects of climate change on farming and grazing in the Pyrenees, initial investigations seem to agree on the possible increase in pasture productivity owing to the lengthening of the growing season, since temperature is the most limiting factor at altitude. However, it is likely that climate change will negatively impact the performance of many crops as well as livestock production. The negative effects of climate change or other factors which are exacerbated by this — greater spread of plagues and pathogenic organisms, more frequent and intense extreme climate events, and the gradual reduction in the quality of crops, fodder and related products, for example — could present serious challenges to the sector in the coming years. Short term adaptation strategies based on relatively simple agricultural practices — such as changing sowing dates or crop varieties — may not be sufficient in the long term. It is therefore essential to bridge knowledge gaps on the impacts of climate change on the main crops and agro-ecosystems of mountain areas. It will also be vitally important to support farmers and livestock managers in the adaptation process, with a view to increasing the resilience of the farming and grazing sector in the Pyrenees to climate challenges. What follows is a non-exhaustive summary of the main challenges facing agriculture in the Pyrenees in the coming decades, and various recommendations for adapting to these. The recommendations are set out based on three types of adaptation measures: *green, grey* and *soft*.

Main challenges

- Reducing uncertainty around the greatest risks, possible negative effects and future pressures on farming and grazing ecosystems in the Pyrenees.
- Increasing the resilience of mountain farming and grazing systems to the pressures of climate change.
- Strengthening pro-conservation land management to increase its natural fertility and maximise its function as a carbon sink.
- Encouraging management techniques in the sector which ensure sustainable water use and integrated management of this resource.
- Developing systems for monitoring emerging pathogenic organisms and diseases in livestock and crops.
- Limiting abandonment in the sector and incentivising diversification and modernisation based on overall climate change challenges.

Recommendations

This section compiles a set of general measures geared towards establishing mechanisms which increase resilience of the farming and grazing sector to the future climate and its variability. There is not one effective pre-established combination of measures for all farming and grazing systems in the Pyrenees. Rather, the differences in geography and microclimate, as well as the diversity of socio-economic circumstances and frameworks across the Pyrenees, require specific studies into the vulnerability of each local area. This is the only way to identify adaptation priorities and subsequently design a set of climate adaptation measures which can feasibly be implemented and which are optimal in terms of effectiveness and efficiency (cost/benefits).

Soft measures [55]

- Develop multidisciplinary, cross-border, stable long term working groups comprising representatives from all relevant sectors (livestock managers, farm owners, local authorities, scientists, etc.) to discuss the effects of climate change on the farming and livestock sector using participative observation models.

• Develop agrosystem models which integrate regional climate projections on future climate variability to evaluate the potential impacts of climate change on agricultural and livestock productivity and on alpine pasture productivity (quality of end products, evolution of ideal growing areas, etc.): develop dynamic simulation models for different crops which can detect the incidence of solar radiation on leaves, biomass generation (above and below ground), water and nitrogen ratios and performance.

• Strengthen and, where necessary, proactively redirect existing plans for monitoring and detecting plagues and other pathogenic organisms. This should be carried out in an integrated manner and in line with new climate evidence and its consequences: monitor the possible spread of vectors and pathogenic organisms owing to potential changes in wind patterns; step up monitoring and control of the anthropogenic introduction of new harmful and potentially dangerous organisms which could spread or become naturalised because of climate change (develop models which simulate the behaviour of different pathogenic agents with respect to the climate, their ability to adapt to the biotope and the seasonal dynamic of the different processes).

• Encourage new agricultural technologies to adapt the sector to climate change and minimise the damage caused by extreme climate events to crops and livestock, in line with mitigation objectives and sustainable water management: promote techniques for managing the risk of water scarcity, diversify mountain crops by introducing alternatives or new varieties which are more resilient to drought, adjust sowing dates in response to new climate and environmental conditions, and assess the possible relocation of some crops based on changes in areas with the ideal climate conditions.

• In the livestock sector, encourage a reduction in animal numbers (extensive livestock farming) and the necessary changes in grazing management (transhumance during hotter and drier seasons), and help farming operations to become climate-proof (insulation systems and natural ventilation to combat heat waves).

• Establish interventions which support farmers to adapt to climate change (technical advisory services and adaptation of existing insurance provisions).

Green measures [56]

• Support the development of efficient systems for managing agricultural waste with a view to reusing all available natural nutrients and reducing external inputs.

• Strengthen pro-conservation land management to increase its natural fertility, maximise its function as a carbon sink and natural water storage capacity, and to protect mountain biodiversity and prevent erosion.

Grey measures[57]

• Incentivise the modernisation of farming operations: improving ventilation/cooling systems in stables; encouraging the use of renewable energy as far as possible (focus on energy expenditure and greenhouse gas emissions).

• Use of shading techniques such as shade netting: significant impact in terms of solar radiation, but no impact on temperature or humidity (low cost intervention).

• Promote more efficient irrigation techniques and management measures (subirrigation, drip irrigation and appropriate times for irrigation).

(55) Soft or non-structural measures reduce or alleviate the negative effects of climate change. This category of measures typically comprises research to bridge knowledge gaps or to enrich the knowledge base on climate change, its impacts and the most vulnerable sectors. It also includes the development of specific methodologies and systems for reducing the risks associated with climate change (e.g. developing a cross-border early warning system for managing heat waves in the mountain range).
(56) Green measures are based on ecosystem services: these include all measures, good practices, studies and initiatives around the use of the ecosystem services obtained from natural resources, and which seek to alleviate the negative effects of climate change (e.g. forestry practices which conserve the ability of forests in the Pyrenees to reduce hydrogeological risks).
(57) Grey or structural measures are all those involving the construction or implementation of specific infrastructure to alleviate the effects of climate change (e.g. building dykes in inhabited areas at risk of flash floods).

KEY MESSAGES

• The diminution of the frost periods and the increase in average temperaturas could favour the extension of crops not usually found in the Pyrenees, such as Mediterranean or subtropical crops.

• No-irrigated crops could see their area of distribution and production restricted as a result of a higher variability in the precipitation regime and the increase in temperatures.

• The modification of distribution areas of some crops and their higher sensitivity caused by conditions of climatic stress could foster changes in the distribution and spread of current diseases and plagues in crops, effectively increasing the risk of expansion of new diseases.

• Climate change could have a negative impact on livestock production because of the lower disponibility of quality pastures and water, the higher spread of diseases and its vectors as well as heat waves through thermic stress and its impact on the livestock's health.

• The progressive abandonment of the traditional use of the Pyrenean Mountain is conditioned by processes of very quick matoralization and forestation, with importat consequences in the loss of mosaic landscapes.

• Climate change is an added stress factor acting in synergy with changes in land use.

3.3 Energy

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ABSTRACT

Energy plays a Key role in contemporary society and the sector is responsible for a significant proportion of the human-induced greenhouse gas emissions (Edehofer et al., 2014). At the same time, this is a sector that is vulnerable to the effects of climate change both with regards to energy supply (effects on energy production) and demand. As far as renewable energy production is concerned, it is foreseeable that climate change will negatively affect the hydropower, thermoelectric and wind power production in the Pyrenees, while the effects on the production of photothermal and[58] photovoltaic[59] energy could be positive in certain areas.

It is extremely likely that the impact of the expected changes in the volume of precipitation, and its spatial and temporal distribution, will lead to a reduction in the water flows of the main rivers, directly affecting the dam or reservoir storage capacity and bringing about a reduction in the hydropower production capacity of the mini-hydro plants in the mountains and, to a lesser extent, that of the larger hydropower plants in the valleys. Furthermore, the water reserves in the form of ice and snow will progressively decrease and become more short-lived. The ever- increasing temperatures are advancing the time of the melting of ice and snow in the Pyrenees which, in the past, provided a water reserve that was more constant and could be used in summer. Moreover, the reduction of the minimum water flows of the rivers, together with the increase in water temperature, will very likely impose limits on the thermoelectric generation capacity, due to the reduced efficiency of the thermoelectric plant cooling systems, particularly during the summer period. Although to a lesser extent, the higher mean temperatures and the maximum summer temperatures in particular could have a negative impact on the performance of the thermodynamic cycle, reducing plant efficiency. The expected positive impacts shall probably be seen through an increase in the production potential of some renewable energy. In particular, the production capacity of photovoltaic and photothermal solar energy could be boosted due to a higher level of insolation, related to a decreasing cloud cover.

By contrast, the change in wind patterns and the reduction in wind speeds predicted for the Pyrenees in the forthcoming decades could have a negative impact on the wind power production capacity in certain zones of this mountain range. Moreover, the predicted increase in the frequency and intensity of extreme weather events could pose a threat to the energy production systems due to the greater exposure of the electricity storage, transmission and distribution infrastructures to climate risks. With regard to the evolution of the energy demand in the Pyrenees, the expected demand scenario is characterised by a significant increase in the energy demand during the summer months, in response to the growing energy needs for air conditioning in homes due to the increasingly hot summers and the increasingly more frequent heat waves. This increased summer demand could be offset, although only in part, by a reduction in the winter electricity demand for heating, in response to increasingly milder winters.

3.3.1 Reduction in the hydropower production capacity

The energy sector in the Pyrenees is marked by the importance of the hydropower sector on both watersheds of this mountain range. The river basins of the Ebro, Garonne and the inland basins of Cataluña have considerable importance from an energy point of view, both regionally and nationally. For the Ebro-Pyrenees water basin, the installed hydropower capacity is around 1080 GW (REE, 2017) and accounts for more than 50% of the installed energy capacity of

(58) Photothermal systems convert solar radiation into heat and transfer it to a working fluid. The heat is then used to heat buildings, water or to drive turbines to generate electricity.
(59) Photovoltaic solar energy produces electricity from renewable sources, directly obtained from solar radiation through a semiconductor device called a photovoltaic cell, or else through a metal deposition on a substrate referred to as a thin film solar cell.

the entire Pyrenean territory (IAEST, 2016). With regard to the French watershed, in Occitanie hydropower accounts for 49% of the regional installed energy capacity (Bilan électrique 2016), while in Nouvelle-Aquitaine it is around 15% (RTE Nouvelle-Aquitaine, 2016). On the other hand, Andorra is in a unique position insofar as its territory is located entirely in a mountainous area, and its energy system is characterised by the import of a large proportion of the consumed energy.

