Chapter 13: Europe

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Executive Summary

1. Where are we now?

A 1° C warmer world is already impacting natural and human systems in Europe (*high confidence*). There is increasing confidence since AR5 in detected and attributed impacts of warming, heat extremes, droughts, floods, and coastal erosion, resulting in loss of and damages to species, ecosystems, food systems, infrastructure, energy, public health, the economy and wellbeing. Forest fire risk, consecutive climate extreme events and compound hazards have become more frequent in Europe, with widespread ecological, social, and economic consequences (*low to medium confidence*). {13.1, 13.3.1, 13.10.1, 13.10.3}

Risks are increasing in European sectors, regions, and vulnerable groups (*high confidence*); threatening ways of life, especially for traditional lifestyles and for poor households (*medium confidence*). Impacts result in deepening regional inequalities, with southern regions being more negatively affected (*high confidence*), while there are some benefits in northern and central regions. Traditional lifestyles, for example in the European Arctic, are threatened already (*medium evidence, high agreement*). Poor households have lower capacity to recover from, and adapt to, impacts and are vulnerable as they are more likely to settle in flood-prone areas and supplement food by self-provisioning (*low evidence, medium agreement*). {13.5.1, 13.8.1.1, 13.8.1.2, 13.8.2, 13.10.3}

Adaptation measures are being developed and implemented across Europe, some of which are successful in reducing impacts/risks *(medium confidence*). These measures have reduced flood risks compared to those projected in AR5, heat-related deaths in Mediterranean Europe and ecological impacts in coastal systems. While most progress is observed in cities, there continues to be a gap between planning and implementation of adaptation measures (*high confidence*). {13.2.1, 13.4.2, 13.6.2.1, 13.7.1, 13.11}

The solution space for adaptation has increased in most parts of Europe since AR5 (*high confidence*), but the speed of adaptation is lagging the speed of climate change impacts (*medium confidence*). Countries are developing national adaptation plans and pledge increasing spending on adaptation, but these actions are insufficient to fill the adaptation gap. International collaboration within and beyond Europe to address the impacts of climate change have increased. {13.9.3, 13.11}

2. What are the future risks?

Europe will *very likely* continue to warm faster than the global mean in the 21st century, widening regional and seasonal disparities (*high confidence*). Differences will increase, with some benefits in the north (e.g., increased yields, forest growth) and largely negative impacts in the south (e.g., increased energy demand and water demand while availability decreases). At 3°C warming, benefits are offset by negative effects within and amongst sectors. {13.1.3, 13.2, 13.3, 13.5.1, 13.6, 13.10.3}

Climate change will impact across sectors and regions of Europe, with considerably higher risk severity with projected warming 3°C and higher compared to 1.5°C warming (*high confidence*). Key risks are: increased stress to ecosystems and stress to and mortality of people, due to warming and its extremes; loss in agricultural productivity and ecological resilience due to combined heat extremes and droughts; risks to people, coastal ecosystems, economies, and infrastructure, due to floods; and water stress to multiple interconnected sectors (*high confidence*). The severity of key risks is dependent on socio-economic developments, and is highest under SSP3 and SSP5 and lowest under SSP1. {13.10.3}

Due to warming, changes in precipitation and sea level rise, the risk of flooding and water scarcity will increase in Europe (*high confidence*). Risks of permanent and extreme flooding will increase with accelerating pace along Europe's coasts, due to sea-level rise (*high confidence*), leading to at least a 10-fold increase in coastal flood damage by end of the 21st century, with high adaptation and mitigation. Low adaptation or mitigation result in significantly greater increases in economic losses (high confidence). In southern Europe, more than a third of the population will be exposed to water stress under 2°C warming; this risk will double under 3°C warming and increase in extent to central and eastern Europe (*medium confidence*). {13.2.2, 13.10.3}

In response to warming and more severe drought, an expansion of fire-prone areas and longer fire seasons are projected across Europe (*medium confidence*). Fire damage can offset the effectiveness of management strategies aiming to increase the forest carbon sink. Adaptation actions, including fire management, afforestation and reforestation, agroforestry, and soil restoration, can increase resilience and ensure ecosystem services. {13.3.2.11, 13.3.3, 13.5.2}

Climate change will decrease suitable habitat space for terrestrial, freshwater and marine ecosystems, particularly in Mediterranean and temperate Europe at warming of 3°C and more (*high confidence*). The ranges of warm-adapted species will increase as they disperse into the new climate and habitat space (*high confidence*). Trade-offs between adaptation and mitigation options (e.g., coastal defences, renewable energy production) will result in risks for the integrity and function of ecosystems, and the goods and services they provide (*medium confidence*). {13.3.1, 13.3.4, 13.4.1, 13.4.3, 13.5.3}

Projected gains in food production in northern Europe will not offset losses in other European regions over the 21st century (*high confidence*). Yield losses for maize, especially in Mediterranean Europe, will reach up to 50% in response to 3-4°C warming. Yields of some crops may increase in northern Europe when warming does not exceed 2°C (*medium confidence*). The ability to reduce the impact of droughts on agriculture, especially in response to warming above 3°C, will depend on water availability for irrigation and competing uses (*high confidence*). The combined impacts of ocean warming, and acidification will increase vulnerability of marine biotas and thus food production from the sea. {13.4.1, 13.5.1}

With increasing warming, heat, floods, and droughts are projected to increase in cities, which are already affected, and expand across Europe (*high confidence*). More frequent and intense heatwaves will affect most of Europe, except northern Europe, significantly increasing overheating and demand for cooling in buildings under all levels of further warming (*high confidence*). Increasing drought risks are projected for almost all cities under 3°C warming, particularly when considering competing water demands. Both structural and intangible cultural heritage is threatened across Europe. {13.2, 13.3.1, 13.6.1.5.2, 13.8, 13.10.3}

Warming beyond 2° C is projected to result in widespread impacts on infrastructure and businesses (*high confidence*). These include constraints to energy supply (*high confidence*) increased risks for transport infrastructure (*medium confidence*), increases in air conditioning needs (*very high confidence*), and high water consumption for snowmaking (*high confidence*). {13.2.2, 13.6.1.1}

Variability in health impacts among European regions will persist, with strongest projected increases in mortality due to hot days in Mediterranean Europe and urban areas (high confidence). The number of people at high risk of mortality will triple with 3°C compared to 1.5°C warming, in particular in central and southern Europe (*high confidence*). There are limits to the adaptation potential of existing health systems, particularly in Mediterranean and eastern Europe and places where health systems are under pressure, due to non-climatic causes. {13.7.2, 13.7.4}

Climate risks from outside Europe are emerging due to a combination of the position of European countries in the global supply chain, shared resources, and links with overseas territories (*medium confidence*). Trans-European effects will impact biodiversity, food production and marine resources beyond Europe, and ultimately food prices and security (*medium evidence, medium agreement*). {13.9.2, 13.5.2}

3. What are the solutions and limits of adaptation?

The solution space is expanding (*high confidence*). Financial resources are increasingly dedicated to adaptation, and governance systems are being adjusted. Public perception of climate risk is increasing, especially in the young generation (*medium confidence*). Adaptation knowledge is increasing in the private and public sector (*medium confidence*). The solution space for compound and interconnected risks is not yet explored. {13.5.2.1, 13.10.3, 13.11.2}

Public and private actors in Europe are planning to increase their efforts to enhance adaptation (*high confidence*). The 'implementation gap' between adaptation planning and action needs to be tackled to reduce or remove risks. {13.11.3.2}

Adaptation to increased climate risks for European businesses and industries, be they direct, or indirect via supply chains, is occurring; adaptation happens in response to financial crises, extreme events or to regulatory, shareholder or customer pressures (*medium confidence*). Concrete adaptation measures are limited, and many businesses and citizens remain under-prepared. Key barriers to implementation of measures include limited resources and space, lack of stakeholder involvement and (political) leadership, and low sense of urgency. Sectors such as flood management, insurance and energy have generally made most progress on adaptation planning. {13.6.1.3, 13.11.3}

Both infrastructural and nature-based solutions can reduce coastal and riverine flood risk in Europe, though with residual risks (*high confidence*) and with *low evidence* for the effectiveness of nature-based solutions at large scale and to rapid sea level rise (*medium confidence*). There is *high agreement* and *medium evidence* that adaptation to the *likely* range of projected sea-level rise for Europe's coasts is possible during the 21st century if started in time. Beyond the *likely* range or after 2100, more radical, transformative decisions for adaptation are required. Low-lying areas will experience impacts over the coming decades, requiring continued adaptation. {13.2.2, 13.2.3, 13.10.3}

Large-scale, connected conservation areas in Europe provide both the space and time for ecosystems to adapt naturally and climate mitigation benefits (*medium confidence*). In degraded areas, rewilding and large-scale restoration may create renewed carbon sinks and increase biodiversity. {13.3, 13.4.2}

Implementation of nature-based solutions across Europe highlight key barriers, such as space, dedicated resources, and legal and administrative structures (*medium confidence*). Nature-based adaptation options are themselves under threat from warming, extreme heat, drought and sea level rise. They compete for land and water resources with food production, bioenergy and mitigation options. Their implementation can also have negative consequences e.g., creating new hotspots for infectious diseases. {13.2, 13.3, 13.3.2, 13.4, 13.4.2, 13.5, 13.5.2, 13.6, 13.7, 13.10}

Indigenous knowledge, wisdom and practices can play a role in finding and implementing adaptation measures (*medium confidence*). Indigenous communities like the Sámi herders in Northern Europe have learned over centuries to read early signals of change and adapt to climatic changes, yet there are limits to their ability to adapt. Incorporation of the local context is important in climate change adaptation (*high confidence*), particularly in European overseas territories (*low evidence, high agreement*). {13.8.2, 13.9.3}

Adaptation actions considered or implemented are often not transformative and do not always exploit the synergies with Sustainable Development Goals (*medium confidence*). Systemic barriers prevent transformations of vulnerable sectors, regions and societal groups. Transformative and climate-resilient development (CRD) pathways can reduce future adaptation gaps despite uncertainty about the timing and scale of future changes. Behavioural adaptation remains limited amongst the European public (*medium confidence*), due to socio-economic, psychological, cognitive and cultural factors (*high confidence*). In European cities, CRD is most leveraged in the areas of green infrastructure, energy-efficient buildings and construction, and transport. {13.10.3, 13.11, 13.11.3.2, 13.11.4}

The ability to adapt to climate change will depend on our knowledge of which adaptation options are feasible and effective in their local context (*high confidence*). Actionable knowledge about 'what works, where, and why' is important to support future decision-making within local contexts, but large knowledge gaps remain about the effectiveness of options. Upscaling and a systematic assessment is missing across all regions of Europe (*high confidence*), particularly for risks resulting from interacting climatic and non-climatic drivers (*high confidence*). {13.10.4, 13.11}

Existing literature does not yet allow assessment of the potential for adaptation to reduce climate risks in Europe beyond 2100 and for high-end warming scenarios (*high agreement, medium evidence*). These uncertainties include low-probability/high-impact risks and unclear interactions between climatic and socio-economic developments. While multiple scenarios and adaptive plans are increasingly integrated into decision-making, many sectors, regions and vulnerable groups are not adapting to long-term risks and beyond the *likely* range. {13.2, 13.10.3, 13.11}

13.1 Point of Departure

13.1.1 Introduction and Geographical Scope

This chapter examines the impacts of climate change on the sectors, regions and vulnerable populations of Europe, assesses the causes of vulnerability, and analyses ways to adapt, thereby considering socio-economic developments, land use change, and other non-climatic drivers. Compared to AR5 and in the context of the Paris Agreement (2015), we have placed more emphasis on the solutions being implemented and assessed their feasibility and effectiveness where possible. We have considered the Sustainable Development Goals (SDG) as an explicit component in our assessment, although recognizing that scientific literature is only slowly beginning to emerge.

With the rapidly growing body of scientific literature since AR5 (Callaghan et al., 2020) our assessment prioritized systematic reviews, meta-analysis, and synthesis reports. Global and European-level studies have been prioritized for their broad coverage, and detailed regional and topical studies were assessed to ensure depth and breadth of our assessment. Feasibility and effectiveness assessments reported in this chapter used revised methods developed in SR15 (de Coninck et al., 2018; Singh et al., 2020). The protocol can be found in the Appendix 13.A as can supporting material for figures and tables.

This chapter generally follows the overall structure of the report. We first present our point of departure (13.1) followed by the sectors central to the WGII AR6 assessment report (Chapters 2-8), starting with water, as water is interconnected and of fundamental importance to subsequent sections (13.2-13.8). For each section, we assess the observed impacts and projected risks, the solution space and adaptation options, and the knowledge gaps. Section 13.9 discusses transnational aspects, followed by the key risks for Europe (13.10). Our chapter ends with an assessment of the adaptation solution space, climate resilient development pathways, and the Sustainable Development Goals (13.11).

The geographical scope of European land, ocean and coastal regions is largely the same as in the WGII AR5 Chapter 23 (Kovats et al., 2014). Four land sub-regions follow the new WGI AR6 regions: Southern Europe, including the Mediterranean region (MED), Western Central Europe (WCE), Eastern Europe (EEU) and Northern Europe (NEU). They include quite diversified (cold, temperate, Mediterranean, subtropical, arid, Alpine and polar) climates within relatively short distances (see Figure 13.1). Overseas territories and the European part of the polar region (which is extensively captured in Cross-Chapter Papers 6 and 7) are not systematically assessed, but are considered particularly in 13.8 and 13.9. Other parts of Europe are discussed in cross chapter papers, including the European biodiversity hotspots (Cross-Chapter Paper 1) coastal cities and settlements (Cross-Chapter Paper 2), mountains (Cross-Chapter Paper 5) and Mediterranean region (Cross-Chapter Paper 4). European seas are broadly divided by latitude into (a) European Arctic waters (incl. the Barents Sea, White Sea and Nordic seas (EUAW), (b) European Temperate Seas (EUTS) encompassing the Greater North Sea, Celtic Seas, Bay of Biscay, Iberian Coast and Baltic Sea, and (c) Southern Seas with the Mediterranean and Black Sea (EUSS).

European countries are differently affected by extreme weather and climate events (Figure 13.2) and express different levels of concern about climate change, which is an indicator of their intention to mitigate and adapt. The adaptive capacity correlates positively with income and tends to be higher in European countries and regions with higher purchasing power (measured in GDP per capita) and lower unemployment rate.

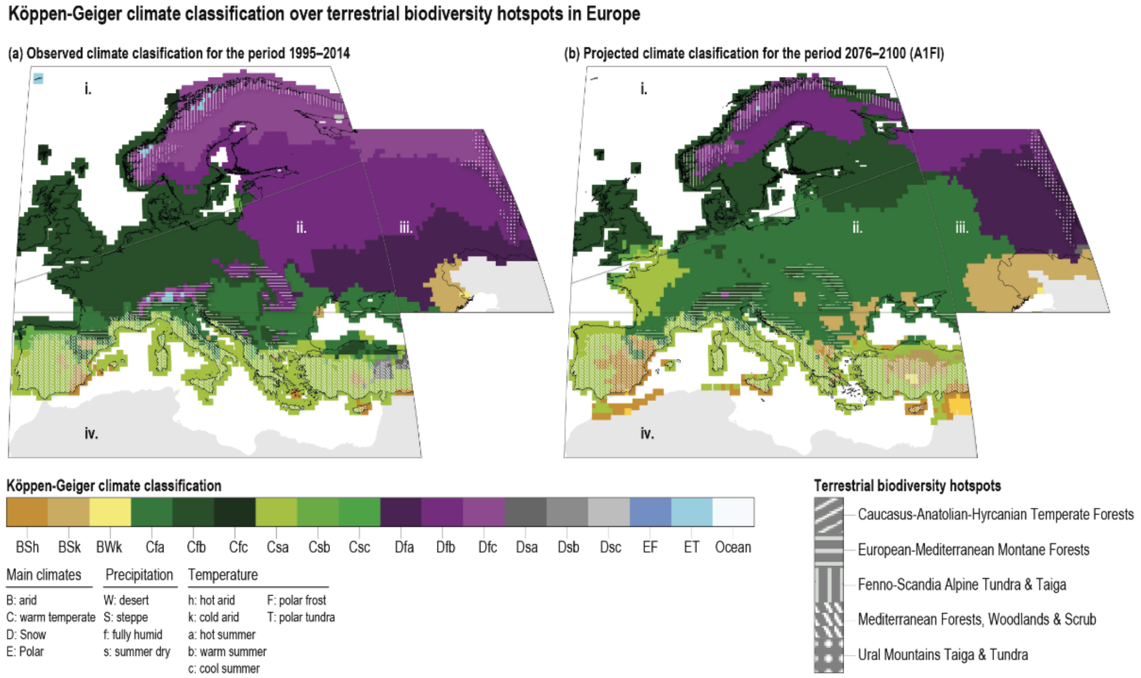


Figure 13.1: Köppen-Geiger climate classification with the boundaries of the (a) NEU, (b) WCE, (c) MED, (d) EEU regions for the recent past (left, 1985-2014) and future A1FI scenario (right, 2076-2100, approximately corresponding to global warming of 4°C), based on Rubel and Kottek (2010). Figures not finalized: to be completed with endangered ecoregions: Fenno-Scandian, Mediterranean and Montane ecoregions (Olson and Dinerstein, 2002) and large protected areas of the Natura 2000 network (https://www.eea.europa.eu/data-and-maps/data/natura-11)

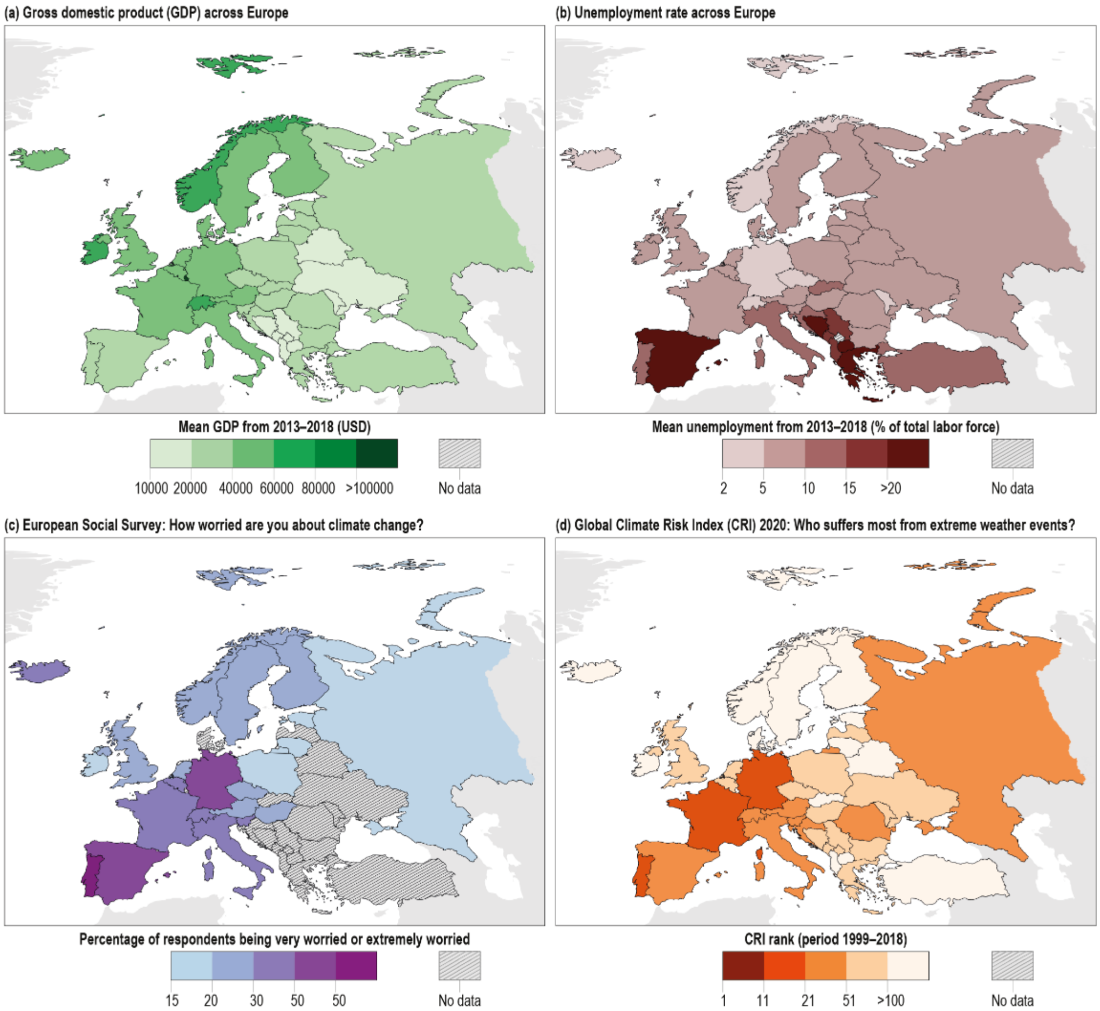


Figure 13.2 Point-of-departure in Europe from a socio-economic perspective, based on four indicators, by country: (a) Mean GDP from 2013-2018, in constant international dollars (WorldBank, 2020); (b) Unemployment as percent of total labour force (WorldBank, 2020); (c) Level of climate change concern, post-stratification weight including design weight (European Social Survey ESS8 2016); and (d) Climate Risk Index (WorldBank, 2020).

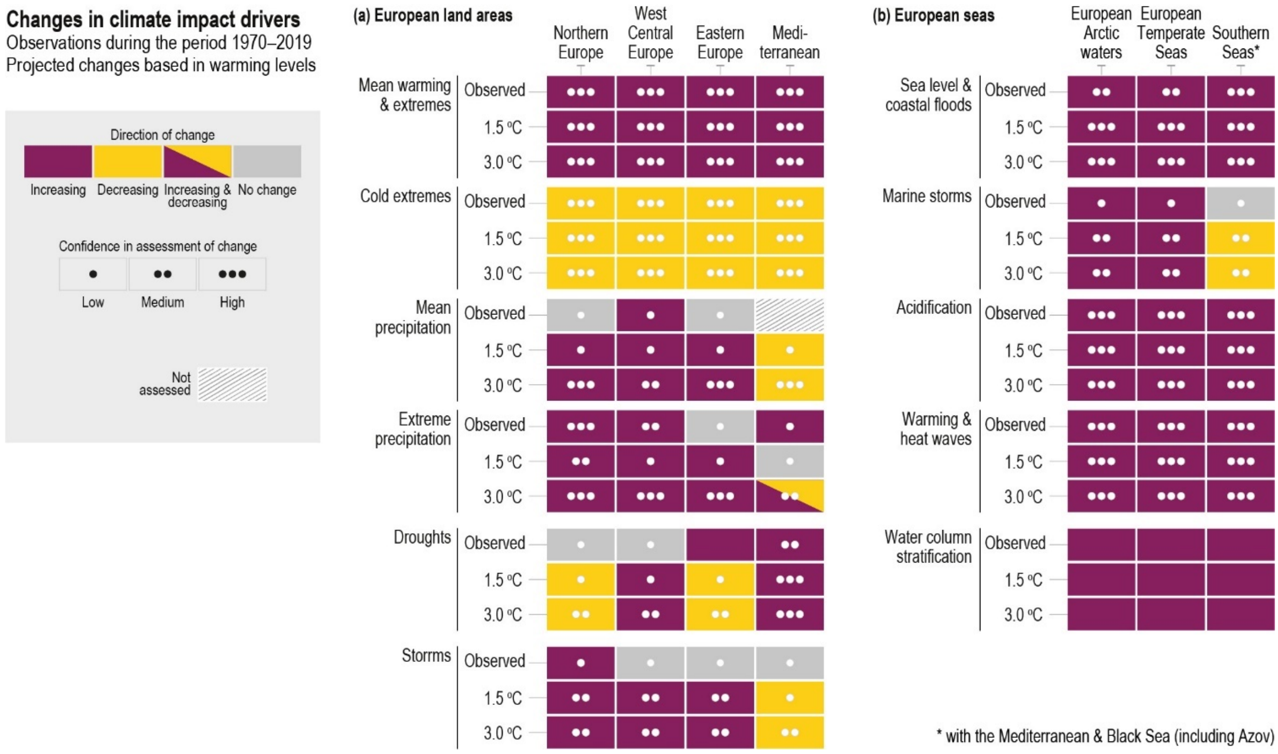
13.1.2 Impact Assessment of Climate Change based on Previous Reports

The main findings of previous reports, particularly the AR5 (Kovats et al., 2014) and Special Reports (Hoegh-Guldberg et al., 2018) highlight the impacts of warming and rainfall variations on terrestrial and marine ecosystems, the services that they provide, food sector and human systems. At 2°C warming, 9% of Europe's population is projected to be exposed to aggravated water scarcity and 8% of the territory of Europe with high or very high sensitivity to desertification (UNEP/UNECE, 2016). These impacts are driven by changes in precipitation, irrigation developments, population growth, agricultural policies, and markets (EEA, 2017a). Droughts and heat are projected to impact southern Europe and mountainous areas, while heat is the main hazard for high-latitude ecosystems which may increase opportunities (Kovats et al., 2014; Jacob et al., 2018; Hock et al., 2019b). The combined impacts on tourism, agriculture, forestry, energy, health and infrastructure are suggested to make southern Europe highly vulnerable and increase the risks of failures and increase vulnerability for urban areas (Kovats et al., 2014). These reports stated that capacity to adapt in Europe is high compared to other regions of the world, with limits to adaptation from physical, social, economic, and technological factors. Evidence suggests that staying within 1.5°C of warming significantly increases our ability to adapt to climate impacts (de Conick and Revi, 2018).

13.1.3 European Climate: Main Conclusions from Recent Reports Including WGI AR6

Changes of several climate drivers have already been observed in Europe and will become larger and significant for more drivers as global warming will intensify over both land and sea (Table 13.1). Mean temperatures, frequency of warm days and nights, maximum temperatures, heat extremes and heat-wave frequency have increased since 1950, while the corresponding cold indices have decreased (*high confidence*, WGI AR6 Chapter 11, WGI AR6 Chapter 12). Annual warming will be larger than the global mean in all sub-regions, with largest winter warming in northern and eastern Europe and largest summer warming in the Mediterranean (WGI AR6 Chapter 12, WGI AR6 Atlas, Hoegh-Guldberg et al., 2018) (*high confidence*). Increases of warm extremes (Figure 13.3.a,b) and decreases of cold extremes (*high confidence*) are very likely. Increases of warm extremes (Figure 13.3.a,b) and decreases of cold extremes are *very likely*.

Table 13.1 Observed and projected (at global warming levels of 1.5°C and 3°C) direction of change of climate drivers with confidence levels for European sub-regions and European Seas.



The majority of mountain glaciers have lost mass during the last two decades (*very high confidence*), snow depth and duration are decreasing, permafrost in the European Alps and Scandinavia is reducing (high confidence,Hock et al., 2019a). Projections suggest during the 21st century a substantial reduction of European ice glacier volume and of snow cover below elevations of 1500-2000m, permafrost thawing and degradation (*medium confidence*, WGI AR6 Chapter 12). In central Europe, Scandinavia and Caucasus glaciers will lose from 60% to 80% of their mass at the end of the 21st century depending on climate scenario (Hock et al., 2019a).

During the recent decades total precipitation has increased over north and eastern Europe, not changed in west Europe and decreased in some areas of southern Europe (*medium confidence*, WGI AR6 Chapter 8; WGI AR6 Chapter 12, WGI AR6 ATLAS). Precipitation extremes have increased in northern Europe, central west Europe, and in the eastern Mediterranean (*medium confidence*; WGI AR6 Chapter 11). There is *high confidence* of future increase of mean precipitation in northern and Eastern Europe and of its decrease in the Mediterranean, *medium confidence* in the widespread increase of precipitation extremes, except in the southern areas of the Mediterranean region (Figure 13.3c,d, WGI AR6 Chapter 12; WGI AR6, ATLAS). Dry conditions have increased and will increase in the future in the Mediterranean region (*high confidence*, AR6 WGI Chapter 11 and 12) with magnitude and frequency more pronounced if the global warming will exceed the 1.5° C threshold (figure 13.3e,f; *medium confidence*; WGI AR6 ATLAS).

Projections for the 21st century show a future decrease of wind speed extremes in the Mediterranean (*medium confidence*) and increase in the three other European regions (*medium confidence*; WGI AR6 Chapter 12).

A widespread surface warming between 0.25°C and 1°C since 1982-1998 has been observed in the European seas (*high confidence*; WGI AR6 Chapter 12). Water temperature will continue increasing (*high confidence*) particularly in the Mediterranean Sea and at the European Artic coastline, with values above 2°C and 4°C, respectively, for a global warming of 3°C (Figure 13.3g,h; WGI AR6 ATLAS). Salinity has increased in the Mediterranean Sea and decreased in northern European seas and such trends are expected to continue in the future (Bindoff et al., 2019). European waters have been and will continue acidifying and deoxygenating through the 21st century (Figure 13.3i,j) (*virtually certain,* WGI AR6 Chapter 3, WGI AR6 Chapter 11). Projected pH changes are largest at high latitudes. A mean decrease of surface pH of about 0.05 and 0.020 pH units is projected under the 1.5°C and 3.0°C warming levels (WGI AR6 ATLAS).

Relative sea level (WGI AR6 Chapter 12, Oppenheimer et al., 2019) has risen along the European coastlines, though it has been mitigated by post-glacial rise of land masses in Scandinavia. It will very likely continue for the 21st century (Figure 13.3k,l) (*high confidence*), with regional deviations from global mean sea level rise (*low confidence*). Future sea level rise will be the main driver of extreme water levels, coastal floods, sandy coastline recession (*high confidence*), which are projected to increase along European coastlines (*high confidence*) with few exceptions (the Baltic Sea, Iberian Atlantic coast and British Isles (*low confidence*).

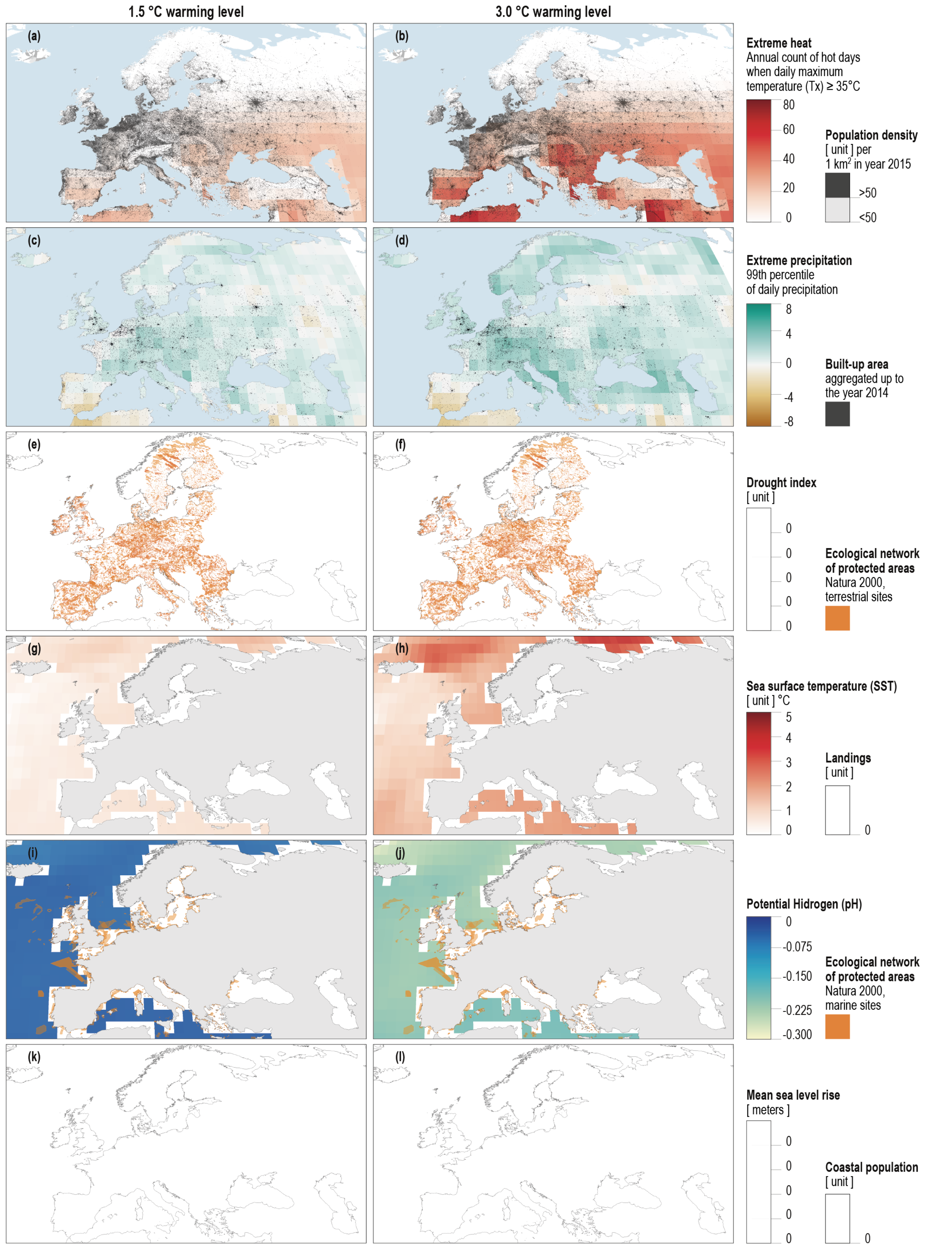


Figure 13.3: Changes of climate drivers with respect to the CMIP5 baseline (WGI AR6 ATLAS) for global warming levels of 1.5°C and 3°C: (a,b) number of days with temperature maximum above 35°C, (c,d) 99th percentile of daily precipitation, (e,f) drought index [not yet available in the ATLAS], (g,h) sea surface temperature, (i,j) potential Hydrogen, (k,l) mean sea level rise [not yet available in the ATLAS]. [PLACEHOLDER FOR FINAL DRAFT: figure will be completed with information on present exposure: population density; built area; selected crop (maize) area; fish catch landings; marine protected areas; coastal populated places]

13.2 Water

13.2.1 Observed Impacts and Projected Risks

13.2.1.1 Risk of coastal flooding and erosion

Almost 50 million European citizens live in the low elevation coastal zone (McEvoy et al., 2020) with an additional 150 million within 50 km from the coastline (Vousdoukas et al., 2020a). Coastal protection has been constantly upgraded in Europe over centuries. Migration towards coastal zones is continuing (Neumann et al., 2015; Jones and O'Neill, 2016). Extreme sea level magnitude and occurrence frequency is projected to increase throughout most of Europe (*high confidence*), contributing to coastal flooding and coastline recession along most sandy coasts (*high confidence*) with lack of consensus around the Baltic, Iberia and the British Isles (WGI AR6 Chapter 12). Increasing sea level will further increase coastal erosion today, evidenced around the Baltic and North Sea (Pranzini et al., 2015; Castelle et al., 2018; Luijendijk et al., 2018; Mentaschi et al., 2018) (*medium evidence, high agreement*).

Without adaptation, flood risks along Europe's coasts will increase due to sea-level rise compounded with storm surges, rainfall and river runoffs (*high confidence*) (Mokrech et al., 2015; Arns et al., 2017; Sayol and Marcos, 2018; Vousdoukas et al., 2018a; Bevacqua et al., 2019; Couasnon et al., 2020). The number of people exposed to coastal flooding is projected to increase by 1.52 to 3.65 million, with increasing pace after 2050, but at lower rates under SSP1 and SSP3 due to declining population trends. Expected annual damages due to coastal flooding are projected to rise from € 1.25 billion today to € 12.5–39 billion by 2050 and accelerates to € 93–960 billion by 2100 (RCP4.5-SSP1, RCP8.5-SSP5) (Vousdoukas et al., 2018a; Oppenheimer et al., 2019). UNESCO World Heritage sites in the low elevation coastal zone are at risk due to sea-level rise, coastal erosion and flooding (Marzeion and Levermann, 2014; Reimann et al., 2018b) (Cross-Chapter Paper 4; Section 13.8.1.3). Local sea level rise will be lower in Fennoscandia as it continues to rise after the end of the ice age (Frolov et al., 2014).

There is *high confidence* that sea-level rise will increase coastal erosion in Europe, especially for sandy shorelines (WGI), but *low confidence* in quantitative values (Athanasiou et al., 2019; Le Cozannet et al., 2019; Thieblemont et al., 2019). Without nourishment or other natural or artificial barriers to erosion, sandy shoreline retreat reaches 65m [30-105m] in southern Europe and 100m [50-180m] in northern Europe in response to 4°C warming (Athanasiou et al., 2019). Limiting climate change to less than 3°C warming reduces these values by 50% (Vousdoukas et al., 2020b).

[START BOX 13.1 HERE]

Box 13.1: Venice and its Lagoon

Venice and its lagoon (a UNESCO World Heritage Site) constitute a socio-ecological system that is the result of millennial interactions between people and the natural environment and it is presently exposed to climate-driven and non-climatic hazards: frequent floods, warming, pollution, non-indigenous species, hydrodynamic and bathymetric alterations, reduction of saltmarshes, waves generated by cruise ships and boat traffic.

The average level of the city and of its monumental area are only 80cm and 55cm above the present relative mean sea level (RMSL), respectively. Consequently, floods may be caused even by small surges and compound events, when they are superimposed to astronomical tide maxima (tidal amplitude is about 50 cm) (Lionello et al., 2020a). During the 20th century, RMSL has risen at about 2.5 mm year-1, due in approximately equal parts to mean SLR and land subsidence, with both natural and anthropogenic components (Zanchettin et al., 2020). Consequently, the frequency of floods affecting most of the city has increased from 1/decade in the first half of the 20th century to 40/decade in the last decade (2010-2019, Figure 13.4a).

In 1973, the Italian government established a legal framework for safeguarding Venice and its lagoon. The approved solution (1994) is a system of mobile barriers (MoSE), which will close the lagoon inlets during storm surges only, while under normal conditions they lay on the seabed, thus allowing ship traffic and the renovation of the lagoon water. It needs to be integrated with other measures to prevent the flooding of the central monumental area. MoSE's construction was initiated in 2003 and it has been successfully tested in October 2020 (Lionello et al., 2020b). Other adaptation solutions that have been proposed are pumping seawater into deep brackish aquifers, which could raise the city's level about 30 cm (Comerlati et al., 2003; Castelletto et al., 2008; Gambolati et al., 2009; Schrefler et al., 2009; Teatini et al., 2010; Teatini et al., 2011a; Teatini et al., 2011b), restriction of the inlets and expansion of saltmarshes, which could reduce the average sea level maxima up to 30 cm (Umgiesser, 1999; Umgiesser, 2004).

The risks for the lagoon environments will be posed also by the ecosystem sensitivity to accelerating warming (Solidoro et al., 2010) and the vulnerability of the salt marshes to fast RMSL rise (Day Jr et al., 1999; Marani et al., 2007). Without adaptation, potential economic damages in the range from 5.5 to 16 billion have been estimated for the 21st century (Caporin and Fontini, 2016). Flood duration is expected to increase from 2-3 weeks to 2 and 6 months per year for RMSL rises of 30, 50 and 75cm, respectively (Lionello, 2012; Lionello et al., 2020b; Umgiesser, 2020) (Figure 13.4b). Frequent closures of the inlets would prevent ship traffic and lagoon water renovation. The lagoon would have to be disconnected from the sea for most of the time for RMSL rise exceeding 75 cm. Adaptation pathways considering the full range of plausible RMSL rise levels in Venice are not available. As their planning and implementation require several decades (Haasnoot et al., 2020b), delays might prevent effective protection against future RMSL rise.

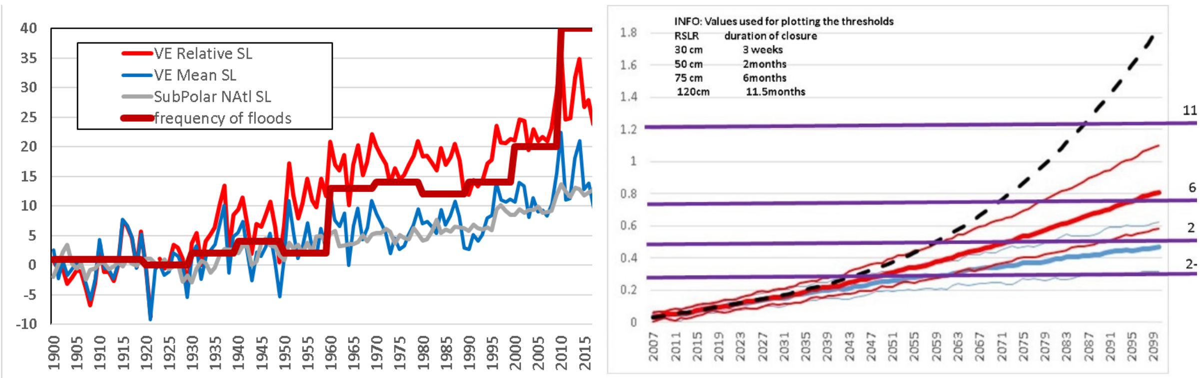


Figure 13.4: Venice sea level rise and flooding. Left panel: Evolution of relative and mean sea level in Venice, of the Subpolar North Atlantic (Frederikse et al., 2020) and decadal frequency of floods above the safeguard level in the city centre. Right panel: Projected MSL evolution at the Venetian coast (Thieblemont et al., 2019) and required duration of closure of the lagoon inlets as a function of RSL (Lionello, 2012; Umgiesser, 2020). Figures adapted from Lionello et al. (2020b).