Observed impacts

The amount of electricity generated by the hydropower plants largely depends on the installed energy capacity, but particularly on the availability of water resources stored at the dams, in the case of reservoir hydropower plants[60], and on the variations in river water flows, in the case of run-of-river hydropower plants[61]. The water supply largely depends on the seasonality of the water cycle and, specifically, on the precipitation patterns and on the snowmelt times. Climate change is modifying both the precipitation pattern and the snowmelt times (Lopez-Moreno et al., 2013), with significant effects on the water storage capacity of the reservoirs and on the water flows of the main rivers (Moran-Tejeda et al., 2017).

Over the last few decades, the early melting of the snow due to high temperatures has brought forward the spring peak water flow of the Pyrenean rivers, resulting in an increase in water flows in winter and a decrease in summer (Morán-Tejeda et al., 2017). This is causing greater inter- annual variability in hydropower production. In addition to the effects of the greater precipitation variability and the changes in the snowmelt times, there is also a greater drought frequency and intensity, which in 2003, 2005, 2007 and 2012 already caused substantial decreases in hydropower production, in both the Ebro and Haute-Garonne river basins (Van Vliet et al., 2016).

Observed impacts:

It is extremely likely that the increased climate variability predicted for the forthcoming decades will have a negative impact on the hydropower production capacity in the Pyrenees. The reduction in the river surface flows, and the seasonal changes in the availability of water resources predicted by the principal models suggest a greater availability of water during the winter months, accompanied by a sharp drop in water availability during the summer season (Bangahs et al., 2013; Michelle et al., 2013; Morán-Tejeda et al., 2017). On the other hand, if mean temperatures continue to rise the water reserves in the form of snow will decrease further (Lopez-Moreno et al., 2013).
As well as being of a significantly lower volume, it is extremely likely that snowmelt will start earlier and, consequently, it will peak at a time of year when the reservoirs and dams could already be at their maximum capacity limit (Beniston et al., 2013). In contrast, the water runoff from the snowmelt typical of spring shall be increasingly lower, reducing the water reserves stored for the summer season, a time of year during which there is a greater energy demand for cooling, in addition to the water resources required for agriculture and cattle (Finger et al., 2012). If such projections are confirmed, then the hydropower production capacity in the Pyrenees could drop by up to -10% on average, and even by up to - 35% during the summer season in 2070 compared to present times (Rojas et al., 2012; Van Vliet et al., 2016). This agrees with the more detailed estimated values for the southern watershed of the eastern Pyrenees (Bangash et al., 2013). However, a precise quantitative estimation of the importance of these changes, at a detailed level, is unquestionably complex. In fact, there are considerable uncertainties related to the estimation of future climate variability in relation to precipitation behaviour in a system as climatically complex and orographically heterogeneous as the Pyrenees. As well as for the mean annual and monthly values, these complexities make it particularly difficult to estimate the values relating to short and particularly intense precipitation episodes. However, these estimations are fundamental in order to determine flooding and the total water intake.

3.3.2 Reduction in the efficiency of thermoelectric power production [62]

Thermoelectric power generation could also be affected by climate change through the reduction of water resources available for plant cooling, and,

(60) Reservoir plants are the most common type of hydropower plants. They use a reservoir to store water and regulate the water flow through the turbine. Energy can be generated all year round if sufficient reserves are available.
(61) Run-in-river hydropower plants, also known as «diversion hydropower plants» or «river power plants», use part of the river flow to generate electricity. They operate continuously given the fact that they have no reservoir to provide water storage capacity. The moving water available spins a turbine to drive a generator. The system is limited by the installed capacity. For this type of plant, the turbines can have either a vertical shaft, when the river has a steep drop, or a horizontal shaft, when the river has only a small one.

although probably to a lesser extent, by a decrease in the efficiency of the thermodynamic cycle caused by high temperatures (Wilbanks et al., 2007).

Observed and projected impacts

An increase in the ambient temperature could result in the decreased efficiency of the thermoelectric conversion process[63]. The increase in the temperature of the water used to cool the plants could slow down the cooling process and impose a reduction on production capacity, particularly during the summer season and during periods with a minimum water flow (Eskeland et al., 2008).

Moreover, the increase in the river temperatures, together with the expected reduction in water flows during the summer season (Van Vliet., 2016; Morán-Tejeda et al., 2017) could lead to potential restrictions due to failure to comply with the European directive on minimum water flows (the minimum ecological water flow[64] established by Water Framework Directive 2000/60/EC), imposing limitations on the discharge of cooling waters and on thermoelectric production. Finally, the increase in the ambient temperature results in the reduced efficiency of the thermoelectric conversion process, caused by a decrease in the density of the air supply powering the turbines (Hewer et al., 2006).

3.3.3 Climate change and renewable energies

Climate change could affect the generating capacity of some renewable energies that are widely deployed in the Pyrenees, such as photovoltaic and photothermal solar energies, and wind energy. The changes in the behaviour of some Key variables such as wind speed and distribution, the extent of cloud cover and atmospheric transmissivity could have significant effects on the production capacity of these energies, of a different scale and nature, depending on the energy source and the site considered.

Observed and projected impacts

According to the principal studies conducted to date, in the future, the photovoltaic and photothermal sectors could be moderately boosted by climate change (Bartók et al., 2010; Crock et al., 2011; Jerez et al., 2015; Wild et al 2015; Vliet et al 2016). The probable change in the atmospheric water vapour content, in addition to the variation of the cloud cover index and cloud characteristics, could directly affect the atmospheric transmissivity of solar radiation. In south-western Europe, including the Pyrenees mountain range, an increase is expected in the average solar irradiation in the forthcoming decades (Bartók et al., 2010; Gaetini et al., 2014; Jerez et al., 2015) which could vary between 5-10% in summer and autumn, and between -2% to + 8% in winter and spring (Pašičko, 2010). According to Jerez et al., 2015, and Gaetani et al., 2014, this could involve an increase in the potential production capacity of up to 10 ± 3 % for 2070-2099 in relation to the baseline period 1970-1999.

Another study conducted at a global level concluded that, for the period 2051-2080, the photothermal energy production potential could increase by up to 10% in relation to 2010, while photovoltaic production would increase to a lesser extent, with increments of around 3.5%(Crook et al., 2011), slightly lower than the estimates of Jerez et al., 2015 and Gaetani et al., 2014.

However, it should be considered that the increase in temperatures could negatively affect the efficiency of the photovoltaic cells. Specifically, it has been estimated that the efficiency of crystalline silicon cells will drop by around 0.4-0.5 % for each mean temperature increase of 1°C (Pašičko, 2010). Assuming a mean temperature increase of 1.5 oC for the period 2050-2070 (most optimistic scenario predictions), the impact on the photovoltaic cell efficiency, without considering possible emerging technology breakthroughs, could involve a reduction of - 0.75% in efficiency in relation to present values.

(62) Thermoelectric power is the energy resulting from using a fuel to heat water and drive an AC generator to produce electricity.
(63) Process consisting in the use of a fuel to convert water into steam to drive the turbines or AC generator to produce electricity.
(64) The term ecological water flow, referring to a river or to any other flowing watercourse, can be defined as the water required to preserve the ecological values of the watercourse, such as: the natural habitats hosting a wealth of flora and fauna; environmental functions such as the dilution of pollutants; cushioning of extreme weather and water events; countryside conservation.

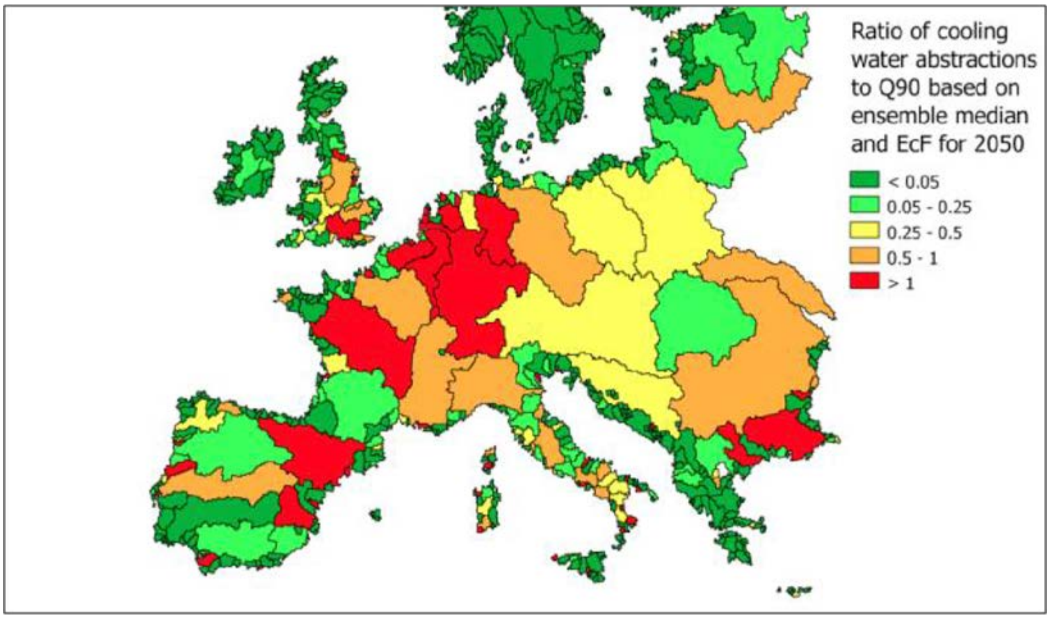

Figure 3.3.2. Estimate of the impact of climate change on the efficiency of the thermoelectric plant cooling processes in 2050, based on the A1B emission scenario, with no adaptation measures. The values shown in the Key refer to the possible intensity of the impact, in relation to the European average. Source: ClimWatAdapt project, 2011.

With regard to wind energy generation, the most recent studies agree that climate change will have a negative impact on the wind energy production potential in the Pyrenees (Santos et al., 2014; Gonçalves-Ageitos et al., 2015; Tobin et al., 2015). The predicted changes in wind patterns and the expected reduction in the daily mean speed of surface winds (up to -9% slower) could reduce the wind energy production potential by around -1 ± 0.5 MWh/day in the forthcoming decades in relation to current values.

It is considered that this reduction will be far greater in summer and autumn than in winter and spring; during the latter seasons, the wind power potential could even increase slightly in some areas (Santos et al., 2014). The areas most affected by this reduction would be the central and eastern Pyrenees, while no substantial variations are expected on the Atlantic watershed of this mountain range where, according to some models, the wind power potential could even increase slightly (Gonçalves-Ageitos et al., 2015).

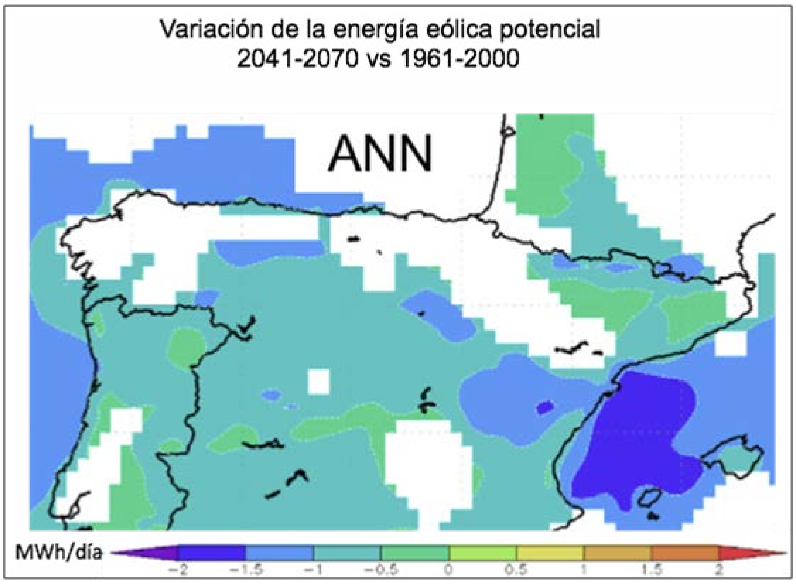

Figure 3.3.3. Estimated variation in the annual potential wind energy for the period from 2041-2070, in relation to the mean values for the period from 1961-2000 using the COSMO-CLM model and the A1B emissions scenario. Source: Santos et al., 2014

3.3.4 Seasonal variation in the energy demand

The use of HVAC in homes and other buildings accounts for a considerable proportion of the energy used in Europe (EEA. 2016). The heating and cooling requirements largely depend on the weather and climate conditions, and on temperatures in particular. The principal studies conducted on the subject (PESTA II, ClimateCost, POLES, ESNSEMBLES) agree that the seasonal energy demand in Europe has undergone considerable fluctuations over the last few decades due to climate change, and that it will continue to do so in the future.

Observed and projected impacts:

Approximately a third of the energy demand for heating European homes is supplied through electricity (Mideksa and Kallbekken, 2010). In contrast, the energy demand for cooling through air conditioning is exclusively covered by electricity. In the last few decades, the increasingly milder winters and the hotter summers, marked by heat waves, have led to changes in the structure of the energy demand for heating and cooling in homes and business premises. To determine whether the energy demand is in keeping with the heating and cooling requirements, most studies use an indicator termed HDD[65] (Heating Degree Day) and CDD[66] (Cooling Degree Day). Both indicators refer to the amount of energy required to either heat or cool homes in order to achieve a given comfort temperature. Between 1981 and 2014 there has been a reduction in the indicator value of between -8 ± 2 HDD/ year, due to milder winters (figure 3.3.4). In contrast, over this same period there was an increase of +2 ± 1 in CDD /year, due to the increasingly hotter summers (EEA. 2016).

According to the projections for these two indicators, made in the context of the ENSEMBLES European

(65) The heating degree day (HDD) is a measurement designed to quantify the demand for the energy required to heat a building. HDD is a direct function of the outdoor air temperature. The heating requirements of a given building at a specific place are considered to be directly proportional to the HDD number for that place.
(66) The cooling degree day (CDD) is a measurement that is analogous to the HDD measurement, showing the amount of energy used to cool a home or business. The baseline value for HDD and CDD is defined as the temperature at which there is no need for cooling or heating (Schaeffer et al, 2012).

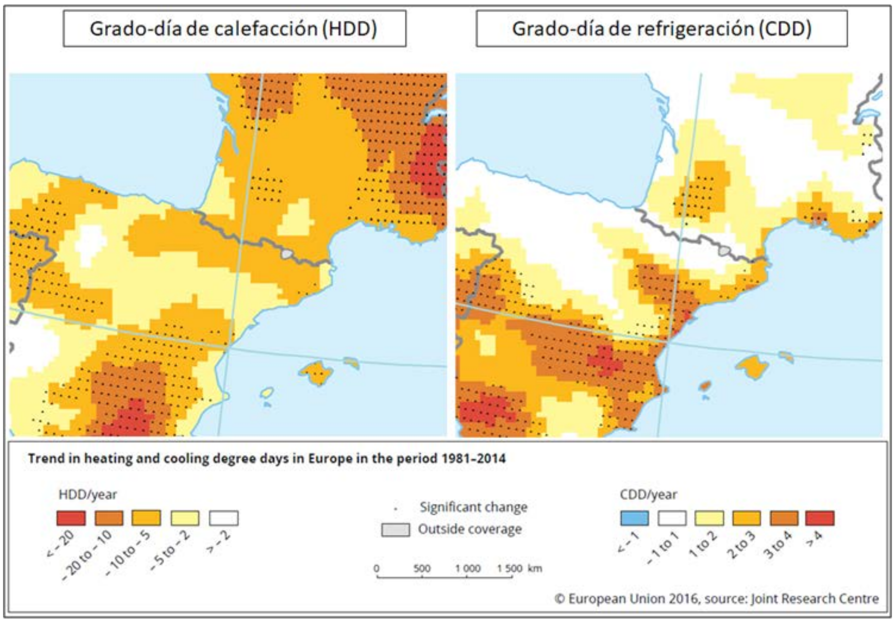

Figure 3.3.4.Trend for the HDD (left) and CDD (right) indicators in the period from 1981 to 2014 in the Pyrenees. Source: EEA, 2016 from JRC. 2016

project, by the end of the century the prediction is that there will be a progressively greater reduction in the energy needs for heating homes in winter and an increase in the energy required for cooling in the civil, industrial and services sectors. It should be pointed out that the increase in the energy demand to cover the growing cooling requirements (demand peaks) will most probably occur at times in the year that are critical for the generation of hydropower and with possible limitations on the use of water resources for the cooling of the thermoelectric plants (Förster and Lilliestam, 2009). To this, we should add the effects on the power supply and demand caused by the increasingly frequent and intense extreme weather conditions. Specifically, it is highly probable that, during the summer season, the energy demand peaks get increasingly higher in order to cope with the hot summers, while the energy production drops due to the lower water availability for hydropower production.

3.3.5 Increased risk of damage to energy infrastructures

The greater frequency and intensity of extreme weather phenomena could pose a threat to the integrity of the energy production system from the point of view of the storage, transmission, transformation and distribution of electricity in the Pyrenees (Sathaye et al., 2011; Muriel et al., 2016).

Observed and projected impacts

Many of the infrastructures and facilities making up the energy transmission and transformation systems on both sides of the Pyrenees are particularly exposed to climate risks and to the natural hazards that are either induced or boosted by such risks. On the one hand, energy infrastructures are characterised by an average service life that is relatively long (20 to 80 years) and, therefore, they are particularly exposed to the said risks in the long term. On the other hand, a significant part of the network is located in areas of the territory that are at risk from flooding, with steep slopes that are often unstable or affected by frequent landslides and rock falls, typical of mountain environments. Moreover, the change in the precipitation pattern could lead to a greater number of short, yet exceptionally intense periods of rainfall, acting as a triggering factor for many geological and hydrological risks. Other extreme weather events that will probably increase in frequency in the future, such as strong winds and storms, could lead to falling trees and telephone posts, causing damage to the distribution networks and subsequent power outages. Finally, during heat waves, the high temperatures may cause power transformer failures, temporarily affecting the power supply (Karl et al., 2009; Sathaye et al., 2011). Given the fact that, to date, there are no quantitative studies on these impacts in the Pyrenees, it would be appropriate to make an in-depth evaluation of the risk levels of the energy infrastructures, either derived from, or induced by climate change. An in-depth quantitative analysis would make it possible to determine whether this aspect of climate change requires the adoption of specific measures to avoid or mitigate potential damage. However, and as a preventive measure in the short and medium term, it is important to ensure that the design and operating conditions of new-build energy infrastructures are adapted to make them more resilient to climate risks, taking advantage of the lessons learned from other mountain areas.

3.3.6 Findings and recommendations

The energy sector is particularly vulnerable to the impacts of climate change. Climate change is expected to modify the behaviour of supply and demand over the forthcoming decades. The reduction in the hydropower and thermoelectric production capacity due to the implications of climate change could involve a reduction in the energy supply at critical peak energy demand periods. In this respect, during the increasingly hotter summers, characterised by more intense and frequent heat waves, changes are set to happen in the energy demand pattern, with the demand peak increasingly concentrated in this period. This out-of-sync situation between the periods of greatest demand and the periods with the lowest production capacity could lead to potential conflicts between different socio-economic sectors with regard to the use of water resources, particularly in summer due to a scenario of increased scarcity. In fact, it is foreseeable that the combined impact of climate change on water resources will make it difficult for the water requirements of the farming, energy and environmental sectors to be completely met. For this reason, the implementation of cross-cutting adaptation measures constitutes a core element to ensure the resilience of these sectors against the challenges of climate change.