[END BOX 13.1 HERE]

13.2.1.2 Risks related to river flows and groundwater

13.2.1.2.1 Riverine flooding

Precipitation is raising river flood hazards in WCE and decreases in EEU and MED making Europe one of the regions with largest increases in flood risks except for EEU. River flow observations show that discharges have increased in central western Europe, UK and Iceland with a rate of 11% per decade and decrease of roughly 23% per decade in Eastern and Southern Europe (WGI AR6 Chapter 12, Blöschl et al., 2019). Incidence of summer floods is expected to decrease across the whole alpine region, whereas winter and spring floods will increase as a result of extreme precipitation (Beniston et al., 2018 trends, and future challenges). In regions dominated by snowmelt-induced peak flows, projections agree on decreasing of extreme streamflow and earlier spring snowmelt peak flows (Frolov et al., 2014; Madsen et al., 2014; Beniston and Stoffel, 2016) intensified by the regime shift in glacierised catchments, where maximum discharge will happen earlier in the year such as Po, Danube, Rhine and Rhone (Stoffel et al., 2016; Beniston et al., 2018).

Economic flood damages typically increased significantly, even considering inflation (Hu et al., 2018) though not normalised to GDP (Paprotny et al., 2018) reflecting increasing exposure of people and economic assets (Visser et al., 2014). New research increases confidence in AR5 statements that without adaptation measures, increases in extreme rainfall will substantially increase flood damages (e.g., Madsen et al., 2014; Alfieri et al., 2015a; Alfieri et al., 2015b; Bloschl et al., 2017). Socio-economic conditions will exacerbate flood impacts more than global climate change (Hoegh-Guldberg et al., 2018). Damages from river flooding in Europe (assuming a baseline 5 M€ losses annually) are projected to increase by 116% at 1.5°C and 137% at 2 °C warming (Alfieri et al., 2018). Flood risks are estimated to increase from once in a 100 year to annual for about 5 million Europeans (Ipcc, 2018). The frequency of these flood events is halved if the warming is kept to 1.5 °C.

13.2.1.2.2 Low flows and water scarcity

Low flows are projected to decrease, making streamflow drought and water scarcity more severe and persistent in many parts of Europe (WGI AR6 Chapter 12, Forzieri et al., 2014; Prudhomme et al., 2014; Schewe et al., 2014). MED will experience very low river flows with reductions in minimum flows of up to 40% and annual flow up to 40-60% by the end of the century (Forzieri et al., 2014; Frolov et al., 2014).

With 1.5°C warming, in southern Europe the number of days with water scarcity (projected water availability vs water demand) and drought will increase slightly (Schleussner et al., 2016; Naumann et al., 2018) while in WCE and EEU there is no clear trend in the number of days with water scarcity and drought (Schleussner et al., 2016; Naumann et al., 2018). Under 4 °C warming areas in central Europe experience water scarcity, especially in summer and autumn. Future intensive water use can aggravate the situation in southern Europe (see 13.10.4) and reverse the climate induced reduction of droughts in northern Europe (Forzieri et al., 2014).

Most European regions rely on groundwater for water supply. Groundwater abstraction rates reach up to 100 million m^3/year across CEU and MED, and partially exceed 100 million m^3/year in southern Spain, Italy, and south-eastern Europe (Wada, 2016). Across Europe, groundwater abstraction is widely sustained through substantial groundwater recharge (De Graaf et al., 2015; de Graaf et al., 2019). However, low recharge rates lead to a depletion of groundwater resources in parts of south-eastern and eastern Europe (Döll et al., 2014; Wada, 2016; de Graaf et al., 2017) increasing the impacts on water scarcity in the MED were all possible water is being used. Groundwater pumping and associated declines in groundwater discharge already threaten environmental flow limits in many European catchments extending to almost all basins and sub-basins within the next 30-50 years (de Graaf et al., 2019).

The combined effect of increasing water demand and successive dry climatic conditions further exacerbates groundwater depletion lowering groundwater levels particularly in the driest regions of Europe (WGI AR6 Chapter 12) but also WCEU due to warming (Goderniaux et al., 2015). Declines in groundwater recharge of up to 30% further increase groundwater depletion (Aeschbach-Hertig and Gleeson, 2012) especially in EEU and semi-arid to arid regions (Moutahir et al., 2017). Abstraction rates are projected to increase due to growing water demand. Even where groundwater resources are not depleted, e.g., WCE and NEU, projected increases in groundwater abstraction will impact groundwater discharge, threatening sustaining environmental flows under dry conditions.

The risks for soil moisture drought are projected to increase across all regions of Europe (except possibly Northern Europe) and for all climate scenarios but are especially critical in the Mediterranean and Eastern Europe (Grillakis, 2019; Tramblay et al., 2020). Compared to 1.5°C, the drought area across Europe under 3°C will increase by 40% and the population under drought by up to 42%, especially affecting southern, and to a lesser extent also eastern and central Europe (Samaniego et al., 2018).

13.2.1.4 Water temperature and quality

Water temperatures in rivers and lakes have increased over the past century (~1 to 3°C in major European rivers; (CBS et al., 2014; EEA, 2017a; Woolway et al., 2017). Warming is accelerating for all European river basins (Wanders et al., 2019) and are projected to further increase by 0.8°C in response to 1.5°C warming and 1.2°C for 3°C warming relative to the control period 1971-2000 (van Vliet et al., 2016b). Rates are higher than atmospheric warming due to declines in summer river flow. The duration of high water temperatures is projected to double until 2050 and quadruple by the end of the century (van Vliet et al., 2013).

Projected precipitation and streamflow increases in winter are expected to increase nitrogen fluxes and eutrophication risks, especially in northern Europe (van Vliet et al., 2015; Sinha et al., 2017). In coastal areas such as southern Italy, Denmark and the Netherlands, (ground)water extractions or drainage caused land inundation (Rasmussen et al., 2013; Ketabchi et al., 2016). During summer, seawater will penetrate estuaries further upstream in response to reduced river flow and sea level rise, which results in more frequent closure of water inlets in the downstream part of the rivers in a period when water is most needed (e.g., Haasnoot et al., 2020b). Additionally, sea level rise will cause saltwater intrusions (*high agreement, low evidence*).

Higher water temperature affects cooling power (13.6), ecology (13.3), and recreation through algae blooms (13.3, 13.4). The low flows further impact water-cooling capacity for power plants and the dilution capacity for industrial effluents (13.6). Changes in streamflow regimes, groundwater levels and water quality impact ecology (13.3), navigation (13.6), drinking water (13.6), irrigation for crops (13.5) and/or hydropower generation (13.6) (Beniston et al., 2018).

13.2.2 Solution Space and Adaptation Options

In recent decades water management in Europe has increasingly shifted more towards integrated and adaptive strategies, with most noticeable shifts in western Europe (*high confidence*) (e.g. Kreibich et al., 2015; Bubeck et al., 2017). Adaptive strategies are increasingly considered as an approach to strengthen flexibility and implement climate change adaptation actions, given deep uncertainty about the future(Ranger et al., 2013; Klijn et al., 2015; Orsato et al., 2017; Radhakrishnan et al., 2018; Bloemen et al., 2019; Hall et al., 2019; Pot et al., 2019; Thaler et al., 2019), but more traditional water management approaches still dominate across Europe (OECD, 2013; OECD, 2015). Progress on adaptation since AR5 is observed in the increasing number of policies, plans and guidance documents (Section 13.11.1) (Leitner et al., 2020), as well as the rapidly expanding academic literature on the various types of adaptation options and approaches (Biesbroek and Delaney, 2020). Water policies and guidance documents increasingly consider mainstreaming climate impacts and adaptation options (Runhaar et al., 2018). For instance, countries across Europe are planning for SLR, but 25% still do not (Figure 13.5) (McEvoy et al., 2020). The planning horizon 2100 is most common and many countries are considering around 1m (adjusted for local conditions) of SLR at that point in time. However, there are significant differences between countries, which may lead to unequal impacts, over time (McEvoy et al., 2020). RCP4.5 and RCP8.5 are the most widely used climate change scenarios.

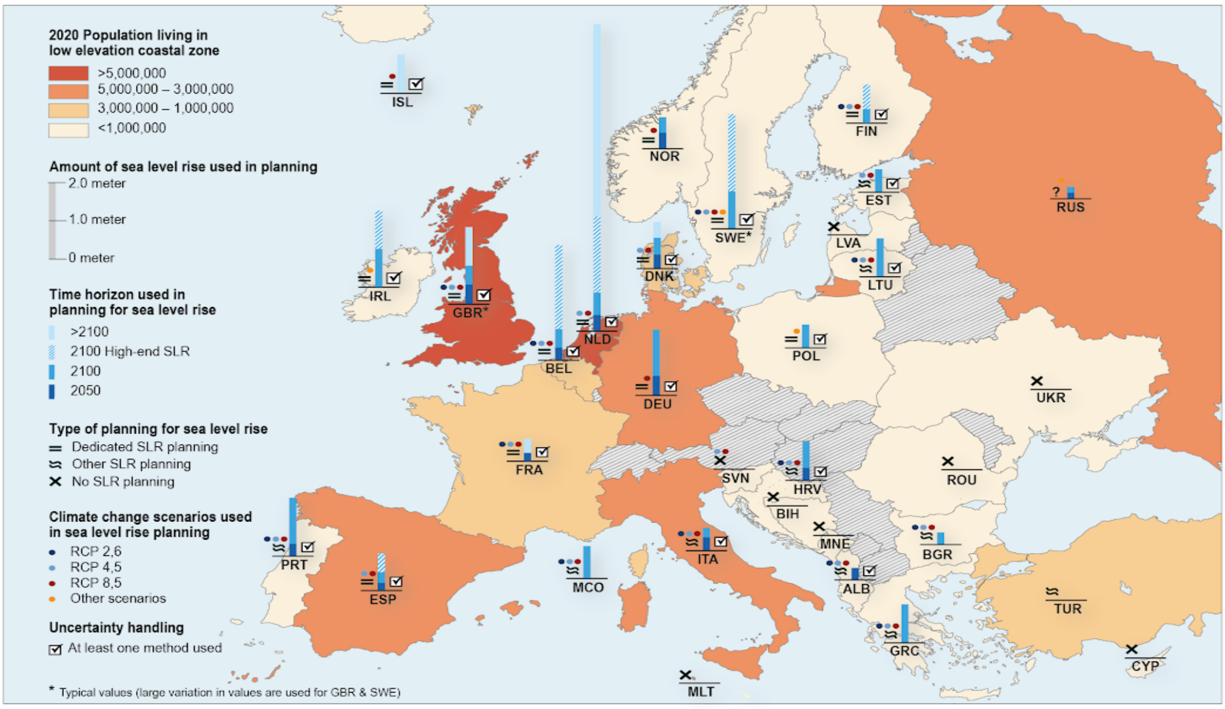


Figure 13.5: Sea level rise preparedness. Map of countries in Europe summarizing: the 2020 population living in the low elevation coastal zone, the amount of sea level rise each country is planning for, at different time horizons, what type of planning is used, which climate change scenarios are employed in sea level rise planning and whether uncertainty handling is accounted for in sea level rise planning. The question mark for type of sea level rise planning in Russia reflects the unclear response on this topic and lack of confirmed planning documents. The amounts of sea level rise and time horizons reflect national guidance, local or project-based levels may differ (McEvoy et al., 2020).

13.2.2.1 Flood risk management

Across Europe a range of hard and soft measures have been implemented in flood risk and water resources management (Table 13.2). Flood risk measures include protect, accommodate, retreat and avoid options, with protect as a most used strategy in Europe (*high confidence*). Early warning and flood defences have been successful in reducing vulnerability to coastal and river flooding, also in Europe (Jongman et al., 2015; Kreibich et al., 2015; Bouwer and Jonkman, 2018). Fatalities due to river flooding have decreased in high income countries like Europe, despite similar numbers of people exposed (1990-2010 compared to 1980-1989).

Structural measures in mountain areas are used to increase water retention and storage (dam reservoirs, channelization and flood embankments), while in lowland regions river floodplains and coastal regions are protected through flood embankments. Such measures can be effective. For Europe at least 83% of flood damages due to coastal flooding could be avoided by elevating dykes along ~23-32% of Europe's coastline. Protection against coastal flooding is considered an economic beneficial option for densely populated areas (Lincke and Hinkel, 2018; Tiggeloven et al., 2020). For Europe benefit-cost-ratios vary from 8.3 to 14.9, with higher ratios for higher warming levels (Vousdoukas et al., 2020a). Building flood defences has limitations including cost-benefit considerations in rural areas, and space and social acceptability in densely populated areas (Hinkel et al., 2018; Haasnoot et al., 2019).

Nature-based and sediment-based solutions are increasingly considered for environmental, economic and/or societal reasons (e.g. Stive et al., 2013; Kreibich et al., 2015; Pranzini et al., 2015) (Cross-Chapter Box NATURAL in Chapter 2). In riverine areas, these solutions include (forest) restoration for upstream storage, restoration of river channels, widening riverbeds (Kreibich et al., 2015; Barth and Döll, 2016; Wyżga et al., 2018). In coastal regions, nourishment of beaches aims to maintain the sandy coast and is increasingly considered as a flexible approach to adapt to uncertain changes (Kabat et al., 2009). Coastal wetlands can be effective to reduce for example wave height, but their feasibility to implement is restricted, particularly for densely populated areas with competing land use and sediment starved deltas like the Rhine delta (Edmonds et al., 2020) and rapid SLR (Kirwan et al., 2016; Oppenheimer et al., 2019; Haasnoot et al., 2020b). Combining NBS with structural defences might still be needed for long term coastal protection in urbanized coastal regions.

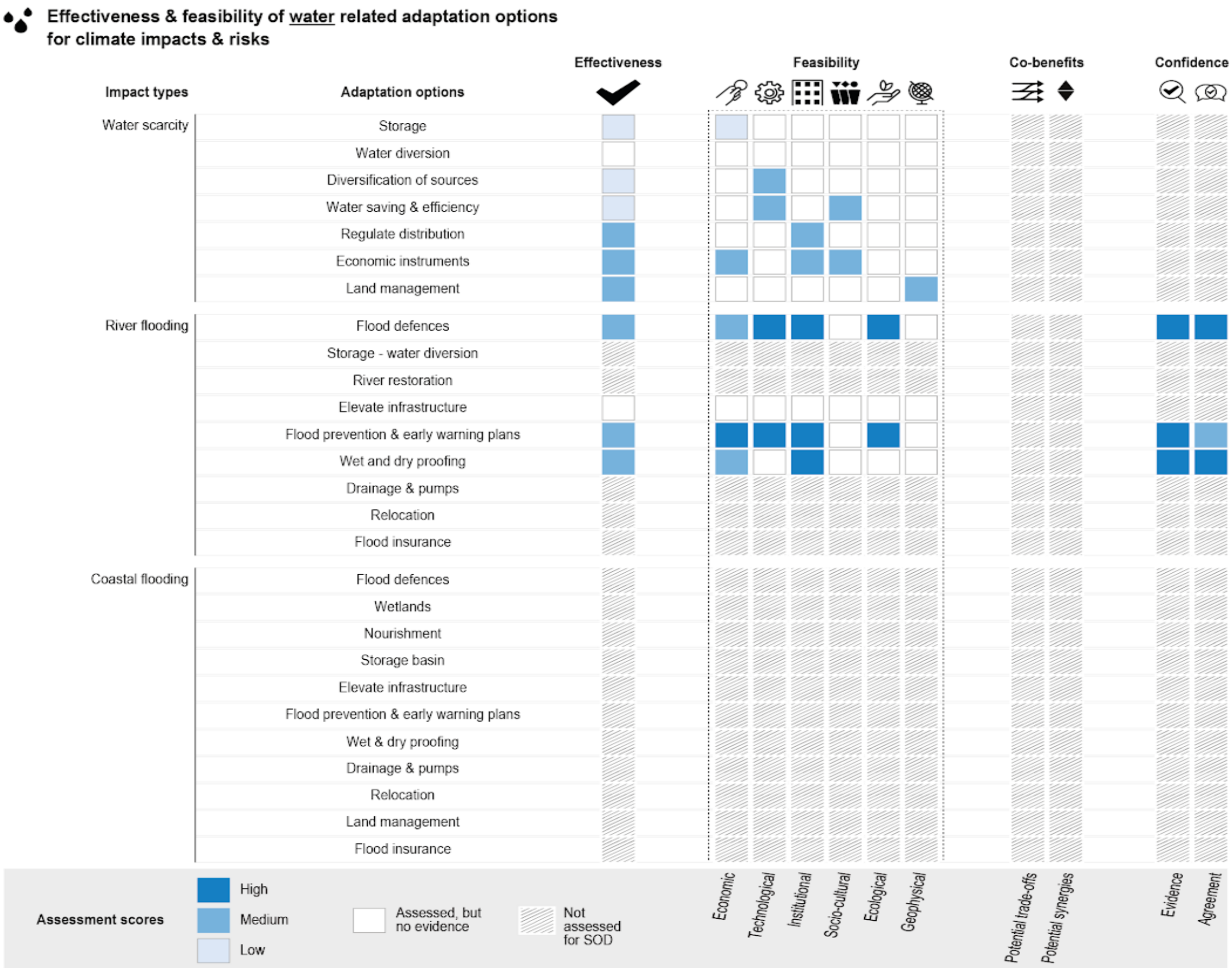
Measures are also implemented to reduce flood exposure for example through zonation and early warning systems (EWS) and vulnerability through flood proofing, smart design and building codes (Dieperink et al., 2016; Driessen et al., 2016; Hegger et al., 2016) (Table 13.2).

Retreat options are often considered as a last resort (Haasnoot et al., 2019; Siders et al., 2019), and rarely applied in Europe (Mayr et al., 2020). Along parts of the coast in the UK (e.g., The Wash), Germany (e.g., Langeoog Island), and the Netherlands (e.g., Westerschelde) retreat has been applied to restore salt marshes and to aid coastal defence (Haasnoot et al., 2019). Household relocation has occurred in response to river flood events (Mayr et al., 2020; Thaler and Fuchs, 2020).

While measures taken at household levels can reduce the risk of flooding, there is often insufficient investment in even low-cost measures, as e.g., observed in CEU (Bamberg et al., 2017; Aerts et al., 2018). Reasons for this include low awareness or under-estimation of the risk, short-term planning (Kellens et al., 2013), and low perceived efficacy or social norms related to adaptation measures (van Valkengoed and Steg, 2019).

Behavioural adaptation to flooding relies on one's appraisal of the threat and of one's capacity to respond, both of which are often lacking (Bamberg et al., 2017; Haer et al., 2019) (Section 13.11.3).

Table 13.2: Assessment of effectiveness and feasibility of water related adaptation options to achieve objectives under increasing climate hazards. The assessment steps are described in Figure 13.A.1. [PLACEHOLDER FOR FINAL DRAFT: to be updated]



There is diversity of flood risk insurance and compensation systems across European countries, reaching from ex post disaster relief payments by the state, to compulsory flood insurance, to public-private partnerships where the state acts as reinsurer (Section 13.6). With increasing future flood risks due to both climatic and socioeconomic change, government budgets could be overburdened with public assistance and damage compensation (Section 13.11.2) (Paudel et al., 2015; Mysiak and Perez-Blanco, 2016; Schinko et al., 2017; Mochizuki et al., 2018), customers could be faced with unavailable or unaffordable insurance (13.8.3) (Hudson et al., 2016; Surminski, 2018), and insurance companies could face problems of underfunding and insufficient solvency to pay out insurance claims (Section 13.6.2.5) (Lamond and Penning-Rowsell, 2014).

13.2.2.2 Water resources management

Availability of fresh water has been increased through water storage (both local and in reservoirs), reduction of water demand (including regulations and efficient water use) and transfer of runoff. On the demand side, measures include those aimed at monitoring the consumption (e.g., water meters) and those aimed at regulating demand and consumption (Garnier and Holman, 2019). Water restrictions are particularly efficient to regulate consumption in areas exposed to droughts and water scarcity. As drought frequency and conditions of water scarcity are projected to intensify in the future for certain regions, prolonged water abstraction restrictions could result in economic losses to certain sectors, for example, irrigated agriculture (Section 13.5.2) (Salmoral et al., 2019).

Water efficiency measures can potentially limit conflicts across sectors, but necessitate technological advances and changes of practice together with a willingness to cooperate across multiple sectors (Garnier and Holman, 2019), for example wastewater reuse e.g., for agriculture (Lavrnic et al., 2017). Changes in irrigation efficiency are effective in reducing water scarcity, particularly in MED (De Roo et al., 2020). The positive effects of water savings are insufficient to counteract a large reduction under global warming (RCP8.5) (*medium confidence, low evidence*) (De Roo et al., 2020). Increasing desalination capacity is also a widely used option towards water scarcity mitigation in particular in the Mediterranean but has adverse side effects in terms of the brine produced and high cost and energy demands (Jones et al., 2019).