Main challenges

- Optimise energy production and the use of water resources in the production of hydroelectric and thermoelectric power.

- Ensure that the management of the energy sector is responsive to potential variations in demand.

- Conduct an in-depth study of the potential limitations of the current energy system to meet climate challenges.

- Identify potential emerging opportunities.

- Promote energy saving measures and campaigns.

- Ensure the progressive adaptation of electrical and water infrastructures to future demand dynamics.

- Identify the most critical energy distribution network nodes that are located in mountain territories, with regard to climatic, hydrological and geological risks.

- Ensure a good response capacity and grid distribution recovery when faced with extreme weather events.

- Drive the transition to a distributed energy generation model to replace the current centralised production model.

Recommendations

This section lists a series of adaptation recommendations directed at facilitating the process of designing and developing instruments to increase the resilience of the energy sector against the future climate and its variability. It should be noted that there is no effective combination of pre-established measures and that the priority level of the actions will depend on the energy production system in question and on the specific geographic location of the production, transmission and storage infrastructures, It is also important to consider the particularly cross-cutting nature of the energy system, for the detailed assessment of the predicted impacts and also for the definition of possible adaptation measures.

This cross-cutting nature is particularly evident in the question of water resources and in the aspects related to the mitigation policies and objectives. It is essential to consider all these aspects in order to be in a position to establish priorities before defining and implementing a set of optimum measures in terms of efficiency and effectiveness (cost/benefits) in order to increase the resilience of the sector to climate change in the area of the Pyrenees.

Soft measures [67]

- Integrate considerations on the evolution of the climate variables and their implications on the annual energy demand, on the current systems for predicting a crisis and demand peaks.

- Drive and promote thermally efficient building systems with passive air conditioning and heating systems, capable of coping with temperature increases and thermal comfort requirements with a low or zero energy consumption (for example:

increase the system of incentives to improve the energy efficiency of refurbished and new buildings).

• Consolidate new modelling approaches with regard to hydro-meteorological projections, integrating, as far as possible, any relevant natural and man-made processes at a basin level.

• Systematically integrate the ecological water flow considerations, defined by the Framework Directive on Waters (200/60/EC) in the reservoir management plans and practices, in order to guarantee the functional needs of the river ecosystems, also in consideration of a scenario with the worsening of minimum water flow rates.

• Promote studies to assess the sensitivity of the main sources of renewable energy to climate change (for example, reducing the uncertainties on the future implications of climate change on the production of hydroelectric, thermoelectric and wind power) with a sufficient level of detail to make it possible to advise on the actions and investments in the field.

Green measures [68]

• Develop alternative energy production systems, making use of local resources (example: biomass or pellet boiler).

Grey measures [69]

• Facilitate the transition to a decentralised energy generation model.

• Promote the use of thermally efficient construction materials and techniques and passive HVAC systems (double and triple glazing, cooling by passive air conditioning systems, the use of green roofs, etc.

• Recover, where feasible, the most critical reservoir and dam storage capacity, to facilitate the multi-annual planning and management of the water resources through the adoption of actions to optimise storage despite the variability in intake.

• Increase the interconnectivity of large-scale water infrastructures to increase the resilience of the system (integration in distribution networks and introduction of instruments for the exchange and temporary transfer of concessions).

• Implement an intervention strategy for the regular maintenance and safety of infrastructures that are particularly vulnerable to extreme weather events and to resulting risks (for example: energy infrastructures located in areas with a risk of flooding or landslides).

• Promote the creation of a trans-Pyrenean smart grid, facilitating the interconnection of small-scale production plants and renewable sources, whether these are photovoltaic, wind power or hydroelectric.

(67) Soft or non-structural measures to reduce or mitigate the negative effects of climate change. This category of measures is typically represented by investigation studies focussed on bridging knowledge gaps or to enrich the knowledge bases on climate change, its impacts and the most vulnerable sectors. This category also includes the development of specific methodologies and systems to reduce the risks resulting from climate change (e.g. the development of a cross-border early warning system to manage heat waves in the Pyrenees).
(68) Green measures or measures based on ecosystem services: measures of this type include all the measures, good practices, studies and initiatives that are based on the principle of the use of the ecosystem services conferred by the various natural resources in order to mitigate the negative effects of climate change (e.g. conservative silvicultural practices to increase the capacity of the woodland in the Pyrenees and to reduce the hydrogeological risks).
(69) Grey or infrastructural measures are those that base their mitigation action on the construction or implementation of specific infrastructural elements (e.g. the construction of dikes in inhabited areas with a high risk of torrential flooding).

KEY MESSAGES

- It is previsible that climate change will negatively affect the disponibility of water resources for hydroelectric production in the Pyrenees.

- The reduction of the minimum flow of rivers, jointly with the increase in water temperature will very likely limit the thermoelectric energy generation capacity.

- The photovoltaic and photothermal energy production capactity could increase due to a greater rate of sun radiation linked to the decrease in cloud cover.

- The change in wind patterns and speed projected for the comming decades in the Pyrenees could have a negative impact on the wind energy production capacity in some areas of the Pyrenean range.

- The projected increase in the frequency and intensity of extreme climate events could bring about a risk for the energy production and distribution systems.

- Climate change could cause an increase in the summer energy demand for cooling purpouse that could be compensated only in part by the decrease in electricity demand for heating in the winter.

3.4 Natural hazards

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ABSTRACT

This chapter presents the main elements of knowledge currently available on the potential influence climate change can have on hazard associated with the main natural risks that may be encountered in the Pyrenees. It thus appears that in the future, the Pyrenean territory could face an increase in minimum and maximum temperatures, heat waves and episodes of drought; an increase in the frequency and occurrence of episodes of intense rain and in the intensity of episodes of hail; an increase in the risks associated with surges and floods in spite of the absence of clear indications on the future evolution of their frequency of occurrence and their intensity; increased weakening of the stability of slopes and rocks in very poorly known proportions but which could result from the combination of the future evolution of precipitation, of temperatures (wildfires), and the likely thawing or degradation of permafrost. The chapter concludes with a reflection on the strategies of adaptation that can be considered in order to cope with these concerning developments, and recommends a number of measures that can be implemented to adapt to them.

Europe is experiencing an increasing number of natural disasters that are caused by a combination of changes in its physical, technological and human/social systems. Of the disasters due to natural hazards that occurred in Europe since 1980, about 90% of the events and 80% of the economic losses were caused by hydrometeorological or climatological hazard (EEA, 2010). Given the conditions of global environmental change such as outlined in the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change, impacts from natural hazards on natural and human systems will probably grow and manifest worldwide. Europe will probably see a progressive and strong increase in overall climate hazards with a prominent spatial gradient towards south-western regions (Forzieri et al., 2016).

This chapter provides a synthetic review of the main elements of knowledge currently available on the potential influence of climate change on the hazard associated with the main natural risks that may be encountered in the Pyrenees. The importance of the hazard presented by a given type of natural phenomenon (storm, drought, flood, landslide,..) on a territory, depends on the combination of the hazard of the phenomenon (which qualifies its occurrence and its intensity) and on the vulnerability of the territory on which the natural phenomenon occurs (which is all the more important when the territory is populated and urbanised). In this chapter, we will not discuss the notion of vulnerability. Instead we will focus on a presentation of the state of the current knowledge on the hazard of the main natural phenomena described on the Pyrenean territory and their future evolution. Four types of natural phenomena are considered here: 1) Extreme Weather Events, 2) Floods, 3) Landslides and Rockfalls and 4) Degradation of Permafrost and 5) Avalanches. In conclusion, suggestions are presented in terms of adaptation actions to undertake.

3.4.1 Increase in extreme weather events

Current Evolution

The monitoring and analysis of the evolution of extreme events (torrential rains, droughts, heat waves, ...) is an activity that is complicated not only by the scarcity and the suddenness of their occurrence; the sensitivity of the variables that one seeks to observe; the changes in methods and measurement equipment used to document them, but also because of the difficulty of agreeing on how to define them. In general, it is the evolution of the extreme temperatures that is best documented; the other weather variables are often affected by gaps (monitoring equipment can be destroyed during a storm, for example) and are not always consistent depending on the regions. The IPCC, in its last publication on the question (Hartmann et al., 2013), proposes a general illustration (Figure 3.4.1) on developments observed since the middle of the 20th century. Studies carried out specifically on hail have shown that throughout France, it is probably on the mountain ranges, and in particular in the Pyrenees,

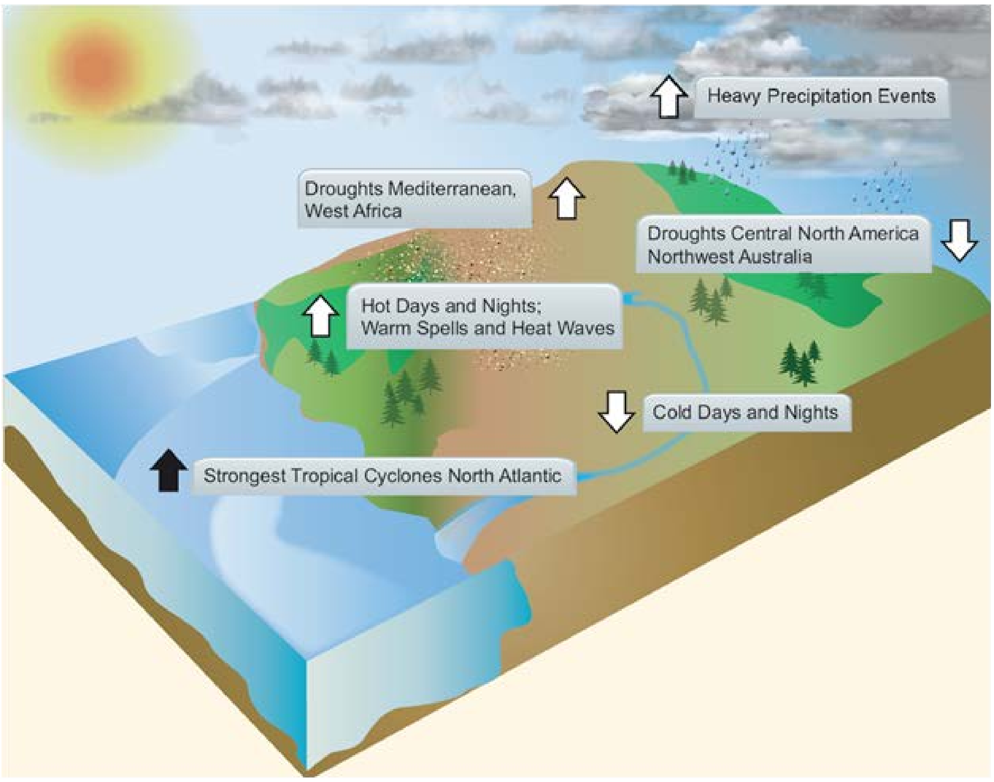

Figure 3.4.1. Evolution of the frequencies (or intensity) of different types of extreme events (the evolution of the increase or decrease is indicated by the direction of the arrow), since the middle of the 20th century (extract of Hartmann et al., 2013).

that episodes of hail are the most frequent and intense, influenced by moist air inflow from Spain at certain periods or fronts of cold air from the Atlantic in others. The observation of the episodes of hail in the past 40 years concludes to an increase in the intensity of episodes, in correlation with the increase in spring temperatures, although no trend has been detected on their frequency of occurrence (Berthet et al., 2011).

Future Projections

To this day, the relationship between the changes in total precipitation and the evolution of extreme events has not been established. However, the projections made with the assistance of climate models indicate that, at the global scale, precipitations may be more intense during the rainy season, in particular in the high latitudes and in the regions benefiting from the monsoon rains (Collins et al., 2013). In the framework of the special report of the IPCC on extreme events IPCC (2012), contributors expect an evolution towards more intense rain events and less events of low intensity rain. Similarly, this evolution could potentially cause a more important accumulation of energy and generate more violent storms, even if this has only been documented in the territories of the United States. At seasonal level, the increase in evapotranspiration linked to warming could cause more frequent and longer periods of drought, especially in semi-arid regions such as the Mediterranean basin. In addition to these droughts, qualified as "meteorological", "agricultural" droughts can also take place more frequently in regions where the water content of the soil will be in sharp decline (see chapter 3.2). Again, this phenomenon may particularly affect the Mediterranean basin (Collins et al., 2013).

BOX 3.4.1. SOLUTIONS TO LIMIT THE IMPACT OF DROUGHTS IN THE CITIES

Several cities have begun to implement solutions based on the creation of islets of freshness to fight the rise in temperatures[70]. In Orleans (France), the development of green roofs and green spaces, the reduction of waterproofed surfaces, the maintenance or creation of natural areas by planting preferably local species, and the management and renewal of heritage trees, allows the city to present itself as "garden-city." In Stuttgart (Germany), a binding construction regulation has been adopted, which encourages the use of nature-based solutions, and has helped the city to cover 60% of its surface with vegetated areas. The 1900 m2 of green roofs on Chicago City Hall, implemented according to the Chicago Climate Action Plan has helped decrease stormwater runoff and reduced the urban heat island effect around the site (UNEP, 2014).

3.4.2 Increase in the frequency of floods and flooding

Current evolution

The summaries of the papers on the subject of floods proposed in the framework of the IPCC up to this date, have not detected a statistically robust trend of evolution of floods at the global scale. The only robust signal relates to the evolution in the spring in regions where snowpack is important and where runoff is strongly influenced by snowmelt (Hartmann et al., 2013). In its SREX report (IPCC, 2012), the IPCC declares it is also necessary to take into consideration the changes in vulnerability, exposure, and even in basin activities. The more recent WGII report of AR5 (IPCC, 2014) points out that the recorded growing tendencies in impacts of flooding are more correlated to these changes, as to a direct consequence of climate change, as is also concluded in Hall et al. (2014).

Mediero et al. (2014), when analysing the evolution of the maximum yearly discharges in basins properly gauged and relatively large in Europe, report tendencies more negative than positive, for the period of 1959-2009. In the specific case of flooding in headwaters, in basins much smaller and generally not gauged, there are practically no reports; therefore it is not possible to extend these Findings to the local scale. López-Moreno et al. (2006), and Renard et al. (2008) find negative tendencies in the peaks of discharges within the Central Pyrenees for the periods 1955-1995 and 1968-2000 respectively, however these might be largely justified by the increase in forest mass and changes in uses of land. Bulygina et al. (2009, 2011) demonstrated that in small basins the increase in forest mass may result in reducing the average river flow by up to 10% during floods.
In the Pyrenees, floods mostly result from high intensity rains, as quick response "flash-floods". It is only in a few occasions that thaw plays an important part, as shown by the episode in Garonne, where melting triggered catastrophic floods that affected Catalonia, Aragon, Andorra and Central-Pyrenees (Water Agency of Adour-Garonne, 2014; Llasat et al., 2017). An increase in the frequency of spring floods was also recorded in the mid -19th century, at the end of the Little Ice Age (Llasat et al., 2005). Nevertheless, floods most commonly occur in autumn, with outstanding floods in October 1940 (rains beyond 860 mm) and November 1982 (rains beyond 600 mm) (Llasat et al., 2017), and those in 1999 (North of Catalonia and highest number of victims in the recent years in the South of France, Boudou, (2016)).

No tendency could be detected in these catastrophic floods (Llasat et al., 2013). On the other hand, "extraordinary" floods have been detected, that are more frequent but cause less damage, correlated with the increase in vulnerability and exposure, especially in coastal areas (Llasat et al., 2013). For example, between 1981 and 2015 there have been 77 floods in Catalonia; 23% of these were catastrophic, and 51% were "extraordinary", with a total of 100 fatalities (Llasat et al., 2017). In parallel, 97 catastrophic events occurred between 1981 and 2010, in the Occitanie and Nouvelle Aquitaine regions, with a total of 94 fatalities. In Andorra, extraordinary floods occurred in 1907, October 1937 and November 1982, the latter with fatalities. A slight yet significant increase (0.4 events/decade) in summer floods (July-August-September) was recorded in the Catalonian Pyrenees. These data show the necessity to analyse the seasonal variations on the basis of high temporal resolution rainfall series, which is currently limited by the lack of in situ observations. Álvarez-Rodriguez et al (2016), show that since 1950 to this day there has been little changes in the distribution of altitude stations beyond

(70) http://uicn.fr/solutions-fondees-sur-la-nature/

1.400 m. In the last decades some regional services have installed new stations beyond this level, but mostly with the purpose of monitoring the snow cover as well as forecasting avalanches.

Future projections

It is difficult to develop future projections for floods in view of the uncertainties concerning projections for high-intensity rains, land-use changes, etc., (Hall et al., 2014). The IPCC (2012, 2014) reports merely present a projection for the frequency of high-intensity precipitation events (for a 20-year return period) in southern Europe. Nevertheless, they identify as a future challenge, with a high level of confidence, the increase in economic and human losses caused by river and coastal floods, resulting from growing urbanisation, rise in sea level, coastal erosion, and peak discharges in Europe. In the case of the Pyrenees, this might affect mostly the peripheral coastal regions. On the contrary, in the Pyrenean area itself, ever growing rural desertion and increase in forest cover results in problems occurring only in the touristic areas (settlement of river and torrent banks, with a high level of risk, such as, for example, in the case of River Garonne in June 2013 (Llasat et al., 2017), or of Biescas, in August 1996 (García Ruiz et al., 2004). Regarding future projections of floods, the studies of Rojas et al. (2012), found no significant indication in the Western Mediterranean regions. Dumas et al., (2013) predcit an increase in the frequency of flood events for Rhone, with a 100-year return period. Referring to the index for yearly maximal rain within 24 hours, Turco et al. (2016) found a change in the Pyrenean region, for the period of 2070-2100 in comparison to 1971-2000, ranging from -5% to +5%, which would be clearly negative in spring and summer.

3.4.3 Increase of landslides and rockfalls

Current and future evolution of the number and types of landslides

Some studies have been conducted into historical records analyses of landslide occurrence (Seneritvane et al. 2012). They show a wide range of results, due to local effects, uncertainties, and undetermined effects. Amongst them, several studies have shown that the elevation of air temperatures has resulted in the increase of landslide activity, especially rock falls, rock and ice avalanches and debris flows (Ravanel and Deline, 2011, 2015; Stoffel and Beniston, 2006; Paranunzio et al., 2016; Huggel et al., 2012, 2013).