Adaptation to sea level rise and river flooding is possible with limited residual risks (if timely started) in some regions (Dottori et al., 2020; Vousdoukas et al., 2020a), if timely started, but not in all locations (Box 13.1) (*high agreement, medium evidence)*, leaving residual impacts (Section 13.2.2). Limits to adaptation to extremely high sea-level rise scenarios have been identified for coastal defences, such as the Thames Barrier in the UK (Ranger et al., 2013) and the Maeslant Barrier in the Netherlands (Kwadijk et al., 2010; Haasnoot et al., 2020b), and maintaining sandy coastal and for fresh water supply (Haasnoot et al., 2020b). However, the scale and pace of adaptation required to face such high-end scenarios along all the coasts of Europe remains poorly studied so far. Given the lead and long lifetime of large critical infrastructure, there is a growing need for high end scenarios that look beyond 2100 to support the design of new infrastructure (Cross-Chapter Box SLR in Chapter 3). Some countries have looked at such scenarios, but these are not uniformly used across Europe (Figure 13.5). Ultimately, the regulated long-term retreat of human populations from coastal at-risk regions is increasingly considered as a realistic adaptation option in case of extreme sea-level rise impacts on shorelines (Tol et al., 2016).

Limits to adaptation to drought and low flows, exist under high warming levels, when water saving and efficiency measures may not be sufficient to counteract the reduction in water availability (De Roo et al., 2020). Successful adaptation in the water sector also depends on the extent water management is integrated into other sectoral policies including health, agriculture, energy, transport, and biodiversity (KR4, Section 13.10.4).

13.2.3 Knowledge Gaps

While high-end scenarios and scenarios beyond 2100 are considered to be beneficial for risk-averse decision making, in particular in water infrastructure (Hinkel et al., 2019; Haasnoot et al., 2020b), such studies are still rare. Adaptation to low-end scenarios (e.g., RCP2.6), and thus minimum adaptation needs, are even less studied than the impacts of high-end sea-level rise scenarios. Quantification of the effectiveness of measures in reducing risk is limited in the scientific literature. Nature based solutions are increasingly implemented, though often in small scale pilot projects. There is limited evidence on the ability to upscale these measures, and their effectiveness to high global warming.

13.3 Terrestrial and Freshwater Ecosystems and their Services

13.3.1 Observed Impacts and Projected Risks

Climate change has multiple impacts on European terrestrial and freshwater ecosystems, significantly affecting biodiversity and key ecosystem functions and services. Terrestrial ecosystems of Europe include from the North to the South: snow and ice-dominated systems, glaciers, polar deserts, tundra; peatlands; nival mountain belts, alpine and subalpine systems; boreal and temperate forests and woodlands; temperate grasslands, Mediterranean forests, woodlands and scrubs;; subtropical dry and humid forests; steppes and deserts. Inland surface waters contain freshwater systems and enclosed seas and saline lakes (IPBES, 2018). Projected risks for these systems are assessed in Table 13.3.

13.3.1.1 Impacts on biodiversity

In the EU, around 14 % of habitats and 13 % of species of interest are currently under pressure because of climate change and multiple direct anthropogenic pressures *(high confidence*) (Füssel et al., 2017). About a quarter of species are currently threatened by habitat degradation and other global change impacts in the EU (EuropeanCommission, 2015; Füssel et al., 2017; Seibold et al., 2019; van Strien et al., 2019; van Klink et al., 2020). In freshwater habitats, the groups with the highest proportion of threatened species are molluscs (55%) and freshwater fish (43%). Other endangered groups include marine mammals (43%), amphibians (22%), reptiles (21%) and birds (18%) (EuropeanCommission, 2015; Füssel et al., 2017). Sensitivity to increasing climate-change impacts in Europe varies among species, functional and taxonomic groups (*high confidence*). Strong climate-induced biodiversity declines have already been detected in thermosensitive taxonomic groups, such as bumblebees and other cold-adapted species (Balint et al., 2011; Hellmann et al., 2016; Habel et al., 2019a; Harris et al., 2019; Crossley et al., 2020; Soroye et al., 2020). In contrast, stable and increasing trends in local species richness have been also reported, and in some groups the loss of native species is balanced by the establishment of new native and non-native species (Dornelas et al., 2014; McGill et al., 2015; Hillebrand et al., 2018; Outhwaite et al., 2020). Table 13.3 summarises climate-change risk of biodiversity loss due to reduced habitat availability and increased extinction risk for key endangered groups in Europe.

Table 13.3: [PLACHOLDER FOR FINAL DRAFT] Summary of key impacts and risks for terrestrial ecosystems (reported trends are preliminary). See Table 13.A.1.

LEGEND:	Direction of change	Confidence of detection	
	Increasing	•	Low
	Decreasing	••	Medium
Both>		•••	High
	No Evidence		
	Not assessed		

IMPACT / RISK	Main Climatic Driver(s) / Hazard(s)	Affected systems biotas, habitats, ecosystems	Direction of Change	EUROPE	MED	WCE	EEU	NEU
A. Reduced habitat availability and biodiversity	Warming, heatwaves	Species, communities (freshwater, terrestrial)	Observed	•	•••	••	?	?
			Projected: +1.5 °C	•••	•••	•••	?	?
			Projected: +3 °C	•••	•••	•••	?	?
B. Local extinctions	Warming	Species (freshwater, terrestrial)	Observed	••	••	••	•	•
			Projected: +1.5 °C	?	•••	•••		
			Projected: +3 °C	?	•••	•••		
C. Range shifts	Warming	Species (terrestrial)	Observed	•••				
			Projected: +1.5 °C	•••				
			Projected: +3 °C	•••				
D. Invasions of non-native species	Warming	Communities (freshwater, terrestrial)	Observed	•••	•••	•••	?	•••
			Projected: +1.5 °C					
			Projected: +3 °C					
E. Shifts in community composition	Warming	Communities (freshwater, terrestrial)	Observed	••	••	•••		•••
			Projected: +1.5 °C	•••				
			Projected: +3 °C	•••				
F1. Non-gradual, abrupt biome shifts (critical transitions)	Warming	Mountain systems, cold-adapted biomes	Observed	?				
			Projected: +1.5 °C					
			Projected: +3 °C	?				
F2. Large-scale gradual biome shifts	Warming	Mountain systems, cold-adapted biomes	Observed	?	••	••	••	••
			Projected: +1.5 °C					
			Projected: +3 °C	?				
G. Changes in phenology and reproductive success	Warming	Species	Observed					
			Projected: +1.5 °C					
			Projected: +3 °C					
H. Foodweb disruptions	Warming	Communities, ecosystems	Observed	?	••	••	••	••
			Projected: +1.5 °C	?				
			Projected: +3 °C	?				
I. Incidence of fire	Warming, drought	Boreal systems, all mountain ranges, MED ecosystems, temperate ecosystems	Observed	••				
			Projected: +1.5 °C	•••				
			Projected: +3 °C	•••				
J. Vegetation die-back, mortality events, population collapse	Extreme climatic events: heatwaves, ...	Boreal systems, all mountain ranges, MED ecosystems, temperate ecosystems, marine/freshwater	Observed					
			Projected: +1.5 °C					
			Projected: +3 °C					
K. Emergence trade-offs limiting adaptation options and solution space		Mountain systems, endemic hot spot areas, low dispersal and specialist groups, cold-adapted species	Observed					
			Projected: +1.5 °C					
			Projected: +3 °C					
L. Changes in regulating ecosystem services (carbon capture)	Warming	Ecosystems (terrestrial)	Observed	?				
			Projected: +1.5 °C					
			Projected: +3 °C					
OTHERS			Observed					
			Projected: +1.5 °C					
			Projected: +3 °C					

13.3.1.2 Shifts in species distributions

Across many animal and plant taxa, a northward shift in latitudinal distribution and an upward shift in altitudinal distribution have been observed in Europe (*high confidence*) (Parmesan et al., 1999; Wilson et al., 2007; Devictor et al., 2008; Lenoir et al., 2008; Chen et al., 2011; Devictor et al., 2012; Pauli et al., 2012; Kovats et al., 2014; Ancillotto et al., 2016; Füssel et al., 2017; Mills et al., 2017; Mori et al., 2018; Steinbauer et al., 2018; Termaat et al., 2019). Elevational ranges of thermophilic plant species expand, while those of cold-adapted species contract (Rumpf et al., 2018). Plant species display more stable distributions at low altitudes than at higher altitudes, and altitudinal changes in the distribution of plants may increase interspecific hybridization processes (Rumpf et al., 2018; Gómez, 2019). In southern Europe, northward shifts in the rear edge of tree species distributions are not consistently detected, indicating tree species persistence (*medium confidence*) (Vilà-Cabrera et al., 2019). Regional extinctions of species have also been observed in response to climate change in Europe (*medium confidence*) (Wiens, 2016; Füssel et al., 2017; Soroye et al., 2020). Although local microclimatic variability can potentially buffer warming impacts on natural populations (*medium confidence*) (Scherrer and Körner, 2011; Lenoir et al., 2013; Carnicer et al., 2019c; Zellweger et al., 2020) shifts in species distributions are projected for the coming decades for multiple taxonomic groups (*high confidence*), showing a wide range of species-specific responses (Tables 13.A.1 and 13.A.2).

13.3.1.3 Trends in population densities

Climate change is having both positive and negative effects on population trends and densities, with contrasting regional and habitat-specific trends (*high confidence*) (Füssel et al., 2017; Bowler et al., 2018; Outhwaite et al., 2020; Soroye et al., 2020). Positive effects of warming on population growth have been reported across multiple aquatic and terrestrial taxonomic groups in temperate Europe (Bowler et al., 2017). Populations of warm-adapted insects in central Europe and warm-adapted birds across Europe increase under warming while those of cold-adapted species decline (Bowler et al., 2015; Jørgensen et al., 2016; Stephens et al., 2016; Bowler et al., 2019; Lehikoinen et al., 2019). An increase in the proportion of warm-adapted species in communities of butterflies, birds, plants and lichens in Europe has been detected (Füssel et al., 2017). In contrast, declines in insect populations have been detected in southern Europe (Stefanescu et al., 2011; Zografou et al., 2014; Melero et al., 2016; Carnicer et al., 2019c; Herrando et al., 2019). Climate change impacts in Europe strongly interact with local habitat structure and resource dynamics (De Frenne et al., 2013; Oliver et al., 2014; Oliver et al., 2015; Carnicer et al., 2017; Carnicer et al., 2019c). Observational analyses suggest that declines in population abundance for both birds and mammals are greater in areas with larger warming (Spooner et al., 2018a).

13.3.1.4 Ecosystem functions and services

Europe's land ecosystems have presently a neutral role as a source/sink region considering all main greenhouse gases (*low confidence*) (Nabuurs et al., 2003; Schulze et al., 2009; Kovats et al., 2014; Tian et al., 2016). The European carbon sink is significantly constrained by reduced soil moisture, increasing drought trends, increasing atmospheric evaporative demand and associated land-atmosphere feedbacks (*high confidence*) (Humphrey et al., 2018; Sanginés de Cárcer et al., 2018; Stocker et al., 2018; Carnicer et al., 2019b; Green et al., 2019; Xu et al., 2019; Yuan et al., 2019; Zhou et al., 2019; Brodribb et al., 2020; Lian et al., 2020; Schuldt et al., 2020; Zhang et al., 2020). All these emerging climatic pressures may progressively limit the carbon sink capacity of European land ecosystems in the next decades, shifting from dominant positive fertilization effects of increased CO_2 to increased negative effects of warming (*medium confidence*) (Peñuelas et al., 2017; Lugato et al., 2018; Green et al., 2019; Natali et al., 2019; Ito et al., 2020; Wang 2020). Climate change is significantly affecting key ecosystem functions in Europe, such as land respiration, primary productivity, carbon assimilation and nutrient cycling (*high confidence*). Significant impacts of warming on land ecosystem respiration and carbon sink activity have been detected (Ciais et al., 2005; Smith et al., 2005; Reichstein et al., 2007; Fantappié et al., 2011; Keenan et al., 2016; Reich et al., 2016; Yigini and Panagos, 2016; Ballantyne et al., 2017b; Ciais et al., 2019; Fernández-Martínez et al., 2019).

Climate change and land-use changes affect the functioning of European land ecosystems and their services (Schröter et al., 2005b; Schröter et al., 2014; Füssel et al., 2017; Verhagen et al., 2018). The expansion of European forests in boreal regions have a net warming effect because of changes in albedo, evapotranspiration and turbulence effects (Bright et al., 2017; Mykleby et al., 2017) and may influence cloud formation and rainfall patterns (*medium confidence*) (Teuling et al., 2017). European temperate and boreal forests sequester up to 12% of Europe's annual carbon emissions, with a quarter of this European forest area protected under Natura 2000 (Commission, 2013). This service is increasingly impacted by droughts, which induce lagged effects on forest growth and carbon sequestration services across European forests at interannual time scales (*medium confidence*) (Schwalm et al., 2017; Gazol et al., 2018; Carnicer et al., 2019b; Xu et al., 2019). Studies have predicted that future climate change scenarios in Europe will imply positive and negative changes in key ecosystem services (Schröter et al., 2005b; Schröter et al., 2014; Polce et al., 2016).

Throughout Europe, important trade-offs occur between ecosystem services, for instance between provisioning services on the one side and regulating and cultural service categories on the other (Table 13.3) (Maes et al., 2012; Queiroz et al., 2015; Kasimir et al., 2018; Torralba et al., 2018), setting limits to key adaptation options, regional management and land use decisions (*medium confidence*) (Kovats et al., 2014; Valade et al., 2017; Mankin et al., 2018; Saarikoski et al., 2018; Torralba et al., 2018; Lee et al., 2019; Ceccherini et al., 2020; Krause et al., 2020). Projected climate change impacts on ecosystem services are affected by strong and often dominant effects of changes in land use and management (Table 13.3). European ecosystems characterized by higher diversity are often more efficient in providing ecosystem services (*medium confidence*) (Ruiz-Benito et al., 2014; van der Plas et al., 2016; EASAC, 2017; Ratcliffe et al., 2017).

Table 13.4: Adaptation options for European land ecosystems [PLACEHOLDER FOR FINAL DRAFT: adaptation options will be grouped by risk according to Table 13.3; to increase balance between risks and adaptation options covered, the range of adaptation options will be expanded, and the listed options merged into less categories]. See Table 13.A.2.

Risks	Community	Adaptation option
		Promotion of mixed-species stands
		Forest and habitat restoration practices
		Use of drought and/or fire-resistant provenances
		Assisted species migration
		Enhancing and managing tree recruitment and forest resilience using thinning and prescribed burning
		Reducing tree density through thinning
		Randomizing tree spatial patterns in thinning practices
		Increasing the equitability or diversity of tree size classes in thinning practices
		Reducing forest understory cover by thorough mechanical treatments
		Implementing green infrastructure modelling platforms projecting land use changes into the near future
		Promoting participatory forest management planning processes and local self-governance mechanisms Improving current networks of protected areas and corridors, covering altitudinal gradients and integrating climatic microrefugia areas
		Rewilding as a vehicle of adapting to the rapid climate impacts
		Adaptation options for freshwater and coastal land ecosystems include hydrological and land use planning at basin scale, complemented with local restoration and conservation practices
		Preservation of the natural flow variability of rivers and streams
		Ameliorating sea-live rise impacts on land installing coastal protection elements, such as breakwaters, seawalls, dykes, surge barriers and submerged breakwaters
		Using beach and shore nourishment practices, dune restoration, and coastal restoration

	Applying geotextiles
	Managing irrigation canals for conservation and adaptation
	Peatland rewetting and restoration as a key tool for climate-change adaptation and mitigation. In Europe, many peatland areas are under agricultural and forestry usage, requiring active land use and management planning. Saving extant peatlands, rewetting peatland areas and restoring temperate and boreal agricultural peatlands have been assessed as key practices.
	Management of fuel to reduce fire intensity and the extent of large fires
	Using prescribed burning for reducing the risk of high intensity fire and fuel load management
	Incentivizing and planning residential development to withstand inevitable wildfire
	Managing and planning landscape matrix schemes to reduce fire risk
	Improved fire suppression capacities and strategies
	Using forest types and agricultural fields as fire breaks
	Reducing fire risk by promoting biomass extraction for energy purposes
	Combining forest thinning, slash management and prescribed burning techniques

13.3.1.5 Wildfire

Fires affect 0.5 Mha every year in Europe on average (less than 0.5% of a total forested area of 160 Mha), with 85% of the impacted surface concentrated in Mediterranean Europe (Figure 13.6 a,b) (Khabarov et al., 2016; Nolde, 2019). In Europe, human activities cause more than 90-95% of forest fires, although forest fires with a natural origin account for a substantial fraction of burnt area in the case of the Russian Federation (Wu et al., 2015b; Khabarov et al., 2016; Filipchuk et al., 2018).

Many factors impact the likelihood and extent of European fires such as topography, land use, soil moisture, litter and vegetation composition, human behaviour, wind speed, weather and climate (de Rigo et al., 2017b). Wildfire activity in the Mediterranean area is related to warming, increased wind activity and droughts (Turco et al., 2017; Lahaye et al., 2018) while fires in boreal forests are linked to summer droughts (Drobyshev et al., 2015; Drobyshev et al., 2016). Northern, Central and Southern Europe show contrasting trends (Figure 13.6 a,b), with significantly higher risk and emissions in Southern Europe. Fire weather risk indices (Di Giuseppe et al., 2020) have been dynamically changing in Europe in the last decades (1980-2019), with significant increases in Southern and Central Europe (Figure 13.6c). In sharp contrast, estimates of emissions from wildfires from 2003 to present show no significant temporal trends and large interannual variability (Figure 13.6d). Overall wildfires are a key emerging risk for European forests in the next decades, especially in the Mediterranean area. In the face of these increasing risks, fire-specific adaptation options have been thoroughly assessed (Table 13.4).

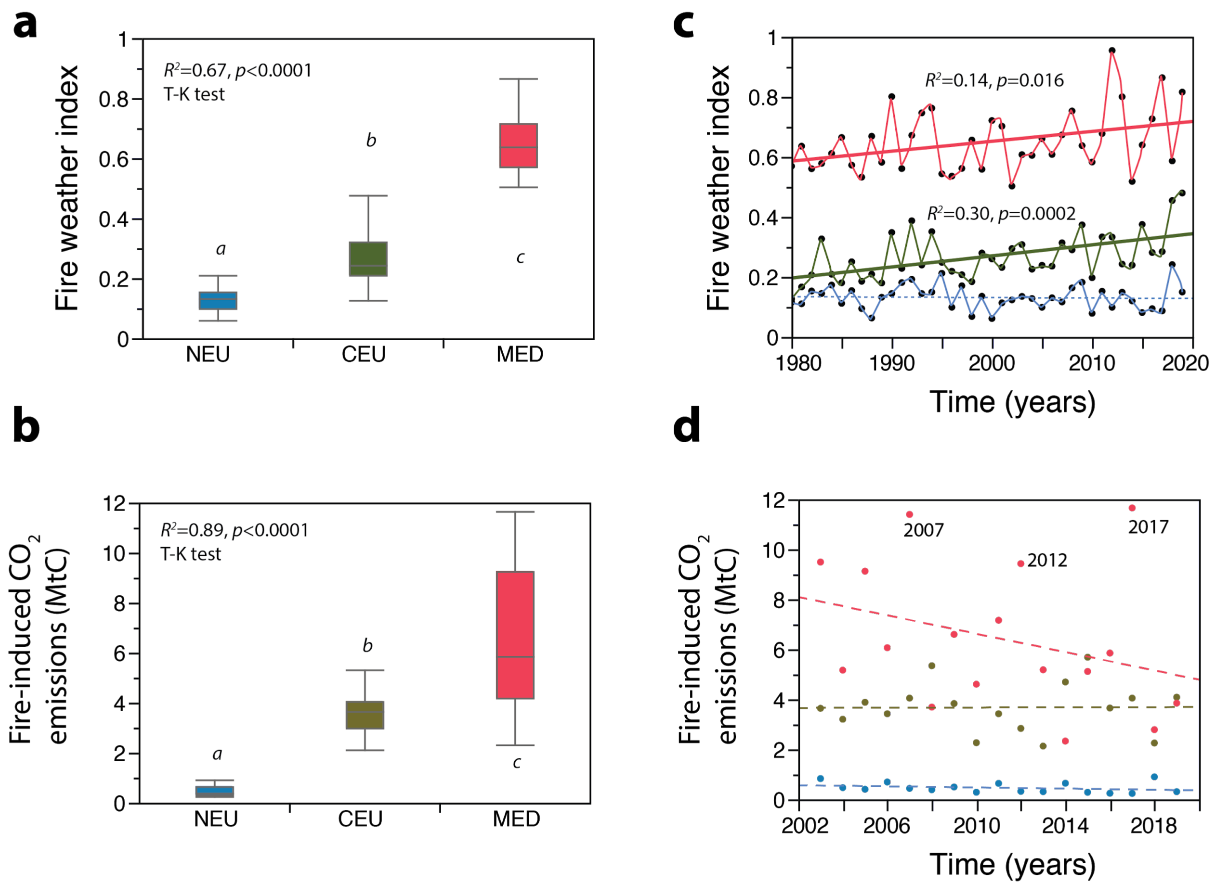


Figure 13.6: Geographical variability and dynamic changes in fire impacts and risks in Europe over the last decades. a) The environmental conditions required for fires to spread and intensify is evaluated using fire danger estimates which utilises the 'Fire Weather Index' (FWI) based on meteorological variables such as temperature, precipitation, wind speed and relative humidity. b) Estimates of emissions from wildfires as an indication of burned biomass extracted from the Global Fire Assimilation System (GFAS), based on satellite observations of fire radiative power providing a daily global dataset from 2003-present. c) Fire weather index trends calculated with the ECMWF ERA-5 FWI reanalysis dataset (Copernicus, 2019). d) Annual total estimates of total carbon from European fires as indication for changes of burned terrestrial biomass show a high degree of interannual variability but overall indicate non-significant trends in NEU, CEU and MED (Copernicus, 2020a; Copernicus, 2020b). In panels a and b, different letters indicate significantly different mean value of weather index and fire emissions, respectively ($p<0.0001$).