BOX 3.4.2. SOLUTIONS TO LIMIT THE RISKS OF FLOODING

In the face of the risk of flooding, strategies based on the construction of protection infrastructures (such as retention basins coupled to automated management systems) have been implemented in the first instance. More recently, several territories have implemented approaches based on development and aimed at upstream management of the phenomenon[71]. For example, the Department of Seine-Saint-Denis, has thus recognised the importance of the natural ecosystems on its territory. They help regulate the floods, as well as improve the infiltration of runoff. A French-Swiss restoration program for the River Rhine has helped to reduce the exposure of populations to the risk of flooding by restoring water supply to some dead arms of the river, as well as modifying the structure of some tributaries. In 2002, the World Wide Fund for Nature (WWF) initiated a program to reconnect lakes in Hubei Province to the Yangtze River (China) through seasonally re-opening the sluice gates and facilitating sustainable lake management through removing or modifying infrastructure, thus increasing the floodwater storage (UNEP, 2014). In Switzerland, up until a few years ago, the River Aïre near Geneva flowed through a straight concrete channel. Periods of heavy rain repeatedly breached its banks and posed a flood risk to some of the city's neighbourhoods. A flood protection project, which is being combined with the ecological upgrading of the watercourse, was initiated in 2002. A long stretch of the streambed was widened, the discharge slowed down as a result and the flood peaks in the lower reaches were dissipated. Since 2011, the Swiss Waters Protection Act has prescribed a minimum space for streams and rivers. The buffer strips along banks that already exist today must be extended, particularly along major watercourses. Around 20.000 ha of land are required for this throughout Switzerland, mainly in agricultural areas. The land will not be lost to agriculture, as extensive grassland use for raising cattle and hay production is still possible (FBA, 2017a)

(71) http://uicn.fr/solutions-fondees-sur-la-nature/

Global changes would have impacts worldwide, but their effects should be even more exacerbated in particularly vulnerable areas, as might be the case in mountain regions. Indeed, in these areas, a range of socioeconomic sectors (e.g., tourism, forest production, agro-pastoralism, ecosystem resources...) has experienced considerable changes in the last two centuries. Moreover, climate change occurring in mountains may imply future changes in temperature and precipitation patterns; this may lead to changes in the balance between snow, ice and rainfall, which ultimately will result in changing the quantity and seasonality. Consequently, natural processes controlled by hydro- meteorological triggers, and among them landslides, will add, in a future climate, further environmental pressures on both social and natural systems. As indicated by the IPCC Report in 2014, "extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent". There is high confidence that this evolution will affect landslides in some regions (Seneviratne et al., 2012). Jomelli (2012), Stoffel et al. (2014) and Wood et al. (2016) indicate that where the frequency and/or the intensity of the rainstorms will increase, shallow landslides, including rockfalls, debris flow and debris avalanches, are also expected to increase. However, no relationship can be found between the rainfall intensity and rockfall triggering from several events documented in Andorra (Copons, 2004).

More specifically, landslides may be sensitive to climate change according to six climate-related factors (Crozier, 2010): total precipitation, rainfall intensity, air temperature, wind speed and duration, changes in the weather systems and the related meteorological variability. These factors may affect different processes, and could then have some effects on landslide occurrence. For instance, an increase of rainfall intensity may imply an evolution of the water table that may weaken the ground stability. The increase of temperature and the decrease of precipitation may imply an increase of forest fires, also resulting in a slopes stability reduction because of the absence of mechanical strength due to the roots. In mountain regions at high elevations, yearly increase of temperature may result in the thawing of permafrost and the weakening of rocks solidity due to glacier decrease, leading to the rising of rock slope failure. The change of wind speed and duration may imply some changes in evapotranspiration, and consequently, in soil moisture. Moreover, in mountain areas, debris flows are a serious threat as they periodically damage critical infrastructure and disrupt transport networks with regional socioeconomical consequences (Utasse et al., 2016).

Situation at the Pyrenean scale

At the scale of the Pyrenees, studies have enabled analysing the geomorphological and climatic conditions to explain the occurrence of landslides (Lorente et al., 2002), but little work has been made to date on the question of the future evolution of these phenomena in the context of climate change. The higher frequency and intensity of extreme weather events will likely increase the exposure of infrastructure and housing to the risks of flooding, avalanches and landslides (ONERC, 2009). The risk of forest fires due to the elevation of mean temperatures could thus result in an increase in gravity processes such as soil erosion, landslides, and mudslides, resulting from the reduction of mechanical contention of soils in place by the root tissue, and from the increase in runoff. Moreover, rising temperatures and the modification of flows in the soils could also cause instabilities in the land.

In the Pyrenees, the increase of landslides is associated with torrential rains and the disappearance of the vegetation or the substitution of the indigenous vegetation by another with a lower rooting. Human actions can therefore increase the risk of landslides. Consequently, urban management plans are an important tool to adapt to the increase of these phenomena.

3.4.4 Increased risks related to the permafrost degradation

The presence of permafrost (part of the soil or the subsoil permanently frozen) is linked to the freezing of the subsoil in layers ranging from 50 cm to 8 m, due to the combined effect of various conditions: climatic (in particular temperature, precipitation, wind, and solar radiation); topographic ("barrier effects" or influence on the wind); and local (snowpack, plant cover, water availability and types of pedogeological formations present) (Gruber et al., 2017). Nowadays, efforts are being made in mapping the mountain permafrost. Allen et al. (2016) have carried out a study in the Himalayan Mountains of the district of Kullu, Himachal Pradesh, which has enabled the mapping of the existing permafrost. They have thus shown that the area covered by the permafrost is in the same order of magnitude as that covered by glaciers in their area of study and that therefore the risks associated with climate change for this type of formation must be studied. Although it is not easy to understand the processes that control the formation of permafrost, it is obvious that the melting of the permafrost induces a risk of destabilisation linked to the subsidence of the ground affected by the loss of the volume occupied by ice, as well as by rupture of the mechanical balance which controls

BOX 3.4.3. THE SAMCO PROJECT: "ADAPTATION FOR COPING WITH MOUNTAIN RISKS IN A GLOBAL CHANGE CONTEXT"

At a local scale, an analysis of landslide evolution due to climate change has been conducted in Cauterets municipality territory, through the SAMCO project. This sort of analysis can be considered as an adaptation strategy aiming at protecting the population and infrastructures from future landslides due to climate change. Two scenarios of emission of greenhouse gases have been analysed (RCP 4.5 and 8.5., ALADIN-Climate model) taken from the DRIAS portal. The projections show a tendency to the increase of extreme events of precipitations at short and long term. For the highest points, the model shows an increase of cumulative precipitations. For the lowest points, the model indicates a slight increase at short term and a small decrease at long term. For temperatures, projections indicate a significant temperature increase at short (+1.5°C) and long term (+ 4°C), resulting in changes in the balance between snow and rainfall. Landslide hazards analysis has been performed with ALICE software (Baills et al. 2011, Sedan et al. 2013). The model is based on a 2D slope stability analysis, for which the main physical characteristics of the soils and surfaces are quantified and also considers the effect of the daily water table fluctuation, computed using the GARDENIA model (Nicolle et al., 2014). A significant increase of the mean water table level is projected for future periods, especially between 2071 and 2100 in the worst case scenario (RCP8.5). ¡Error! No se encuentra el origen de la referencia. shows the mean probability of Safety Factor[72] <1 during the period of 1981-2010, considering a rotational landslide, with a length of 25m, and a depth between 1 and 3m. The results point out to an increase of the water content of the soil (as described in ¡Error! No se encuentra el origen de la referencia.) inducing a reduction of the SF in a large part of the studied area. These changes are not uniform over the area, and are particularly significant for the worst case scenario of RCP 8.5.

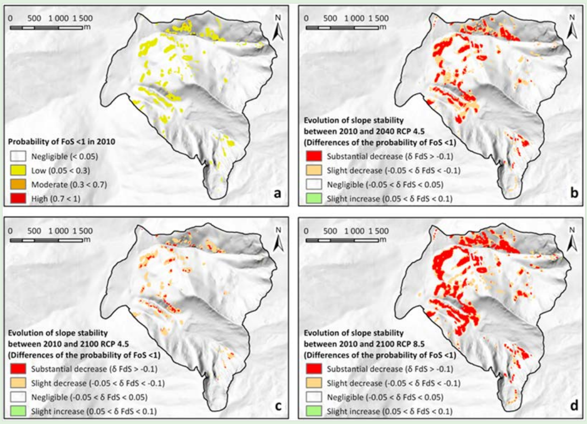

Figure 3.4.2. Evolution of landslide susceptibility according to climate change with two different scenarios: a) probability of SF <1 in 2010, b) differences of the probability of SF <1 between 2010 and 2040 with RCP 4.5 scenarios, c) differences of the probability of SF <1 between 2010 and 2100 with RCP 4.5 scenarios, d) differences of the probability of SF <1 between 2010 and 2100 with RCP 8.5 scenarios. Source: SAMCO Project, 2018.

the process of departure of sediments by landslide or Rockfalls (in the case of rock glaciers melting), even at low gradient (Gruber et al., 2017). This type of risk must be taken seriously in the Himalayas, since it can affect thousands of people, and cause damage that can cost several tens of millions of dollars per year, according to Kääb et al. (2005). It is also important to study it in the European mountains, due to the recreational activities and sports that take place in these environments (Boeckli et al., 2012). Most of the studies referenced on this kind of risks in European mountain environments refer to the Alps. Ravanel and Delile (2011), followed by Krautblatter et al. (2012) have referenced a series of events where the fall of blocks is potentially linked to thawing or degradation of the permafrost. Bodin et al. (2016) studied the degradation of a rock glacier and the triggering of associated torrential flows. Keiler and Fuchs (2016) presented a retrospective analysis in the Austrian Alps on the link between melting of permafrost and risk exposure. Magnin et al. (2017) have studied the evolution of the state of permafrost on the Mont Blanc massif, from the Little Ice Age (1300-1850) to the present day, then proposed a projection to 2100, concluding with an increased frequency of future major crumbling events in glacial environments.

(72) The Safety Factor (SF) is an index provided by a mechanical simulation and used for the characterization of slope stability. For SF < 1, the slope is considered to be unstable; for 1 < SF < 1.2, the slope is considered to be potentially unstable and for SF > 1.2, the slope is considered to be stable.

In the Pyrenees, permafrost is monitored in small extensions and in areas of higher altitude (overall beyond 2.700 m). It can be observed directly on site, but also indirectly through indicators such as rock glaciers (Serrano et al., 2009, 2010; González-García, 2014). Serrano et al. (2009) have proposed a mapping of the permafrost that combines spot observations, topography, solar radiation, and air temperature in the Spanish Pyrenean massif (¡Error! No se encuentra el origen de la referencia..4.3). It shows areas where the formation of permafrost is made possible or probable by the local conditions thus evidenced, at altitudes (always higher than 2.000 m) depending on the orientation of the considered massifs (lower permafrost on the walls facing south than north). On the north-west face of the Vignemale mount, where an increase in crumbling events has been observed over the past few years on its right side, a system for monitoring the evolution of the permafrost has been installed to understand the influence of the local climate on the degradation and thaw phenomena (Rico et al., 2017).