13.3.2 Solution Space and Adaptation Options

Adaptation options are available both within biophysical processes and as human responses. Natural adaptation processes include phenotypic plasticity, acclimatization, trans-generational and evolutionary adaptation, behavioural changes, and shifts in distribution and phenology. Multiple human-managed adaptation options for land and freshwater ecosystems have been assessed in Europe, evaluating their effectiveness (Table 13.3) (Naumann, 2011; Berkhout et al., 2015; van Teeffelen et al., 2015). Most adaptation practices are under continued reassessment and evaluation (Berkhout et al., 2015; van Teeffelen et al., 2015; Hermoso et al., 2017; Hermoso et al., 2018; Baldocchi and Penuelas, 2019a).

The implementation of EU's conservation directives and the Natura 2000 network have effectively contributed to biodiversity protection in both terrestrial and freshwater ecosystems in the last decades (*medium confidence*) (Mazaris et al., 2013; Gaüzère et al., 2016; Regos et al., 2016; Sanderson et al., 2016; Santini et al., 2016; Gallardo et al., 2017; Hermoso et al., 2018). Adaptation to projected impacts of climate change might require changing protected areas from static, conservation style networks to more dynamic conservation units (*low confidence*) (Heino et al., 2009; Barredo et al., 2016; Gaüzère et al., 2016; Kabisch et al., 2016; Nila et al., 2019; Prober et al., 2019; Heikkinen et al., 2020). Such dynamic approaches would explicitly and progressively integrate climate change effects in the improved spatial design of protected areas, facilitating in this way the movement of species, and creating new corridors between protected areas. Climate change risk projections will also increasingly affect regional land use planning, land development plans, agro-system management, and green infrastructures (Habel et al., 2019b; Nila et al., 2019; Heikkinen et al., 2020). A shift to more dynamic conservation networks would require changing existing laws and regulations that constrain these approaches in terrestrial and aquatic ecosystems. Moreover, their future development could also be hampered by elevated financial costs, budget limitations, uncertainty and complexity of regional ecological projections and social barriers. In each European region and protected area system, managing the future impacts of climate change on biodiversity will likely require a relatively complex and site-specific mix of conservation and adaptation options (Prober et al., 2019). There are potential co-benefits in planned adaptation, for example investments in green corridors can contribute to increased public access to green space and benefit human health indicators (Sections 13.6 and 13.7), and contribute to the storage of fresh water resources (Section 13.2) (Kabisch et al., 2016). Despite some examples of early planned adaptation across Europe, widespread implementation and monitoring is limited. Many of the adaptation options are difficult to implement because of management costs; competition for land use; limited knowledge on the effectiveness of options, and laws and regulations which do not consider species shifts (Kabisch et al., 2016). Moreover, despite increasing awareness of climate risks, perceptions of climate change as irrelevant or not urgent due to the perceived high adaptive capacity of ecosystems persist (Uggla and Lidskog, 2016; Esteve et al., 2018; Vulturius et al., 2018).

Harmonised national adaptation policies and governance schemes affecting land ecosystems have been actively promoted since 2013 by the progressive development and implementation of the EU Adaptation Strategy, the EU Biodiversity Strategy, the EU Forest Strategy, and the EU Green Infrastructure Strategy. In addition, since 2018 the EU has included GHG emissions and removals from forestry, land use and land use change (LULUCF) into the 2030 climate and energy framework (Regulation *EU* 2018/841). Land adaptation policies on terrestrial ecosystems have been financed by multiple sources in the EU, including the European Multiannual Financial Framework (2014–2020), the European Structural and Investment Funds, the Life Programme, Horizon 2020 EU Framework Programme for Research and Innovation, and the EU Common Agricultural Policy (CAP) 2014–2020. In addition, the European Investment Bank (EIB) and the European Commission have partnered to create the Natural Capital Financing Facility (NCFF), a financial instrument that supports projects delivering on biodiversity and climate adaptation through tailored loans and investments. Multiple EU-level service platforms have been promoted to track adaptation and climate change impacts on land ecosystems (Climate-Adapt, Copernicus Land and Fire Monitoring Service). Similarly, under the EU Forest strategy from 2020 the Forest Information System of Europe (FISE) collects harmonised Europe-wide information on the multifunctional role of forests, including climate change adaptation and mitigation, bio-economic uses, and biodiversity. Forest Management Plans (FMPs) are considered key instruments for forest adaptation policies. In the 2013-2018 period, a substantial increase in the knowledge base for adaptation was detected linked to the development of the EU Adaptation Strategy (EEA, 2018a). A Joint Programming Initiative on Agriculture, Food Security and Climate Change has been established between 21 European countries to promote measures for adaptation in farming, forestry and biodiversity sectors. However, widespread implementation of planned adaptation policies is often limited by substantial public budget and personnel limitations, and other social barriers (*high agreement*). For example, referring to the Nature 2000 network, recent assessments indicate that the current financial allocations from the EU budget may cover between 9% and 19% of the estimated total financing needs (Hermoso et al., 2018). Overall, widespread implementation of adaptation options in land ecosystems in Europe is currently limited by financial and other socioeconomic barriers (*high agreement*) (Kovats et al., 2014; Hermoso et al., 2017; Lee et al., 2019; Krause et al., 2020). Therefore revised financial, monitoring, planning and maintenance schemes for this network are being discussed at the European scale (Hermoso et al., 2017; Pe'er et al., 2017; Hermoso et al., 2018; Mammides, 2019).

Ecosystem-based adaptation and mitigation strategies in Europe are tightly linked, constraining and defining the available solution space for EU sustainability pathways (*medium confidence*) (Cross-Chapter Box NATURAL in Chapter 2, Luyssaert et al., 2018; Lee et al., 2019; Krause et al., 2020). Adaptation limits on land are linked to trade-offs between adaptation practices, carbon capture services, bioenergy uses, and food production (Kovats et al., 2014; Lee et al., 2019; Ceccherini et al., 2020; Krause et al., 2020). Multiple management strategies modifying European land ecosystems have been simulated at the European scale, finding important limiting trade-offs between carbon sink services, bioenergy and food provision (13.5, Valade et al., 2017; Kallio et al., 2018; Yousefpour et al., 2018; Lee et al., 2019; Krause et al., 2020). For example, policies promoting widespread afforestation in Europe would likely require substantial changes in demand-side food consumption patterns and increased crop productivity (*low confidence*) (Lee et al., 2019).

In this context forest management is emerging as a key strategic axis defining sustainability pathways in Europe, linking planned adaptation practices and the mitigation objectives (Naudts et al., 2016; EASAC, 2017; Grassi et al., 2017; Griscom et al., 2017; Luyssaert et al.; Baldocchi and Penuelas, 2019b; EASAC, 2019a).

Solution space and adaptation options in land ecosystems are also largely determined by mid-term EU renewable energy strategies (*medium confidence*). European forest policies aim to increase the use of forests as a source of bioenergy and as a substitute for fossil energy, with forest biomass contributing substantially to the EU's renewable energy targets. In line with these planned strategies, power system modelling studies indicate that a 100% renewable energy system in Europe is not feasible without substantial investments in biomass energy (Zappa et al., 2019). While biomass plays a critical role in providing peak and load-following capacity in all 100% renewable scenarios, the EU renewable energy targets have been criticized for causing the loss of established forests and carbon sinks in Europe, setting in turn strong limits to the feasible adaptation options and available solution space (Schulze et al., 2012; Kovats et al., 2014; Lee et al., 2019; Ceccherini et al., 2020). EU forest policy objectives and projections contrast with available scientific assessments which indicate that adapting and mitigating climate change through afforestation and forest management may be hampered by complex biophysical and land use trade-offs (Schulze et al., 2012; Lee et al., 2019; Ceccherini et al., 2020). Moreover, all these trade-offs between continental-scale carbon sink and bioenergy uses have been dynamically changing over the last years. Econometric indicators on forestry, wood-based bioenergy and international trade indicate a recent expansion of wood markets in Europe, resulting in an increase in the harvested forest area over Europe for the period of 2016–2018 (relative to 2011–2015), with large losses occurring in the Nordic and Baltic countries, Eastern Europe and the Iberian Peninsula (Ericsson and Werner, 2016; Ceccherini et al., 2020).

Due to these emerging complex socioecological trade-offs and the associated uncertainty, there is currently low agreement on the specific forestry practices that may more effectively contribute to climate change adaptation and sustainability at the European scale (Kolström, 2011; Naudts et al., 2016; EASAC, 2017; Grassi et al., 2017; Griscom et al., 2017; Baldocchi and Penuelas, 2019b; EASAC, 2019b). Overall, adaptation and mitigation need to be jointly considered in the coupled effects of forest management practices on water, energy and carbon cycles (Ellison et al., 2017; Seneviratne et al., 2018). Adaptation and mitigation options could also be limited by the intensification of climate-change impacts on land ecosystems (including wind, insect outbreaks and fire impacts), with a calculated reduction of the carbon storage potential in Europe's forest of over 0.5 GtC in 2021–2030 (*medium confidence*) (Seidl et al., 2017). Similarly, adaptation options and solution space could also be constrained by strong trade-offs between fuel load management to reduce fire risk, carbon sink capacity, and management of blue and green water resources in ecosystems (*medium confidence*). In freshwater ecosystems, adaptation options can be limited by the disruption of hydrological habitat connectivity by dams and by reduced flows (Knouft and Ficklin, 2017; Markovic et al., 2017; Pandit et al., 2017).

13.4 Ocean and Coastal Ecosystems and their Services

13.4.1 Observed Impacts and Projected Risks

13.4.1.1 Observed impacts

Warming continues to be the key climate hazard (Section 13.1) for European marine and coastal ecosystems, with strong and far-reaching impacts (Table 13.5) in the waters of the NE Atlantic and its European tributary seas, as well as the Mediterranean Sea (Hoegh-Guldberg et al., 2018) and the Barents Sea (Frolov et al., 2014). Among these impacts, poleward distribution shifts of species and communities are particularly evident (*high confidence*; Chapter 3). For some biotas, such as kelp species at the Atlantic coasts of Spain and Portugal, range contractions and even local extinctions have been observed (*medium confidence*) (Smale, 2020). Such redistribution trends can be accompanied by immigration, spread and establishment of non-native species (*high confidence*), e.g., the Pacific oyster *Crassostrea gigas* off the northern British Isles (Cottier-Cook et al., 2017) and lionfish *Pterois miles* in the Mediterranean Sea (Castellanos-Galindo et al., 2020). Besides warming, further factors, such as human activities and ocean current regimes, determine the magnitudes and rates of range shifts (Molinos et al., 2016) (*high confidence*). They depend on habitat type, temperature gradient, thermal affinity (*high confidence*) and mobility of species (*high confidence*) and thus vary across regions, taxa, and ecological groups (Berge et al., 2005; Brodie et al., 2014; Birchenough et al., 2015; Montero Serra et al., 2015; Chivers et al., 2017; Burrows et al., 2019; Krovnin et al., 2019; Mieszkowska et al., 2019; Baudron et al., 2020) (Chapter 3). The resulting redistribution of biodiversity (Molinos et al., 2016) has altered community compositions ('subtropicalisation' of temperate European waters and 'tropicalisation' of the Mediterranean Sea; Chapter 3; Cross-Chapter Paper 4), ecosystem functioning (Chivers et al., 2017; Baird et al., 2019) and biogeochemical cycling (Coma et al., 2009; Garrabou et al., 2009; Huete-Stauffer et al., 2011; Munari, 2011; Kersting et al., 2013; Rivetti et al., 2014; Garrabou et al., 2019). The pressures of extreme events like marine heatwaves have already had severe ecological impacts in the Mediterranean region (*high confidence*) (Cross-Chapter Paper 4), particularly threatening sessile benthic biotas and coastal habitats (Coma et al., 2009; Garrabou et al., 2009; Huete-Stauffer et al., 2011; Munari, 2011; Kersting et al., 2013; Rivetti et al., 2014; Garrabou et al., 2019).

Multiple further climatic and non-climatic factors, generally in interaction with the key climatic driver warming or with each other (Chapter 3), have had cumulative or cascading impacts on marine and coastal ecosystems, such as significant biodiversity declines in virtually all European seas (IPBES, 2018) (*high confidence*). Ocean freshening and warming in temperate European seas (Section 13.1) together caused increased water-column stratification (Huthnance et al., 2016) (*high confidence*), which in turn decreased marine primary production (Capuzzo et al., 2018) (*medium confidence*), with cascading negative effects on secondary productivity across several trophic levels (Free et al., 2019) (*high confidence*). In contrast, sea-ice decline as a result of warming caused primary production to increase by 40-60% in Europe's northernmost regions (Arrigo and van Dijken, 2015; Borsheim, 2017; Lewis et al., 2020) (*high confidence*). Ocean acidification is continuing in NE Atlantic waters off Europe (IPCC, 2019) (Chapter 3), but its biological and ecological impacts vary in direction and magnitude due to interactions with other climate-related (e.g., warming, deoxygenation) and human-driven (overexploitation of living resources, habitat destruction, and pollution) pressures (Gattuso et al., 2015), interspecific relationships (Bulleri et al., 2018) and food-web dynamics (Sswat et al., 2018b) (*medium confidence*). For instance, acidification impacts can be amplified by hypoxia in coastal habitats (Melzner et al., 2013) but also substantially mitigated by microclimatic heterogeneity and pH buffering (Suggitt et al., 2018), providing refuge from acidification stress (Wahl et al., 2018) (*medium confidence*). Magnitudes and rates of ocean deoxygenation are generally small in most European waters (Schmidtko et al., 2017), and hence its ecological impacts alone as well. Semi-enclosed seas, such as the Baltic and Black Seas, are exceptions, since there the cumulative effects of deoxygenation and other climatic and anthropogenic pressures, such as eutrophication, coastline modifications, pollution, and overfishing, are strongest (*high confidence*) and pose serious risks to ecosystem health and service provision (Jacob et al., 2014). In both the Baltic and Black Seas, warming has amplified the main effects of eutrophication and regional oceanography in altering ecosystem functioning *(high confidence*), reducing potential fish yield and favouring noxious algal blooms (Anonymous, 2014; Carstensen et al., 2014; Daskalov et al., 2017; Reusch et al., 2018; Stanev et al., 2018) (Chapter 3). Conversely, the impacts of warming and deoxygenation are intensified by eutrophication, increasing the likelihood of harmful algal blooms (HAB) (Berdalet et al., 2017; Riebesell et al., 2018) and the emergence and increase of risks of *Vibrio* pathogens and vibriosis (Baker-Austin et al., 2017; Semenza et al., 2017) (Section 13.7).

Table 13.5: Major impacts (observed) and risks (projected for two warming levels: +1.5 °C and 3 °C) for marine and coastal ecosystems in Europe. Direction of change of impact/risk level (increasing, decreasing, both, no evidence, not applicable) and confidence of detection (low, medium, low) are indicated for Europe and by its marine subregions (EUSS – Southern seas, with the Mediterranean and Black Sea; EUTS – Temperate seas, incl. Greater North Sea, Celtic Seas, Bay of Biscay, Iberian Coast, and Baltic Sea; EUAW – Arctic waters, incl. Barents, White and Nordic Seas), if available. [PLACEHOLDER FOR FINAL DRAFT: to be updated].

LEGEND:	Direction of change	Confidence of detection	
	Increasing	•	Low
	Decreasing	••	Medium
Both>	Both	•••	High
	No Evidence		
	Not assessed		

IMPACT / RISK	Main Climatic Driver (s) / Hazard(s)	Affected Systems		Direction of Change by Regions: EUSS	EUTS	EUAW
A. Reduced biodiversity and habitat availability	Warming, heatwaves	Species, communities	Observed	Increasing •••	Increasing •••	Increasing ••
			Projected: +1.5 °C	Increasing •••	Increasing •••	Increasing •••
			Projected: +3.0 °C	Increasing •••	Increasing •••	Increasing •••
B. Local extinctions	Warming, deoxygenation	Species	Observed	Increasing ••	Increasing ••	Increasing ••
			Projected: +1.5 °C	Increasing ••	Increasing ••	
			Projected: +3.0 °C			
C. Range shifts	Warming	Species, communities	Observed	Increasing •••	Increasing ••	Increasing •••
			Projected: +1.5 °C	Increasing •••	Increasing •••	Increasing •••
			Projected: +3.0 °C	Increasing •••	Increasing •••	Increasing •••
D. Invasions of non-native species	Warming	Communities	Observed	Increasing •••	Increasing •••	Increasing •••
			Projected: +1.5 °C			
			Projected: +3.0 °C			
E. Shifts in taxonomic and functional composition	Warming, acidification	Communities	Observed	Increasing ••	Increasing •••	Increasing •••
			Projected: +1.5 °C			
			Projected: +3.0 °C	Increasing •••	Increasing •••	Increasing •••
F. Changes in phenology and reproductive success	Warming, acidification	Species	Observed		Both	
			Projected: +1.5 °C			
			Projected: +3.0 °C		Both	
G. Changes in foodweb dynamics	Warming, acidification	Communities, ecosystems	Observed	Increasing ••	Increasing •••	Increasing •••
			Projected: +1.5 °C	Increasing ••	Increasing •••	Increasing •••
			Projected: +3.0 °C	Increasing ••	Increasing •••	Increasing •••
H. Changes in productivity	Warming, stratification, sea-ice decline	Ecosystems	Observed	Both	Decreasing ••	Increasing •••
			Projected: +1.5 °C	Both	Decreasing •••	No evidence ••
			Projected: +3.0 °C	Both	Decreasing •••	No evidence ••
I. Emergence of harmful algal blooms and pathogens	Warming, acidification, deoxygenation	Species, communities, ecosystems	Observed		Increasing ••	
			Projected: +1.5 °C			
			Projected: +3.0 °C			
J. Changes in regulating ecosystem services (carbon capture)	Warming, acidification	Ecosystems	Observed			
			Projected: +1.5 °C			
			Projected: +3.0 °C		Both	Both

13.4.1.2 Projected risks

In response to the projected accelerating warming (IPCC, 2019) (Section 13.1), risks to marine and coastal European ecosystems are *very likely* to intensify (Table 13.5). For instance, pronounced changes in community composition and biodiversity patterns are projected by 2100 for the North Sea, eastern Mediterranean Sea and NE Atlantic under both intermediate and strong warming scenarios in both a +3 °C and +4 °C world (Molinos et al., 2016). Such warming-driven shifts will pose, in combination with high anthropogenic pressures (e.g., fishing), severe challenges for future conservation efforts (Corrales et al., 2018; Cramer et al., 2018; Kim et al., 2019). Already by 2040, in a +1.5 °C world under strong warming, particularly in winter, Mediterranean coastal fish communities are projected to lose species, which will exacerbate regime shifts linked to overexploitation in heavily fished areas (Clark et al., 2020) (*medium confidence*). As species- and life cycle-specific thermal bottlenecks define the vulnerabilities of species to warming risks, the percentages of species potentially affected by water temperatures exceeding their tolerance limit for reproduction differ widely among warming scenarios, e.g., for fish from ~10% in a +1.5 °C world to ~60% in a +4 °C world by 2100 (Dahlke et al., 2020). In a warmer-than +4 °C world projected under strong warming by 2150, ocean temperatures will exceed the existing buffer against warming based on the thermal sensitivity of constituent species (community thermal safety margins) of many biotas living in current Marine Protected Areas (MPA) in temperate and Arctic European waters (Bruno et al., 2018). While marine heatwaves are projected to increase in frequency and magnitude (Frölicher et al., 2018), particularly in the Mediterranean Sea in a +4 °C world by 2100 (Darmaraki et al., 2019c) (*high confidence*), their risks levels for marine organisms (Galli et al., 2017), coastal biodiversity, and ecosystem functions, goods and services (Smale et al., 2019) differ among biotas (Pansch et al., 2018) and across European seas (Smale et al., 2015).