3.4.5 Avalanches

Avalanches range from small slides barely harming skiers, up to catastrophic events endangering mountain settlements or traffic routes (EAWS, 2016). Avalanche formation is the result of a complex interaction between terrain, snowpack and meteorological conditions that may lead to the moving of dry or wet snow (EEA, 2017a). EEA (2017a) reports that, *"dry and wet snow avalanche activity increased between 1952 and 2013, especially during the mid-winter season and at high altitude".* Historical observation data and long-term statistics on avalanche fatalities are available in nearly all countries of the Alps. The majority of the fatalities due to avalanches are located in uncontrolled terrain (mostly recreational accidents); few being reported in controlled terrain (settlements and transport corridors) (EEA, 2017a). In the Alps, fatalities can reach an average of 100 persons every winter. In Catalonia, an average of one to two avalanche fatalities per year is reported since 1987, showing a decreasing tendency that may be due to the increasing use of basic personal safety material for mountain activities (Martin-Vide, 2016). Dendrogeomorphology was used to date and reconstruct large-scale snow avalanche events that occurred in the last four decades and showed that the winter of 1995– 1996 was most extraordinary with respect to the occurrence of major avalanche events in the SE Pyrenees (Muntán et al., 2009). However, a statistical increase of big avalanche events has been reported by García-Sellés et al., (2010) and especially wet snow events (Oller et al., 2015) for this region. Castebrunet et al., (2014) projected that avalanche activity in the Western Alps will most likely decrease at low altitudes in spring, due to increasing temperatures, and will increase above 2.500 m in winters due to possible increases in the frequency of heavy precipitation. Over the Pyrenean skiing area of the Nouvelle Aquitaine region in France, the snow covered duration period could reduce from 3 to 2 months and reach 20 cm in height by the end of the XXI century (Le Treut, 2013). For the same temporal horizon, the

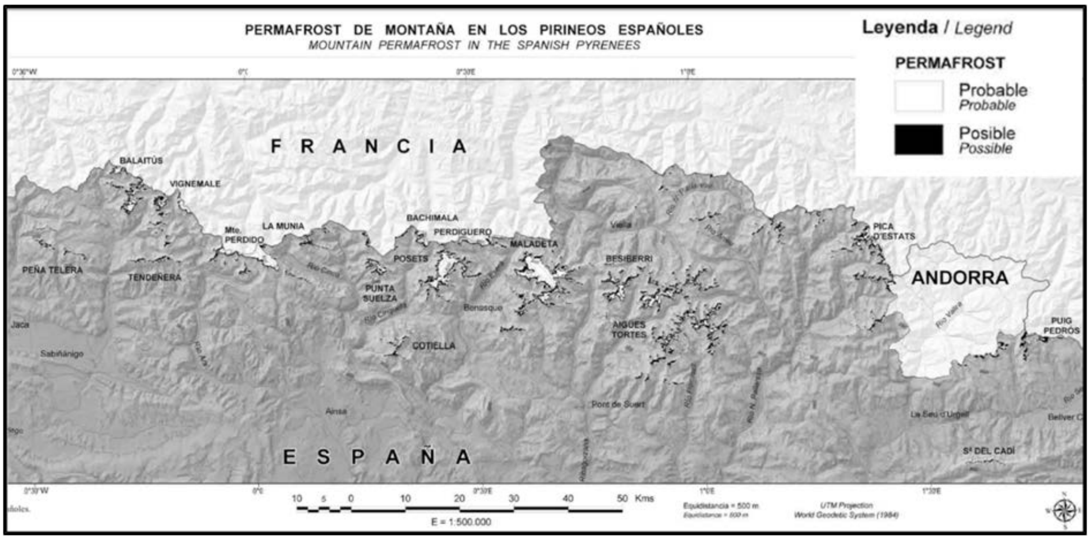

Figure 3.4.3. Presence, possible and likely, of permafrost in the Spanish Pyrenees (modified from Serrano et al., 2009).

occurrence of heavy snowfall events could decrease beloz 2.000 m and increase above this altitude, according to Lopez-Moreno et al., (2011).

Regarding avalanche activity, a general decrease in mean (20-30 %) and interannual variability is projected for the Alps. However, the future evolution will depend on changes in snowpack characteristics and their connection to avalanches. As reported by EEA (2017a) *"The connection between frequency and magnitude of avalanches and climate change is uncertain. In general, it is assumed that possible changes in avalanche frequency and magnitude are related to changes in snow cover, with a decrease in avalanche hazards likely at low and medium altitudes (due to increasing temperatures during winters), although more frequent heavy precipitation events may counteract this trend (PLANALP, 2016)".* For adaptation planning, observations of snow avalanches (such as dendrogeomorphic time series, population surveys and historical data mining) and statistical–dynamical models can be used with reasonable confidence to predict runout distances of avalanches with high return periods (Schläppy et al., 2014). However, future climate change uncertainty requires an active risk management together with the combination of permanent and temporary protection measures (EEA, 2017a).

3.4.6. Designing an adaptation strategy to cope with natural hazards in the future

The capacity of adaptation characterises the capacity of adjustment of a territory to changes in climate (which include climate variability and extreme events) in order to mitigate the potential damage, take advantage of opportunities, or to cope with the consequences. In order to adapt to future hazards associated with natural events, it appears necessary to combine measures of reduction in the risk associated with the current hazard, and measures to adapt to the impact of the climate on their future evolution. If the current hazards are generally well identified in the planning documents, it is still seldom that their future evolution is taken into account.

Some projects[73] are studying the interactions between environmental and social processes in the Pyrenean territories in the context of territorial transformations and climate change. The Pyrenees have suffered important territorial transformations (decline in demography and agropastoral activities, development of tourism). This raises the question of the way in which local communities experience these changes, and the relationship they perceive with natural hazards and climate change. The preliminary results of a survey in the valleys of Aspe and Ossau (Béarn, FR), show that environmental changes are established facts for the majority of the interviewees (authorities, settlers), that they evidence using indicators such as: shortening of the period of snow, increase of storm or drought episodes, or even the presence of animal and plant species at altitudes considered unusual. However, linking climate change and natural hazards is not as easy for the elected representatives interviewed. In fact, most of the time they tend to echo the scientific uncertainties. Thus, the question of adaptation remains marginal in the Plans for the Prevention of foreseeable mountain natural Risks (PPR), which, moreover, are often contested (including the limits of zoning and the methodology used) by the townships and the residents concerned. Also, the mountain municipalities are often sparsely populated and have reduced means, both financial and human. The elected officials also mention that they perceive a reduction in the functions of advice and expertise from state services to the municipalities, which reduces their ability to cope with climate change. However, it is worth noting that in Andorra, extreme situations are considered for planification documents, such as the debris flow hazard official zoning, where the worst climate change scenario is used as reference (Hürlimann et al., 2006).

In France, the National Plan for Adaptation to Climate Change (MEDDTL, 2011), considers that the policy for the management of natural risks implemented so far provides an appropriate framework to take into account their future evolution, conditioned by strengthening certain aspects and anticipating now the disruptions to come. This plan proposes 30 measures of national scope, nearly half of which would already have been implemented, according to the CGEDD (2015). However, this plan does not include territorial actions of adaptation, which are the responsibility of regional schemes for climate, air and energy (SRCAE) and territorial climate-energy plans (CFEP). In Spain, the first national plan for adaptation to climate change, adopted in 2006, targeted the achievement of regional climate scenarios and knowledge dissemination actions on mountains and 14 other topics. The second program has continued this work for the period of 2009-2012, by strengthening the indicators and monitoring

(73) Program Cesar - Environmental Change and Adaptation in the region and the ongoing program RiTTA - Risks and Territorial Transformations in Aquitaine, have been funded by the Regional Council of Nouvelle Aquitaine.

mechanisms. A third program has been adopted for the period of 2014-2020, in order to mobilise the whole of the financial instruments of the European Union.

3.4.7 Findings and recommendations

The elements of knowledge currently available concerning the potential influence of climate change on the hazards associated with the main natural risks that may be encountered in the Pyrenees have been presented in this chapter. It thus appears that in a time frame that is difficult to determine accurately (between 2030 and the end of the century), the Pyrenean territory might have to face the following developments:

• Increase of maximum and minimum temperatures, heat waves and episodes of drought, which will potentially be longer and more intense;

• Increase in the occurrence of intense rains and the intensity of episodes of hail;

• Increase in the risks associated with floods. Signals are as yet undefined, and dependent on the likely increase in the vulnerability of populations and infrastructure, particularly those in coastal tourist zones and those adjoining water courses;

• Poorly known embrittlement of the stability of slopes, which could result from the combined evolution of future precipitation, temperatures and melting or degradation of permafrost;

These future developments are still affected by a significant uncertainty, particularly due to the sometimes decisive role of the future evolution of urbanisation and tourism policies, of occupation and use of land, localisation and exposure of infrastructures. In view of the potential future evolution of these hazards, the strategies in place in the Pyrenees rarely integrate the concept of adaptation. This could be explained, on the one hand, by a lack of knowledge of the phenomena considered and, on the other hand, by the fact that the measures targeted to adapt to a changing climate in the future are generally integrated with other measures implemented for other purposes (protection of populations, securing food production, maintaining or strengthening economic and industrial activity in mountain areas,...) (OPCC, 2013).

BOX 3.4.4. ACCOMPANYING GUIDE: "CLIMATE: ACHIEVING SUCCESSFUL CHANGE[74]"

The members of the Reflection and Action Group for adaptation to the effects of climate change (GRAACC), animated by Rhône-Alpes Environment Energy have published a document presenting the main stages of the implementation of a territorial project integrating the adaptation for the Alpine regions. This guide, published in 2 pages, adopts the views of elected representatives and technicians of communities, who wish to implement an approach aimed at the adaptation of their territory to the effects of climate change. In page 2, after a synthetic explanation of the expected impacts of climate change on the region Rhone-Alpes, essentially derived from the study MEDCIE (2008), the major opportunities and threats are identified for the Rhône-Alpes region, as well as the orientations for adaptation implemented. Then, the guide documents in detail an approach to the construction of these strategies, even going so far as to propose models of brief specifications for contractors who would be in charge of characterising the vulnerability of the territory to climate change. Finally, the definition of the adaptation strategy is discussed, recalling the basic principles and pointing out the elements essential to its implementation.

Recommendations

It is recommended to design an approach to adaptation at the scale of the management of the stakes targeted by the type of natural hazard considered (OPCC, 2013). At these local scales, the approach must of course be accompanied by the characterisation of the current vulnerability of the territory (importance and location of populations and infrastructures exposed) to the natural risk considered, and its future evolution (Fuchs et al. 2017). The Project Climadapt provides a catalogue of examples[75] of adaptation measures, some of which relate to extreme events and high water levels and floods, even if none of these apply to the mountain areas context. The European Commission recommends that the measures taken be subjected to a "Climate check" test, to ensure that the capacity of adaptation of these measures to future climatic conditions is satisfactory. It also promotes the concept of "robust

(74) http://orecc.auvergnerhonealpes.fr/fr/publications/outils-et-methodes/guide-climat-reussir-le-changement.html
(75) http://climate-adapt.eea.europa.eu/knowledge/tools/sat

decision making" (Lempert et al., 2003), which considers that a decision is robust if it delivers good results regardless of the possible future and its uncertainties. The robust measures can be: 1) "No Regrets" measures (which provide benefits in all cases (and often in the short term), 2) Margins of Safety measures, which can be dismantled or extended without loss of the initial investment (as for example the construction of a dike using a technique that makes it easily removable), 3) Reversible and Flexible measures, such as the implementation of warning systems, which can be adapted according to the experience returns on the consequences of the events observed, 4) Soft measures (described below), and (5) Time horizon reducing measures (prefer short life-span infrastructures). Generally speaking, a plan for adaptation consisting in a single measure may be less robust than a plan incorporating a diversity of measures. However, this diversity may also result in higher costs of the measures and therefore, of the total cost of implementation of the plan.

Soft measures [76]

Non-structural ("soft") measures exploit practices and policies on information, dissemination, and education, avoiding physical constructions. Concerning these measures, the NAPCC (MEDDTL, 2011) plan calls to improve the knowledge of the impact of climate change on natural hazards and, in particular, to carry out an inventory of existing measures for the prevention of floods; to develop the mapping of natural risks; to create decision aid tools, all the while integrating climate projections. It is also recommended to replace the climate reference values in current regulations, or the return periods for events (currently based on 30-years statistics), by values simulating the context of future climate, with the assistance of modelling tools (CGET, 2015). The monitoring systems of different natural hazards must be maintained, extended, or optimized to better monitor high-altitude, or difficult to access areas, which can help to explain some of the natural phenomena (floods, ground movements) and which will be more strongly affected by the rise in temperature (peri-nivo-glacial environments). The monitoring systems must also allow the acquisition of greater temporal resolution and accuracy data (continuous and real-time monitoring), and data on the physical compartments in which the processes take place (example: temperature and moisture in the soils). Similarly, the early warning systems, which are often based on threshold values obtained by modelling, must also allow the integration of climate projections. The operators of these monitoring and alert systems must systematise the returns of experience gained from recorded events, to improve procedures accordingly. The territories should be able to have access to climate services providing information both synthetic and detailed, relevant to their future situation (CGET, 2015). Finally, the future distribution of population and infrastructures on a territory must also be oriented in such a way as to limit their exposure to natural hazards. Concerning leisure activities in the mountains: for a better prevention by the populations who practice them, it appears necessary, in tourist locations, to display information maps on current and future hazards (extreme rainfall, floods, landslides and rockfalls, avalanches, and phenomena related to the degradation of the cryosphere). It would also be useful to compile, locally, for use by the public, inventories of essential structures which present vulnerabilities. This implies developing the culture of risk, and expanding it to all the levels of management: communities, neighbourhoods and areas of commercial and industrial activities, companies and employment pools, educational environments (ONERC, 2007). This culture of risk must integrate the uncertainties about future developments, to prepare for them, if possible, by applying robust decision making approaches.

Green measures [77]

Green measures (nature-based solutions, NBSs) are defined as solutions that are "inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (EU, 2015). At the present

(76) Soft or non-structural measures to reduce or mitigate the negative effects of climate change. This category of measures is typically represented by investigation studies focussed on bridging knowledge gaps or to enrich the knowledge bases on climate change, its impacts and the most vulnerable sectors. This category also includes the development of specific methodologies and systems to reduce the risks resulting from climate change (e.g. the development of a cross-border early warning system to manage heat waves in the Pyrenees).

(77) Green measures or measures based on ecosystem services: measures of this type include all the measures, good practices, studies and initiatives that are based on the principle of the use of the ecosystem services conferred by the various natural resources in order to mitigate the negative effects of climate change (e.g. conservative silvicultural practices to increase the capacity of the woodland in the Pyrenees and to reduce the hydrogeological risks).

time, these measures are still few in number for the natural risks, and even more reduced for mountain environments. The project PHUSICOS, a European project that started in 2018 will leverage the multidisciplinary knowledge base of its partnership to collect, develop and maintain NBSs, with the purpose of reducing hydro-meteorological risks in continental/ mountain rural areas. This project should therefore contribute to propose green measures adapted to the Pyrenean context, since a few of these cases of study may occur in the French and Spanish Pyrenees. However, some measures implemented in a variety of contexts can be studied. The forests can stabilise superficial formations prone to generate torrential floods and land movements (for example: reduction of torrential phenomena and debris flow events using reforestation in the Central Apennines of Italy (Gariano and Guzzetti (2016)). Regarding flood control, UNEP (2014) recommends increasing water storage capacity in watershed and urban areas and increasing channel conveyance (e.g. flood velocity reduction), re/afforestation and forest conservation, riparian buffers, reconnecting rivers to floodplains, wetlands restoration/conservation, constructing wetlands and establishing flood bypasses. EEA (2017a) recommends allowing flooding along certain parts of a river with the objective of reducing overall flood height, or moving dikes away from the vicinity of the river channel. For urban stormwater runoff control, UNEP also recommends: green roofs, green spaces (allowing bioretention and infiltration), water harvesting and permeable pavements (these two consisting of built or "grey" elements that interact with natural features and seek to enhance their waterrelated ecosystem services). The web portal of the EU Directorate General Environment[78] presents the benefits of some of these measures.

Grey measures [79]

Grey infrastructure solutions to protect from natural hazards are attractive as they can offer immediate and high visibility impacts. Nonetheless, they also present important drawbacks, as they tend to be capital intensive to build, operate, maintain and replace, can shift amplified risk to other locations not prepared to face it or can lead to ecosystem degradation (for example by disconnecting rivers from floodplains) (UNEP, 2014). Structural measures imply the construction of physical defenses (e.g., walls, piles, drainages, retaining basins), which are designed considering the type and magnitude of the expected hazard and a reference return period for the expected hazardous event. Existing single (e.g., a retaining wall, a check dam, a drainage) or multiple (e.g., a system of retaining barriers/levees or a set of drainages in a slope, a set of check dams in a catchment) defensive structures may require modifications to adapt to the future projected climate conditions (Gariano and Guzzetti (2016)). It will be necessary, for example, to raise dikes, expand the surfaces of expansion of floods, or create larger retention ponds, or even adapt the sewage systems of the large municipalities to the highest precipitation levels. Intermediate measures, such as the cleaning of gutters and ditches, can also be undertaken. Most commonly, the return period, or the expected frequency of the event, is determined assuming a stationary time series of events (i.e., a landslide or flood record) or of triggers (i.e., a record of rainfall or snowmelt events). In the framework of a changing climate, the stationary hypothesis may not be valid; for example, Gariano and Guzzetti (2016) recommend adopting a pragmatic problem solving approach, building on experience (historical records), existing and new information (monitoring) and modern modelling and computational means including the uncertainty inherent to the future climate scenarios. Finally, economic incentives can also be implemented to limit the location of infrastructure and populations in areas at risk - for example, linking insurance premiums to the risk exposure. A 2017 EEA report (EEAb, 2017) provides various examples of financing for nature-/ ecosystem-based and other adaptation actions, including conventional and innovative funding such as crowdfunding and green bonds.

(78) http://nwrm.eu/measures-catalogue

(79) Grey or structural measures are all those involving the construction or implementation of specific infrastructure to alleviate the effects of climate change (e.g. building dykes in inhabited areas at risk of flash floods).

KEY MESSAGES

In a hardly precisely determined time horizon (between 2030 and the end of the century), the Pyrenean territory could have to adapt to the following situations:

- Increase in maximum and minimum temperatures, heat waves and potentially more frequent and intense drought episodes.

- Higher frequency of intense rainfalls and more intense hail episodes.

- Increase in risks associated with floodings, though signals are not yet defined with certainty and it will depend on the probable increase in vulnerability of populations and infrastructures, especially in touristic coastal areas and in contiguous waterways.

- Possible weakening of slopes' stability, due to the future evolution in precipitation and temperatures, associated with thaw and the accelerated degradation of permafrost.

- Possible decrease in the occurrence of avalanches at low and medium altitudes, caused by the increase in temperatures.

In terms of adaptation to these future situations, it is recommended to include in the planning and/or adaptation documents the existing knowledge about the impacts of climate change on natural risks and estimations of the vulnerability of the territory to said risks.

As much as possible it is also recommended to submit the planned actions to climate checks, which insure its adequation to the future climatic context. The adaptation plans need to be conceived with the objective of allowing robust decision making, incorporating or combining different types of measures, soft, green and grey, according to the geographic context and the uncertainties associated to climate change in the territory concerned.

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3 Impacts of climate change on socio economic sectors

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Climate change in the Pyrenees: impacts, vulnerability and adaptation

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