Trends in marine primary production are projected to vary among European waters. In most regions, they will further decrease, by 2100 depending on the warming scenario from 0.3% in a +1.5 °C world to 2.7% in a +4 °C world, mainly driven by further stratification-driven reductions in nutrient availability (Doney et al., 2012; Laufkoetter et al., 2015; Wakelin et al., 2015; Salihoglu et al., 2017; Holt et al., 2018; Bryndum-Buchholz et al., 2019; Carozza et al., 2019; Kwiatkowski et al., 2019) (*high confidence*). In the Barents Sea, however, models project stable production rates under all warming scenarios in response to further sea-ice decline and resulting lower light and temperature limitations (Slagstad et al., 2011), and in the eastern Mediterranean Sea marine production is projected to increase until 2100 in response to reduced stratification due to increasing evaporation rates (Macias et al., 2015; Moullec et al., 2019). Decreasing net primary production in most European waters will have negative implications for the productivity and biomass of higher trophic levels, including fish (Section 13.5.1), for instance in the North Sea and Celtic Seas (Holt et al., 2016; Holt et al., 2018) and the Mediterranean Sea (Stergiou et al., 2016). Marine animal biomass is generally projected to *likely* decline under all warming scenarios, with particularly pronounced decreases of up to 25% in a +2 °C world and 50% in a +4 °C world by 2100 in European waters of the NE Atlantic (Lotze et al., 2019).

With accelerating ocean acidification in European waters (Section 13.1), the ecological risks of this climate hazard are projected to also rise (*medium confidence*). Calcifying organisms, e.g., coralline algae, can be affected by reduced skeletal elasticity under a strong warming scenario in a +3 °C world by 2050, with negative consequences for their ability for habitat formation (Ragazzola et al., 2016) (*medium confidence*). Risks will be higher for the more fragile coralline algae species in southern European shelf regions than for the more robust species in the north (Melbourne et al., 2018). Regionally, for example in the Barents Sea and the Skagerrak, differences in vulnerability to projected acidification will result in shifts from calcifying macroalgae (Ragazzola et al., 2013) (*medium confidence*) to non-calcifying macroalgae (Gordillo et al., 2016) (*high confidence*). Some important habitat formers, such as the deep-water coral *Lophelia pertusa* (Wall et al., 2015), and habitat engineers, such as limpets in the Mediterranean (Langer et al., 2014), can change energetic allocation to continue calcification at acidification levels of –0.3 pH (projected for a +4 °C world by 2100) and even –1.5 pH, which is well beyond a level projected after 2100 under a worst-case warming scenario.

Responses of bivalves to ocean acidification in the Baltic Sea strongly depend on food availability (Thomsen et al., 2013), suggesting that acidification risks will be amplified by increased stratification and reduced primary production (*medium confidence*). Experimental evidence further suggests that elevated CO_2 levels predicted under climate scenarios leading to a +4 °C world by 2100 can have contrasting effects in European waters on the C/N ratio of organic-matter export and thus the efficiency of the biological pump, with up to 20% increase or decrease depending on the variety of plankton taxa and corresponding shifts in food-web structure (Taucher et al., 2020), as well as on ecologically and economically important fish species: Atlantic herring (*Clupea harengus*) can benefit from indirect food-web effects (Sswat et al., 2018a), whereas Atlantic cod (*Gadus morhua*) face overall negative impacts on larval growth and survival (Stiasny et al., 2018; Stiasny et al., 2019) (Section 13.5). Increasing climate hazards are projected to amplify the effect of eutrophication on deoxygenation and lead to a further expansion of anoxic dead zones in the Black Sea (Altieri and Gedan, 2015) and the Baltic Sea (Jokinen et al., 2018; Reusch et al., 2018), e.g., in the Baltic Sea by 5 % in a +4 °C world at the end of the 21st century (Saraiva et al., 2019).

The combination of climate hazards and non-climate pressures will have pronounced impacts on Europe's coastal vegetated 'blue-carbon' ecosystems (subtidal seagrass meadows and intertidal salt marshes), particularly in microtidal areas (*high confidence*), such as the Mediterranean and Baltic coasts, where >75% of coastal wetlands may be lost in a +3 °C world by 2100 (Spencer et al., 2016; Schuerch et al., 2018; Spivak et al., 2019). The Wadden Sea (North Sea), the world's largest system of intertidal flats, will reduce in surface area and height, as the sediment transport capacity limits the possibility of growth with rapidly rising sea levels (Wang et al., 2018; Jiang et al., 2020). For the Dutch Wadden Sea, the critical rate of 6 to 10 mm yr^{-1}, at which intertidal flats will start to 'drown', may be reached already by 2030 in a +1.5 °C world, with subsidence due to human activities, such as water extraction, even earlier (van der Spek, 2018). The loss of ecosystem services driven by sea-level rise and the associated coastal erosion in Europe is estimated at €2.2 to €2.9 billion per year by 2050 under B1 and A1FI SRES scenarios, respectively, resulting in a decrease in coastal ecosystem service values of 7 to 10% compared to 2006 (Roebeling et al., 2013).

13.4.2 Solution Space and Adaptation Options

The capacity of natural systems for autonomous adaptation to the current rapid climate change is limited (Thomsen et al., 2017; Miller et al., 2018; Bindoff et al., 2019) (*medium confidence*). Among human adaptation actions, MPAs have been identified as one of the most practical and cost-effective conservation strategies and adaptation options to lessen the risks to marine biodiversity (Selig et al., 2014; Hopkins et al., 2016; Roberts et al., 2017) (Chapter 3). Climate-change adaptation has not been the primary reason for the establishment of MPAs but rather protection from non-climate stressors. The spatial protection though enhances the resilience of marine and coastal ecosystems by reducing local stresses, such as commercial exploitation (Roberts et al., 2017), which can also lessen the impacts of climate change (Narayan et al., 2016). The extent of MPAs has been increasing in Europe, albeit with strong regional variations: In 2012, only the Baltic Sea (13.5% MPA coverage) had reached the 10% Aichi target, followed by the Mediterranean Sea with 9.5%. In contrast, the Black Sea had only designated 4.5%, and in the EU part of the NE Atlantic, only 4.2% were designated (Eurostat, 2018; Sala et al., 2018). Figures for MPA extent across entire Europe are not published. Management plans that include standardised monitoring and reporting, as well as refined threat assessments in a spatial and temporal context, can improve conservation capacity and outcomes (Mazaris et al., 2013). MPAs have greatest climate-change adaptation capacity and can significantly reduce the sensitivity or enhance the capacity of marine and coastal ecosystems to recover from extreme events (Roberts et al., 2017) when they are highly protected (marine reserves, no-take zones, 'zapovedniks' in Russian). The capacity of the current MPA network to reduce climate change impacts is arguably limited and at best uncertain (Jones et al., 2016; Claudet et al., 2020).

In the European Union (EU), 'green' adaptations, characterized by 'ecosystem-based adaptations' or 'nature-based solutions', are part of adaptive management strategies (Anonymous, 2011). These measures, involving interventions in natural or semi-natural ecosystems, can be of a similar or even higher effectiveness than alternative approaches for reducing climate impacts. They can also often have more synergies than trade-offs with broader ecological, social, and climate-change mitigation outcomes (Chausson et al., 2020). For instance, in coastal ecosystems they can facilitate coastal flood protection (Section 13.2.2; Chapter 3; Cross-Chapter Box SLR in Chapter 3) reducing coastal erosion and storm surges, thus generating benefits beyond habitat creation, e.g., from avoided expenditures for flood defence infrastructure and avoided loss of the built assets (Gedan et al., 2010). Accordingly, in Europe many governance and implementation measures to cope with climate change impacts and to advance sustainable development pathways (Section 13.11.4) are embedded in international and EU-wide strategies, such as the Baltic Marine Environment Protection Commission (HELCOM) Parties commitment to protect the Baltic Sea (Backer et al., 2010), the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) (OSPAR, 2009), and the Marine Strategy Framework Directive (MFSD) and European Water Framework Directive (EWFD). In Russian Arctic waters, mainly the Barents Sea, conservation priority areas (CPA) have been identified, according to a number of criteria, as ecologically and biologically significant areas (EBSA) changes (Solovyev et al., 2017). Assessing the effectiveness of these mostly international transboundary policy frameworks in mobilizing the solution space to accelerate climate-change adaptation (Haasnoot et al., 2020a) are ongoing. Examples for implementing adaptation in marine environments are presented mainly in grey literature, and plans are generally at an early stage (Miller et al., 2018). Integrated Coastal Zone Management (ICM) and Marine Spatial Planning (MSP) are frameworks for addressing climate-change adaptation needs, as well as operationalizing and enforcing marine conservation (Jacob et al., 2014; Ballinger, 2015; Wescott, 2015; Oppenheimer et al., 2019). However, ICM and MSP do commonly not explicitly take climate-change adaptation into consideration yet but have to adapt to climate-change impacts (Elliott et al., 2015) often across national boundaries, requiring transnational agreements (Gormley et al., 2015). Transboundary ICM and/or MSP become even more important with the expected acceleration of range extensions and ecological regime shifts due to climate change (IPCC, 2019).

Climate change impacts and risks are usually not considered as prime aspects in legislation to protect marine biodiversity, e.g., in the site-designation process or management of marine protected areas (e.g., the Habitats Directive (European Council Directive 92/43/EC) and EC Birds Directive (Directive 2009/147/EC of the European Parliament and of the Council), with few exceptions (Frost et al., 2016). On the other hand, a creative interpretation of the law may enable climate change adaptation (Verschuuren, 2015). The European Commission has issued guidance for recognition and incorporation of climate considerations in relation to the management of Natura 2000 sites and advocated for an adaptive management approach (EuropeanCommission, 2013). More recently, MSFD (Directive 2008/56/EC of the European Parliament and of the Council) defines the expectations of EU member states to develop strategies to ensure a healthy marine environment and increase ecosystem resilience to climate change in all European marine waters (MSFD Preamble Paragraph 34). However, there is evidence that better international cooperation is required to make the MSFD effective (Cavallo et al., 2019). Also, there is an observation challenge, which is not yet met, to effectively monitor the indicators for Good Environmental Status (Machado et al., 2019). At the same time, the European Commission promotes a 'Blue Growth' strategy with the aim to increase offshore activities, which has the potential to increase the pressures on the marine environment.

Nature-based solutions can support alleviation of or adaptation to climate-change impacts but are themselves impacted by climate change. For instance, while rising sea levels threaten intertidal and beach ecosystems, they provide additional vertical accommodation space for coastal wetlands, enhancing their ability to capture and store carbon (Rogers et al., 2019) (WGIII AR6 Chapter 4). Many coastal regions of the North Sea, especially in the south, are particularly susceptible to rising sea levels because of the strong tidal regime and the effects of storm surges (Figure 13.3). Hard measures to adapt human infrastructure against sea-level rise (Section 13.2) will lead to loss of coastal habitats, with negative impacts on marine biodiversity (Airoldi and Beck, 2007 ; Cooper et al., 2016) (Cross-Chapter Box SLR in Chapter 3).

Efforts to adapt to the impacts and risks of climate change and to mitigate climate change itself interact. The use of European coastal blue-carbon ecosystems (seagrass meadows, kelp forests, tidal marshes) as effective natural long-term carbon sinks in climate mitigation policies has the potential to interfere with other ecosystem services, which these or other adjacent coastal ecosystem provide in a natural condition, as well as biodiversity conservation issues (Howard et al., 2017; Chausson et al., 2020). Similarly, large-scale offshore wind-park infrastructure is currently developed in European seas as a major component of climate-change mitigation efforts (WGIII AR6 Chapter 6). By 2018, 4,543 turbines in 105 wind farms in 11 countries, primarily the UK and Germany, have been installed, mostly in the North Sea (Anonymous, 2019). Their profound and far-reaching ecological ramifications for the natural marine systems through the introduction of novel hard-substrate intertidal habitats in soft-bottom systems include hydrodynamic changes, stepping-stones for none native species, noise and vibration, and changes to the food web (Lindeboom et al., 2011; De Mesel et al., 2015; Gill et al., 2018; Dannheim et al., 2019) (*high confidence*) potentially resulting in mitigation-adaptation trade-offs (Chapter 3).

13.4.3 Knowledge Gaps

Despite all efforts to assess the observed impacts and projected risks of climate-change driven hazards on European marine and coastal ecosystems and to develop and implement adequate, feasible and effective adaptations, there are still uncertainties and shortcomings in our understanding of these systems, which demand further observational, experimental and modelling studies. In particular, there is still a need for better addressing combined and cascading impacts on European marine and coastal socio-ecological systems, to develop a level of understanding of the multiple processes and their interactions, which is necessary to increase the confidence of impact assessments and risk projections.

Although MPA networks are generally recognized as an important management approach in ICM and MSP frameworks (Hopkins et al., 2016), climate-change impacts, such as shifts of species' ranges, are seldom incorporated into their planning, establishment and management (Solovyev et al., 2017; Johnson et al., 2018). Therefore, their effectiveness is limited (Bruno et al., 2018; Rilov et al., 2019). Reorganizing the spatial distribution of MPA networks can minimize exposure to one stressor (e.g., warming), but may result in an increase of the exposure to another pressure (e.g., deoxygenation) (Bruno et al., 2018). In addition, few European MPAs are currently fully 'no-take zones' and many do not have published management plans, and both these shortcomings reduce the potential effectiveness of MPAs to reach their conservation goals (Bruno et al., 2018). Also, the vast majority of MPAs in Europe are multi-use rather than highly protected and existing no-take areas tend to be very small (< 50 km^2) and nested within multi-use MPAs. Finally, to achieve the protection and adaptation goals, interconnected MPAs (McLeod et al., 2009) (Chapter 3) facilitating connectivity among species, populations, and ecosystems to provide new recruits and enable gene flow (Dubois et al., 2016b; Sahyoun et al., 2016) are best suited. Yet, European MPAs were designed and designated predominately on an individual site basis, with little or no explicit consideration of connectivity between sites (Yates et al., 2013; Jones et al., 2016) (Section 13.9).

13.5 Food, Fibre, and Other Ecosystem Products

13.5.1 Observed Impacts and Projected Risks

13.5.1.1 Crop production

Agriculture is the primary user of land and water in Europe. In 2013, Europe provided 28% of cereals, 59% of sugar beet and 60% of wine produced globally, as well as being part of a globalized food system with a third of commodities produced and consumed in Europe traded internationally (FAOSTAT, 2019).

Observed climate change has led to a northward movement of agro-climatic zones in Europe and earlier onset of the growing season (Ceglar et al., 2019) (*high confidence*). Impacts of drought are pervasive across Europe affecting annual crops, permanent crops, water for irrigation and livestock farming resulting in increased costs and economic losses (Stahl et al., 2016). Heat stress has increased in southern Europe in spring, in summer throughout central and southern Europe, and recently expanded into the southern boreal zone (Fontana et al., 2015; Ceglar et al., 2019). Drought, excessive rain, and the compound hazards of drought and heat (13.2, 13.3, 13.10) cause losses in wheat production in the EU (van der Velde et al., 2018) and north-west Russia (Ivanov et al., 2016) (*high confidence*). Warming and precipitation changes explain continent-wide reductions in yield of wheat and barley and increases in maize and sugar beet (*high confidence*) (Fontana et al., 2015; Moore and Lobell, 2015; Ray et al., 2015; Ceglar et al., 2017). Regionally, warming causes increases in yields of field grown fruiting vegetables, decreases in root vegetables, tomatoes and cucumbers (Potopová et al., 2017) and earlier flowering of olive trees (Garcia-Mozo et al., 2015) (*high confidence*). Delayed harvest due to wet conditions and earlier harvests in central Europe in response to warming both impact wine quality (Cook and Wolkovich, 2016; van Leeuwen and Darriet, 2016; Di Lena et al., 2019). Meteorological extremes due to compound effects of cold winters, excessive autumn and spring precipitation, and summer drought caused production losses in 2012, 2016, 2018 (Ben-Ari et al., 2018; van der Velde et al., 2018; Zscheischler et al., 2018; Toreti et al., 2019b)that were exceptional compared to recent decades (Webber et al., 2020), resulting in higher grain prices (Zakharov and Sharipova, 2017).

Evidence for growing regional differences of projected climate impacts is increasing since AR5 (*high confidence*). While there is high agreement of the direction of change, the absolute yield losses are uncertain due to differences in model parameterization and whether adaptation options are represented (*high confidence*) (Donatelli et al., 2015; Moore and Lobell, 2015; Knox et al., 2016; Webber et al., 2018). In response to 2°C warming, agro-climatic zones in Europe are expected to move northward 25-135 km/decade, fastest in eastern Europe (Ceglar et al., 2019). At 1.5°C warming the likelihood of compound events which led to recent large wheat losses are projected to become 12% more frequent, challenging farming systems and yield forecasting systems (Ben-Ari et al., 2018). Growing regions are projected to shift northward or expand for melons (Fink et al., 2009) (*medium confidence, limited evidence*), tomatoes and grapevines reaching NEU and EEU in 2050 under 1.5°C. In contrast, warming would increase yields of onions, Chinese cabbage and French beans (Bisbis et al., 2018 Potential impacts of climate change on vegetable production and product quality – A review).

Agricultural yield reduction will be higher in the south at 4°C warming, with lower losses or gains in the north (Webber et al., 2016; Szewczyk et al., 2018) (*high confidence*). Largest impacts of warming are projected for maize in MED (Deryng et al., 2014; Knox et al., 2016) (*high confidence*) with losses across Europe of 10-25% at 1.5-2°C and 50-100% at 4°C (Deryng et al., 2014; Webber et al., 2018). Use of longer season varieties can compensate for heat stress on maize in WCE and lead to yield increases for Northern Europe, but not the MED for 4°C warming (Siebert et al., 2017; Ceglar et al., 2019) (*medium confidence*).

Irrigation can reduce the projected heat stress for wheat and maize (Siebert et al., 2017). Negative impacts of warming and drought are counterbalanced by CO_2 fertilization for crops such as winter wheat (*medium confidence, medium agreement*), resulting in some regional yield increases with climate change (Zhao et al., 2017; Webber et al., 2018). The advantages of a longer growing season in northern and eastern Europe are outbalanced by the increased risk of early spring and summer heat waves (Ceglar et al., 2019).

Across western Europe, 1°C warming and higher precipitation is projected to increase farmland value on average by circa 8%, with increases in northern and decreases in southern countries (Van Passel et al., 2017) (*limited evidence*). Increased heat and drought stress and reduced irrigation water availability will cause abandonment of farmland in the Mediterranean region because of decreased profitability of the agricultural sector (Holman et al., 2017).

Warming causes range expansion and alters host pathogen association of pests, diseases and weeds affecting health for European crops (Caffarra et al., 2012; Pushnya and Shirinyan, 2015; Latchininsky, 2017) *(high confidence*) with high risk for contamination of cereals (Moretti et al., 2019). Predicted reduction in rainfall (13.1) may lead to carryover of herbicides (Karkanis et al., 2018).

13.5.1.2 Livestock production

Climate change impacts animals such as dairy cows and goats directly exposed to heat and humidity in open barns and outdoors (Gauly et al., 2013; Bernabucci et al., 2014; Silanikove and Koluman, 2015), and on cold adapted husbandry (see Box 13.2, Section 13.8). Heat impacts animal health (Sanker et al., 2013; Lambertz et al., 2014), nutrition, behaviour and welfare (Heinicke et al., 2019), performance and product quality (Gauly and Ammer, 2020). Climate change also impacts grassland production, fodder composition and quality (Dumont et al., 2015), as well as altering the prevalence, distribution and load of pathogens and their vectors (Morgan et al., 2013; Charlier et al., 2016) (*high confidence*).

Warming increases the pasture growing season and farming period in northern Europe and at higher altitudes (*high confidence*) (Fuhrer et al., 2014), while longer drought periods and thunderstorms can influence abandonment of remote Alpine pastures, reducing cultural and landscape ecosystem services and losing traditional farming practices (Herzog and Seidl, 2018). At high elevations in the northern Alps 2-4°C warming will increase grassland biomass production for forage-fed animals due to sufficient water availability and prolonged growing seasons, while in the southern Alps water scarcity will negatively affect yields (Jäger et al., 2020). Forage yield is projected to increase in NEU while drought and heat will reduce forage production in MED (Gauly et al., 2013), causing regional reductions of cow milk production in Germany and northern Italy (Silanikove and Koluman, 2015). Projected impacts on intensive production systems, e.g., poultry and pigs, are low due to temperature control in large parts of Europe, but greater in Southern Europe where open systems prevail (Chapter 5).

13.5.1.3 Aquatic food production

Seafood production in Europe provides jobs for more than 250,000 people, predominantly in the MED (Carvalho et al., 2017c). Marine fisheries contribute 80% to European seafood production, while marine aquaculture provides 18% and freshwater production 3% (Blanchet et al., 2019). The Russian Federation provides 1/4 of seafood production in Europe (FAOSTAT, 2019), including 850,000-1,150,000 tons/year from the Northern Atlantic (Shibanov and Fomin, 2016).

Climate change has impacted European marine food production (*high confidence*). However, fishing is still the major impact on commercially important fish stocks in Europe (Mullon et al., 2016), with 69% of the total of 397 stocks overfished and 51% outside safe biological limits (Froese et al., 2018). The North Sea, the Iberian coastal Sea and Celtic Sea-Biscay Shelf are globally among the areas most negatively affected with losses of Maximum Sustainable Yields (MSY) of 15-35% (Free et al., 2019). Warming is causing a northward movement and range expansion of Northeast Atlantic fish stocks (Baudron et al., 2020) (13.4). Range expansions provide new target species for fishing such as cuttlefish (van der Kooij et al., 2016;

Oesterwind et al., 2020) and tuna (Bennema, 2018; Faillettaz et al., 2019) in the North Sea region (*medium confidence*). Warm-water species are increasingly dominating fisheries landings in southern Europe (Fortibuoni et al., 2015; Teixeira et al., 2016; Vasilakopoulos et al., 2017).

European marine fisheries and aquacultures are globally among the least vulnerable to the impacts of climate change (*high confidence*), due to low levels of exposure, low sensitivity and high adaptive capacity (Barange et al., 2014; Ding et al., 2017) with salmon farming in Norway being an exception (Handisyde et al., 2017). Within Europe, freshwater production is less vulnerable than marine sectors and marine production vulnerability increases with latitude (Blanchet et al., 2019). Climate risks for fishing communities and the vulnerability of aquaculture sectors is highest in the MED, as well as UK (marine fisheries), the Netherlands and Portugal (aquaculture) (Handisyde et al., 2017; Payne et al., 2020; Peck et al., 2020); Figure 13.7).

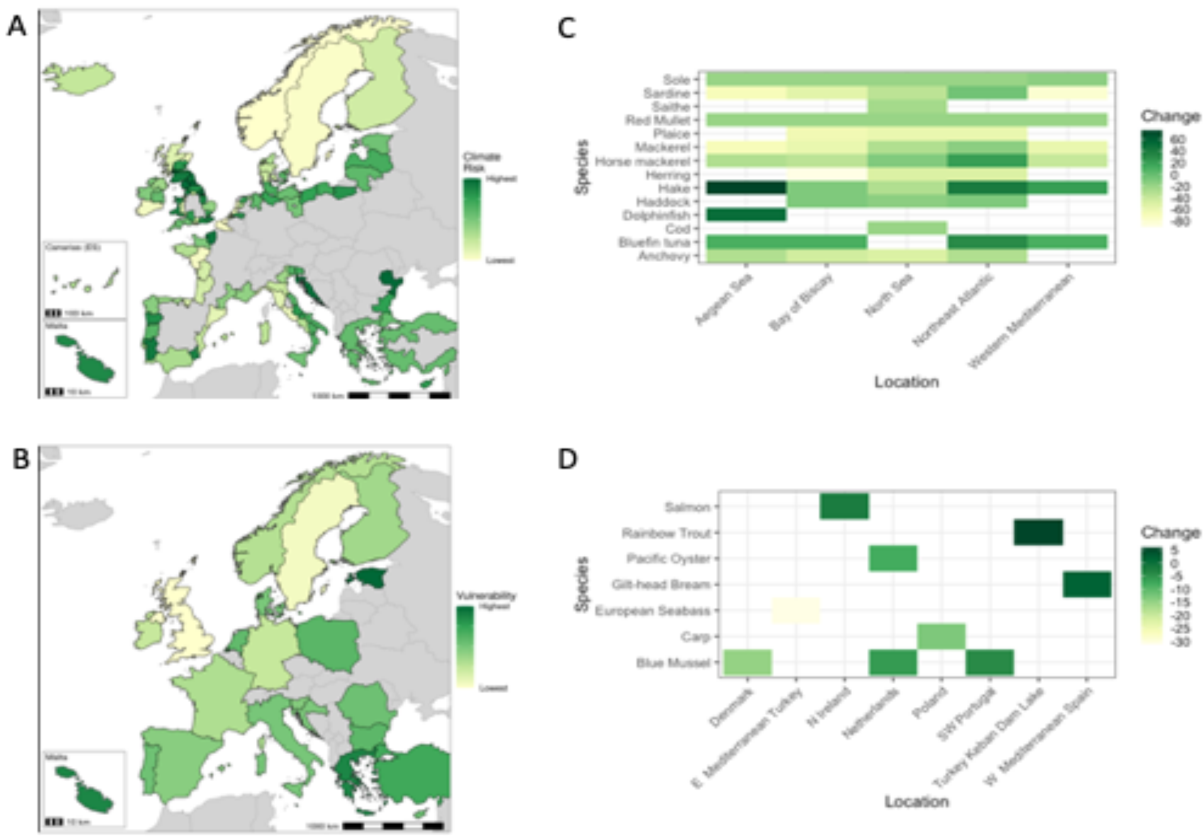


Figure 13.7: A) Climate risk for fisheries in 105 coastal regions across 26 countries (Payne et al., 2020); B) Vulnerability of aquaculture to climate in European countries (Peck et al., 2020); C & D) Differences (%) between projected changes for 1.5°C; and 4°C global warming (Peck et al., 2020), with C) showing changes in population size (i.e. abundance) of major resource species by regional sea, and D) changes in productivity of major aquaculture species by country.

Future climate change will continue to have negative effects on the abundance of most commercially exploited fish stocks in European waters (*medium confidence*). Recent projections, assuming MSY-management, suggest increased losses in abundance of 35% (up to 90% for individual stocks) given between 1.5°C and 4.0°C warming (Payne et al., 2020; Peck et al., 2020) (Figure 13.5.7). Higher trophic level biomass is projected to increase in the Mediterranean Sea under 4°C warming mainly due to increases of small pelagic and thermophilic often exotic species (Moullec et al., 2019). Future risks and opportunities are projected for aquaculture productivity of finfish and shellfish species of economic importance in Europe (Peck et al., 2020) (Figure 13.7).

Ocean acidification (Section 13.4, Chapter 4) will develop into a major risk for marine food production in Europe (*high confidence*). Acidification will affect growth and recruitment of important fish stocks such herring and cod compounding the effect of warming and causing stock declines (Sswat et al., 2018b; Stiasny et al., 2018; Voss et al., 2019), and have negative effects on shellfish production and aquaculture in Europe (*medium confidence*) (Fernandes et al., 2017; Narita and Rehdanz, 2017; Mangi et al., 2018).

13.5.1.4 Forestry and forest products

The most important wood producers in Europe are the Russian Federation and Sweden, with harvests increasing in the EU by approximately 6% after the 2008-2012 recession (*high confidence*) (FAOSTAT, 2020). Climate change affects forest productivity because warming and precipitation interact with other disturbances, such as storms, pests and fire (see 13.3) (*high confidence*) altering the structure and function of European forests (*high confidence*) (Moreno et al., 2018) (13.3). Productivity is currently increasing in response to CO_2 (*medium confidence*) (13.3). While warming and extended growing seasons have positive impacts on forest growth in cold areas (Pretzsch et al., 2014), drought stress impacts old trees and trees growing under high levels of competition (Primicia et al., 2015), especially at high stand volume (Marqués et al., 2018). Over the last two decades, European forests have become increasingly vulnerable to insect pests (Feyen et al., 2020; Senf and Seidl, 2020).

Species-specific responses of trees to drier summers (Vitali et al., 2018) shape regional variability in European forest productivity in response to water and nutrient availability, heat wave and evaporative demand (*high confidence*) (Reyer et al., 2014; Kellomäki et al., 2018). Under SSP1 agricultural land abandonment in NEU and EEU would increase growth of natural woodland, with 2°C warming expansion of bioenergy production would increase especially on abandoned agricultural land in WCEU, while 4°C and SSP3 leads to reduced European forest production (Doelman et al., 2018) (*low confidence*). Assuming acclimation to CO_2, net primary production increases in high latitudes and altitudes and decreases in the Mediterranean region (Reyer et al., 2014) (*medium confidence*). High-end climate scenarios improve yields in areas of Europe with current temperature limitations, but current tree species become climatically stressed (Harrison et al., 2019). Lower levels of precipitation will affect mountain forests in the Mediterranean and continental areas (Bugmann et al., 2017). Hydric stress is exacerbating the incidence and effects from fire and other natural disturbances (13.3), which increases forest productivity declines or cancels out productivity gains from CO_2 (Seidl et al., 2017) (*high confidence).*

13.5.2 Solution Space and Adaptation Options

European food and fibre related adaptations can be both direct, i.e. as a response to climatic conditions in that location, and indirect, e.g., in response to market movements (including demand change) or policy decisions, including those that may be occurring in other locations in Europe or globally.

13.5.2.1 Crops and livestock

Options for crop management adaptations to climate change are available, however their feasibility at large scale or effectiveness, especially of combinations of measures, is rarely assessed (Table 13.6) (*high confidence*).

Yield loss can be reduced by irrigation, e.g., for wheat and maize (Figure 3.5.8), but at the cost of increasing water demand (Siebert et al., 2017). Extensive droughts during the last two decades caused many irrigated systems in southern Europe to cease production (Stahl et al., 2016) indicating limited adaptive capacity to heat and drought (*medium confidence*). Water management for food production on land is becoming increasingly complex due to the need to satisfy other social and environmental water demands (see KR4, 13.10) and is limited by costs and institutional coordination (Iglesias and Garrote, 2015). Agricultural water management adaptation practices include irrigation, reallocating of water to other crops, improving use efficiency, and soil water conservation practices (Iglesias and Garrote, 2015). In-season forecasts of climate impacts on yield, allowing farmers to respond with changes in harvesting or irrigation, have successfully been used in the 2018 drought for European wheat (van der Velde et al., 2018).

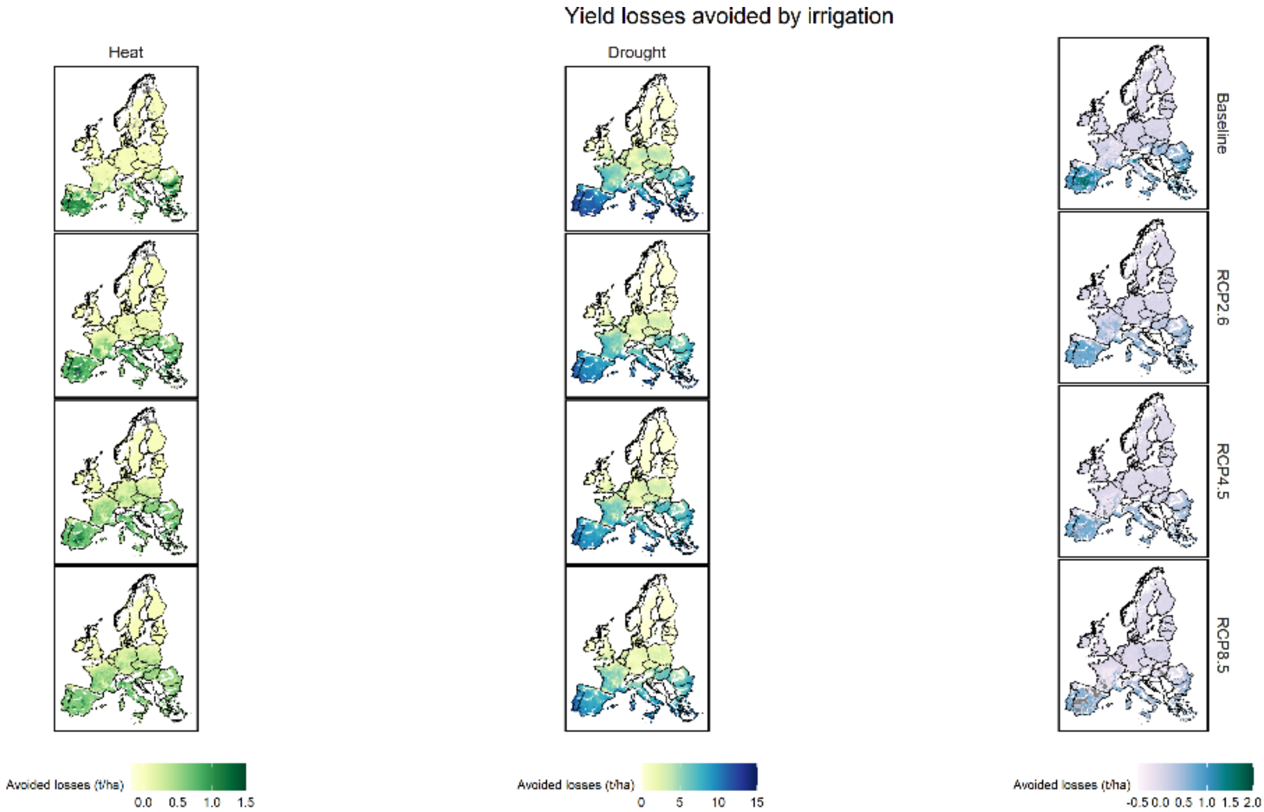


Figure 13.8: Projected yield losses for maize avoided by irrigating all locations, with increasing warming from low (top) to high (bottom). Panel on the left shows avoided yield losses due to heat stress, middle panel avoided yield losses due to drought stress, and right panel additional avoided yield losses arising from the interaction of heat and drought stress. Data represents ensemble median from crop models and HadGEM2_ES GCM (Webber et al., 2018). Results do not consider adaptation in growth seasons.

Management adaptations autonomously used by farmers in response to climate change include changing sowing dates and changes in cultivars (Donatelli et al., 2015). Soil management practices such as crop residue retention or improved crop rotations, generally undertaken as a mitigation option to increase soil carbon sequestration, are not commonly evaluated for European agriculture (Hamidov et al., 2018).

Adaptation practices for livestock systems on European farms commonly focus on controlling cooling, shade provision and management of feeding times (Gauly et al., 2013). These options are used in indoors reared species, e.g., pig and poultry (Gauly et al., 2013), but limited in mountain pastures because of natural constraints and short season length (Deléglise et al., 2019). Response options to insufficient amount and quality of fodder include changing feeding strategies (Kaufman et al., 2017; Ammer et al., 2018), feed additives (Ghizzi et al., 2018), relocating livestock linked to improved pasture management, organic farming (Rojas-Downing et al., 2017; European Environment, 2019), importing fodder and reducing stock (Toreti et al., 2019b). Dairy systems that maximize the use of grazed pasture are considered more environmentally sustainable, but are not fully supported by policy and markets (Hennessy et al., 2020). Genetic adaptation of crops, pasture and animals could be a long-term adaptation strategy (Anzures-Olvera et al., 2019)et al. 2019) but requires tools tailored for specific systems (Deléglise et al., 2019). Furthermore, control strategies for pathogens and vectors include indoor or outdoor rearing and applying new diagnostic tools or drugs (Bett et al., 2017; Vercruysse et al., 2018).

Agro-ecological systems are considered an adaptation option to a range of climate change impacts (Aguilera et al., 2020), and rely on ecological process (e.g., soil organic matter recycling and functional diversification) to lower inputs without impacting productivity (Cross-Chapter Box NATURAL in Chapter 2). High frequency rotational grazing and mixed livestock systems are agro-ecological strategies to control pathogens (Aguilera et al., 2020). Agroforestry, integrating trees with crops (silvoarable), livestock (silvopasture), or both (agrosilvopasture), can enhance resilience to climate change, e.g., by reducing impact of extreme weather events, but implementation in Europe needs improved training programs and policy support (Hernández-Morcillo et al., 2018) (*high confidence*).

Implementation of adaptation at farm level depends on the type of climate impact, the size and economic situation of the farm, and the cultural background and education of the farmer. Technological innovations including "smart farming" and knowledge training can strengthen farmers' responses to climate impacts (Deléglise et al., 2019; Kernecker et al., 2019), although strong belief in "technosalvation" by farmers (Ricart et al., 2019) can reduce the solution space and timing of adaptation options. Agricultural policy, market prices, new technology and socio-economic factors play a more important role in short-term farm-level investment decisions than climate change impacts (Juhola et al., 2016; Hamidov et al., 2018) (*high confidence*).

Effective policy guidance is needed to increase the climate-resilience of agriculture (Spinoni et al., 2018; Toreti et al., 2019b). Financial measures that would be beneficial, include simplifying procedures for obtaining subsidies and insurance premiums and reduction of interest rates on agricultural loans (Garrote et al., 2015; Iglesias and Garrote, 2015; Zakharov and Sharipova, 2017; Hamidov et al., 2018; Wiréhn, 2018). The EU's Common Agricultural Policy (CAP) has increasingly focused on environmental outcomes, and since 2013 the EU Strategy on Adaptation has aimed to contribute to climate-resilience by providing member states support to develop adaptation strategies (Alliance, 2018). However, the CAP is viewed as not yet fully addressing environmental outcomes or providing effective measures for climate adaptation (Leventon et al., 2017; Pe'er et al., 2020). Limits to European farm-level adaptation include lack of resources for investment, political urgency to adapt, institutional capacity, access to adaptation knowledge and information from other countries (European Environment, 2019).

13.5.2.2 Aquatic food

Changes in spatial distribution of fish stocks will be a source of conflict in fisheries management in Europe (*medium confidence*), as demonstrated by the case of the North East Atlantic mackerel (Spijkers and Boonstra, 2017). The Relative Stability Principle applied in the CFP where total allowable catch is split among countries using a fixed allocation based on catches of member states during the 1970s is limiting the adaptive capacity of European fisheries, which is further complicated by the unknown effects of the Brexit (Harte et al., 2019; Baudron et al., 2020).

There is a lack in adaptation planning towards climate-ready fisheries and aquaculture in all parts of Europe, especially accounting for the expected reduced landings of traditional target species and in preparation for a new portfolio of resource species (Blanchet et al., 2019). High-level adaptation strategies have been developed, but examples of implementation and actionable decision making to address climate change impacts are lacking (Bell et al., 2020).

The EU Common Fisheries Policy (CFP) aims at making fisheries and aquaculture environmentally, economically and socially sustainable, but is challenged by the lack of coordinated efforts among European countries, and by the non-inclusion of fisheries and aquaculture in national action plans (Baudron et al., 2020). The reformed CFP has the goal to rebuild fish stocks to maximum sustainable yield (MSY) levels by 2020, but progress is limited (Froese et al., 2018; Stecf, 2019).

13.5.2.3 Forests

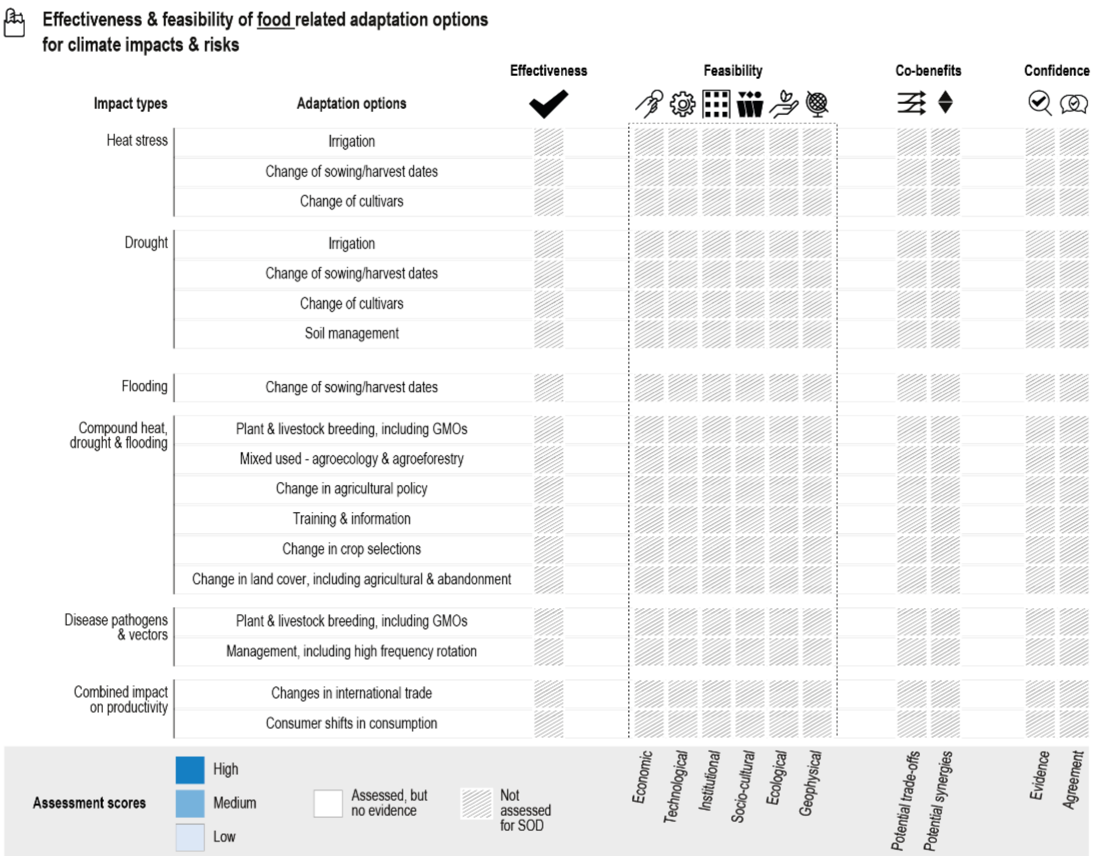
Successful adaptation requires short- and long-term strategies that focus on enhancing the resilience of European forests, especially through altering the tree species composition (Zubizarreta-Gerendiain et al., 2017; Pukkala, 2018). Forest management has been adopted as a frequent strategy to cope with drought, reduce fire risk, and maintain biodiverse landscapes and rural jobs (Hlásny et al., 2014; Fernández-Manjarrés et al., 2018). Greater diversity of tree species reduces vulnerability to pests and pathogens (Felton et al., 2016) and increases resistance to natural disturbances (Jactel et al., 2017; Pukkala, 2018; Pardos et al., 2021) (*high evidence*). Depending on forest successional history (Sheil and Bongers, 2020), tree composition change can increase carbon sequestration (Liang et al., 2016), biodiversity and water quality (Felton et al., 2016) (*high evidence*). Conservation areas can also help climate change adaptation by keeping intact the forest cover and protecting their biodiversity (Jantke et al., 2016) (*low confidence*).

Reforestation reduces warming rates inside forests Zellweger, 2020, Forest microclimate dynamics drive plant responses to warming} and consequently the number of extremely warm days (Sonntag et al., 2016), with impacts for controlling natural disturbances such as fires (*high confidence*). Various active management approaches can limit the impact of fires (see 13.3) on the productivity of forest, including fuel reduction management, prescribed burning, changing from conifers to deciduous, less flammable species, and recreating mixed forests (Feyen et al., 2020). Agroforestry can also reduce the spread of fire. The CAP is limiting tree planting, as the introduction of isolated trees, forest strips and trees on hedgerows leads to losses of Pillar I payments (Mosquera-Losada et al., 2018).

13.5.2.4 Demand and trade

An increasing globalized food system makes European nations sensitive to supply chain disturbances in other parts of the world, but also provides capacity to adapt to production shifts within Europe through changes in international trade (Section 13.9.1) (Alexander et al., 2018; Challinor et al., 2018). Consumer demand for food and timber products can also adapt to productivity changes created by climate changes. Consumer demand changes may be mediated by price (e.g., in response to production changes), reflect changes in preferences (e.g., towards plant-based foods motivated by environmental, ethical or health concerns), or reductions in food waste (Alexander et al., 2019; Willett et al., 2019) (*high confidence*). Although mitigation potentials of dietary changes have received increasing attention, evidence is lacking on potential for adaptation through changes in European food consumption and trade, despite these socio-economic factors being a stronger driver for change than climate (Harrison et al., 2019). Calls are increasing across Europe for sustainable and resilient agri-food systems acknowledging interdependencies between producers and consumers to deliver healthy, safe and nutritional foods and services (Venghaus and Hake, 2018) (Section 13.7).

Table 13.6: [PLACEHOLDER FOR FINAL DRAFT: to be updated] Effectiveness and feasibility of the main adaptation options for food systems in Europe. The assessment steps are described in Figure 13.A.1



13.5.3 Knowledge Gaps

Aggregated projections of impacts, especially of combined drivers, are still rare despite many physiological papers on species specific response to warming in all food sectors (*high confidence*). This is specifically true for scenarios that consider land use change and population growth, though Agri SSPs are currently being (Mitter et al., 2019)). Effectiveness of adaptation options is predominantly qualitatively mentioned but not assessed (*high confidence)*(Ewert et al., 2015; Holman et al., 2018; Müller et al., 2020)). Adaptation planning needs better modelling and scenario development including improved coupled nature-human interactions, e.g., with more realistic representation of behaviours beyond economic rationality and 'bottom-up' autonomous farmer adaptations, as well as greater stakeholder involvement.

Coverage of impacts and adaptation options in Europe are biased towards the EU28 and have gaps within EEU, despite dramatic changes in land use over the recent decades in Russia and Ukraine (*high confidence*). Large land reserves in Russia and Ukraine that were abandoned in the 1990 have the potential to increase production and export of agricultural products, especially wheat, meat and milk, but there is large uncertainty due to the lack of projections (Swinnen et al., 2017).

Crop modelling bias towards cereals, and specifically wheat and maize, overlooking the need for quantitative assessment of impacts of climate change on fruit and vegetables, especially for temperate regions in Europe (Bisbis et al., 2018). The impacts of climate change for European agriculture include a lack of understanding of fundamentals such as irrigation needs and the impact of CO_2 and O_3 on a wide range of variants as assessments tend to focus on individual species and processes (Challinor et al., 2016b; Webber et al., 2016) (*high confidence*).

There is a lack of actionable adaptation strategies for European fisheries. Knowledge gaps include adaptive capacities of local fishing communities to a new mix of target species and the consumer acceptance of the product. Increased knowledge on the effects on freshwater fisheries and their resources is also needed.

13.6 Cities, Settlements and Key Infrastructure

13.6.1 Observed Impacts and Projected Risks

Urban areas in Europe offer home to 547 million inhabitants, corresponding to almost 74% of the total European population (UN/DESA, 2018). In the EU-28, 39% of the total population and 41% of the workforce lives in metropolitan regions (i.e. areas with at least one million inhabitants), where 47% of the total GDP is generated (Eurostat, 2016). This section also covers energy and transport networks as these are interconnected with urban areas and are key for livelihood and economic prosperity, as well as tourist, industrial and business structures and activities which are also part of key infrastructure.

13.6.1.1 Energy systems

The energy sector in Europe already faces impacts from climate extremes. Significant reductions or even interruptions of power supply have been observed during exceptionally dry and/or hot years of the recent 20-year period, as for example in France, Germany, Switzerland and UK during the extremely hot summer of 2018, which led to water cooling constraints on power plants (van Vliet et al., 2016c; Abi-Samra, 2017; Vogel et al., 2019). Heating degree days decreased and cooling degree days in Europe increased during 1951-2014, with more prominent trends after 1980 (De Rosa et al., 2015; Spinoni et al., 2015; EEA, 2017a; Krakovska et al., 2019).

New studies reinforce the findings of AR5 on future risks for thermoelectric power and on the division between Northern and Mediterranean Europe regarding risks for hydropower (Table 13.7). The wind power potential is projected to display both increasing and decreasing trends, with *medium confidence* on decreases in parts of western Mediterranean, particularly beyond 3ºC (Table 13.7). Observed reductions of surface wind speeds at several locations during 1979-2016 (Frolov et al., 2014; Perevedentsev and Aukhadeev, 2014; Tian et al., 2019) support these decreasing trends. The future wind fleet's configuration will affect the spatial and temporal variability of wind power production (Tobin et al., 2016), and total backup energy needs in Europe could increase by 4-7% by 2100 (Wohland et al., 2017), with potentially larger seasonal changes (Weber et al., 2018b). There is *limited new evidence* on solar power potential, projecting a decrease in Northern Europe and contradictory signs of change in the rest of Europe (Table 13.7).

Table 13.7: Projected climate change risks for energy supply in Europe by 2100

Sub-region	Trend/ Confidence	References	Remarks
Wind power potential			
NEU	↓ ↑ *	(Davy et al., 2018; Moemken et al., 2018; Tobin et al., 2018; Solaun and Cerdá, 2019)	Increases particularly beyond 2°C warming. Reductions in parts of Scandinavia. Reductions over extended areas in summer and increases over most areas in winter.
WCE	↓ ↑ *	(Carvalho et al., 2017b; Davy et al., 2018; Devis et al., 2018; Moemken et al., 2018; Tobin et al., 2018)	Projected changes differ across studies, models, and locations in terms of sign and magnitude. Reductions over extended areas in summer and increases over many areas in winter.
MED	↓ ↑ **	(Reyers et al., 2016; Tobin et al., 2016; Carvalho et al., 2017b; Davy et al., 2018; Devis et al., 2018; Moemken et al., 2018; Tobin et al., 2018; Katopodis et al., 2019; Solaun and Cerdá, 2020)	Reductions (possibly up to 15%) particularly beyond 3oC warming. Under 1.5°C warming, increases up to 5% over some islands in the south-eastern Aegean Sea have been estimated. No agreement on the sign of change in summer, while there is *medium confidence* on decreases in winter.
Off-shore	↑ **	(Koletsis et al., 2016; Davy et al., 2018; Moemken et al., 2018; Weber et al., 2018a; Katopodis et al., 2019)	Increases over most of the Aegean and Baltic Seas beyond 2°C warming. Increasing probabilities and persistence of high winds over these seas could create new opportunities.
Solar power potential			
NEU	↓ *	(Jerez et al., 2015; Wild et al., 2015; Bartok et al., 2017; Tobin et al., 2018; Muller et al., 2019)	Reductions in the entire domain of -10% over the largest part beyond 3°C warming, with higher reductions (up to -30%) in winter. Under 2°C warming, reductions up to -6%.
WCE, EEU, MED	↓ ↑ *		Disagreement on sign of change due to different signs of climate models in terms of cloud cover.
Hydropower potential			
NEU	↓ ↑ ***	(van Vliet et al., 2016a; van Vliet et al., 2016b; Tobin et al., 2018)	Increases up to +20% under +3°C warming. Magnitude differs significantly among models. Under 2oC and 1.5°C warming, increases <15% and <10% respectively. Extremely high water inflows to dams may increase flooding risks for plant and nearby settlements (Chernet Haregewoin et al., 2014).
MED	↓ ***		Reductions up to -40% under 3°C warming. Magnitude of change differs significantly among models. Under 2°C and 1.5°C warming, reductions below -10% and -5% respectively.
WCE	↓ ↑ *		Increases up to 20% in many models, small decreases (up to 5%) in some others.
Mountains	↓ ↑ *	(Anghileri et al., 2018; Bombelli et al., 2019)	For hydropower in the Alps, both increases and decreases of electricity production under different warming levels.
EEU	↑ *	(Akentieva et al., 2014)	Risks of flooding for the plant and nearby settlements in case of extremely high water inflows (Porfiriev et al., 2017).
Bioenergy [PLACEHOLDER FOR FINAL DRAFT: more information on sub-regions to be added]			
MED	↓ *	(EEA, 2019a).	Further expansion of energy crop production in water-scarce areas over Europe may be limited due to water-related constraints.

Sub-region	Trend/ Confidence	References	Remarks
Thermoelectric power			
WCE	↓ ***	(van Vliet et al., 2016a; Tobin et al., 2018)	Freshwater cooling plants (particularly with open-loop systems) will face constraints due to higher water temperatures and reduced summer streamflow.
EEU	↓ **	(Porfiriev et al., 2017; Cronin et al., 2018; Klimenko et al., 2018).	Increasing temperatures reduce the efficiency of power plants, with a loss in power output by 0.3-0.6% per +1°C.
MED	↓ ***	(van Vliet et al., 2015; van Vliet et al., 2016a; van Vliet et al., 2016b; Behrens et al., 2017; Payet-Burin et al., 2018)	Under projected capacities by 2030, more regions will experience some reduction in power availability due to water scarcity. In 2050, reductions of usable capacity by ≥15% under RCP8.5 and by <10% under RCP2.6 (with summer reductions possibly reaching -30% in some locations). Climate pressures on water in other sectors will augment constraints.
Thermoelectric power with carbon capture and storage (CCS)			
All	↓ **	(Byers et al., 2016; Murrant et al., 2017; EEA, 2019a).	As CCS increases cooling water requirements, water scarcity may become an additional constraint to onshore CCS in some regions.

* *low confidence,* ** *medium confidenc*e, *** *high confidence*. NEU, WCE, EEU, MED: Northern, Western Central, Eastern, and Mediterranean Europe respectively.

Regarding electricity transmission and distribution, the welfare loss from an hour of power outage affecting entire countries in the summer under the A1B scenario could increase by about 20% in 2055 and 35% in 2089 compared to 2010 (Cohen et al., 2018a).

On energy demand, in line with AR5, new studies estimate a significant southwest-to-northeast decrease of heating degree days by 2100 (mainly in northern Scandinavia and northern Russia), and a smaller north-to-south increase of cooling degree days (Porfiriev et al., 2017; Spinoni et al., 2018). Given present population numbers, total energy demand would decrease in almost all Europe, whereas considering Eurostat's population projections demand would increase in about half of them (Spinoni et al., 2018). There is *medium confidence* that peak load will increase in Mediterranean and decrease in Northern Europe (Damm et al., 2017; Wenz et al., 2017; Bird et al., 2019), while the sign and magnitude for the other subregions are uncertain, particularly under RCP4.5. Under RCP8.5, a shift of peak load from winter to summer in many countries is possible (Wenz et al., 2017). This, together with water-cooling constraints for thermal power, may challenge the stability of electricity networks during heatwaves (EEA, 2019a). Technological factors and electrification influence significantly the temperature sensitivity of electricity demand and consequently risks (Damm et al., 2017; Wenz et al., 2017; Cassarino et al., 2018; Figueiredo et al., 2020).

13.6.1.2 Transport

New research on future climate risks refers mainly to infrastructure and much less to transport flows and disruptions. In parts of Western Central and Northern Europe, heatwaves in 2015 and 2018 caused road melting, railway asset failures, and speed restrictions to reduce the likelihood of track buckling (Ferranti et al., 2018; Vogel et al., 2019).

Future sea-level rise (section 13.2) may disrupt port operations and adversely impact hinterland and foreland, mainly in parts of Northern and Central Europe (Christodoulou et al., 2018). Changes of waves agitation could increase non-operability hours of some ports of the Mediterranean Europe beyond 2ºC warming (Sierra et al., 2016; Camus et al., 2019). Infrastructure in the Rhine River Delta is particularly prone to flooding, with a low water level critical threshold risking to be crossed in consecutive years beyond 2ºC warming (van Slobbe et al., 2016).

Risks of rutting and blow-ups of roads (particularly in low altitudes) due to high temperatures are expected to increase (*medium confidence*) (Frolov et al., 2014; Matulla et al., 2018; Yakubovich and Yakubovich, 2018). There is some evidence since AR5 on increasing landslide risks in Western Central and

Mediterranean Europe beyond a 2ºC warming, threatening road networks (Schlogl and Matulla, 2018; Rianna et al., 2020). In Eastern Europe, the higher number of freezing-thawing cycles of construction materials will increase risks for roads (Frolov et al., 2014; Yakubovich and Yakubovich, 2018).

Current flood risk for railways could double or triple under 1.5-3°C warming, particularly in Western Central Europe, increasing public expenditure for rail transport in Europe by €1.22 billion annually under 3°C warming and no adaptation (Bubeck et al., 2019). Thermal discomfort in urban underground railways may increase, even at a high level of cooling (Jenkins et al., 2014a).

The number of airports vulnerable to inundation from sea-level rise and storm surges may double between 2030 and 2080 without adaptation, especially close to the North Sea coast (Christodoulou and Demirel, 2018). Warming could require some weight restrictions for large aircraft after 2060 under RCP8.5 in France, UK and Spain (Coffel et al., 2017).

13.6.1.3 Business and industry

European business and industry sectors are directly affected by changes in temperature, precipitation, and extreme events like flooding, storm and drought but also indirectly via changes along the global value chain (Section 13.9.1). Climate-induced physical risks arise for many industrial sectors (Gasbarro and Pinkse, 2016; Meinel and Schule, 2018), by affecting a firm's production processes, labour productivity (Section 13.7) and assets, or leading to shortages in supplies, infrastructure disruptions or changes in customer consumption patterns (Weinhofer and Busch, 2013; Schiemann and Sakhel, 2018; TEG, 2019). The European financial and insurance sector is affected by climate change both directly (e.g., through impacts on their premises and the value of their assets) and indirectly through impacts on their customers and financial markets (Bank of England, 2015; Georgopoulou et al., 2015; Battiston et al., 2017; TCFD, 2017; Bank of England, 2019; de Bruin et al., 2020; Monasterolo, 2020).

Compared to mitigation policy risks, such as the EU-ETS, European companies perceive physical climate risks as less relevant (Sakhel, 2017) and recommendations on financial disclosure of and requirements for supervision of physical climate risks are only emerging recently (D'Orazio and Popoyan, 2019; de Bruin et al., 2020; Feridun and Güngör, 2020; Monasterolo, 2020). Opportunities may also arise, such as a market for climate services (Section 13.11).

13.6.1.4 Tourism

Snow cover duration and snow depth in the Alps decreased since the 1960s (Klein et al., 2016; Schöner et al., 2019). Though snowmaking reduced the vulnerability of ski tourism (Abegg and Steiger, 2016; Falk and Vanat, 2016; Falk and Lin, 2018), the number of skiers to French resorts at low elevations during the extraordinary warm/dry winters of 2006/2007 and 2010/2011 was 26% and 12% lower respectively (Falk and Vanat, 2016).

New studies on winter tourism support the AR5 findings. Due to the significant drop of natural snow reliability (Demiroglu et al., 2016; Damm et al., 2017; Campos Rodrigues et al., 2018; Steiger and Abegg, 2018), under 2°C warming the operation of low altitude resorts without snowmaking will likely be discontinued, while beyond 3°C snowmaking will be a necessary but not always sufficient condition for most resorts in the Pyrenees, the Alps and the Aosta Valley (Pons et al., 2015; Joly and Ungureanu, 2018; Spandre et al., 2019b). Increased investment and operational costs will adversely affect the financial stability of small resorts in favour of financially robust large resorts at high elevations with access to snowmaking (Steiger and Abegg, 2014; Pons et al., 2015; Falk and Vanat, 2016; Spandre et al., 2016; Joly and Ungureanu, 2018; Moreno-Gené et al., 2018; Scott et al., 2019; Steiger and Scott, 2020). Increasing snowmaking will also significantly increase water and energy consumption, particularly under a 3°C warming, as in the Alps (Steiger and Abegg, 2014; Spandre et al., 2019a).

Climatic conditions for summer tourism under a 1.5°C and 2°C warming are projected to improve over Europe from May to October and less from June to August, except for the Mediterranean Europe on which there is no agreement (Dubois et al., 2016a; Georgopoulou et al., 2018; Martínez-Ibarra et al., 2019). Tourists' high tolerance to heat and/or low tolerance to rain found by some European studies affects the perceived comfort (Dubois et al., 2016a; Georgopoulou et al., 2018; Martínez-Ibarra et al., 2019). Risks are increasing for Mediterranean Europe under SSP3 (Koutroulis et al., 2018). The amenity of European beaches may decrease as a result of sea-level rise amplifying coastal erosion and inundation risks along the coasts, although less in Scandinavia (Ebert et al., 2016; Toimil et al., 2018; Lopez-Doriga et al., 2019) (see also Section 13.2 and WGI AR6 Section 12.4.5).

Knowledge on the economic consequences of climate change on European tourism is limited (Section 13.10.2). Under a 2°C warming, annual economic losses of 15 Billion Euros were estimated, with losses for Mediterranean Europe and the Alps and gains for northern and Western Central Europe (Ciscar et al., 2014). Climate-induced impacts on transport networks and modal shifts can further affect the exposure and vulnerability of tourism flows.

13.6.1.5 Built environment, settlements and communities

Further shifts of population to cities and coastal areas will increase assets at risk (Section 13.2). The percentage of population in Europe residing in urban areas is projected to increase from 74% in 2015 to 84% in 2050, corresponding to approximately 52 million new urban residents (UN/DESA, 2018), although these highly depend on the SSP scenarios. Most of this increase will take place in northern and western Central Europe, particularly in the UK and France. Moreover, 32% of 571 European cities show a medium to high or relatively high vulnerability against heatwaves, drought and floods (Tapia et al., 2017). Climate change will significantly augment risks for several cities, particularly beyond 3 °C warming (Figure 13.9).

Figure 13.9: Climate hazards, exposure and vulnerability of the 65 largest cities, in Western Central (green dots), Mediterranean (red dots) and Northern Europe (blue dots) with respect to pluvial flooding, heatwaves and drought. Green, grey and orange shading indicate low, moderate and high risks correspondingly. Values for vulnerability derive from literature (Tapia et al., 2017), transformed by the authors into a 0-100 scale. Figures show changes between 'Mid future' (2040-2060)/ 'Far future' (2080-2100) and the baseline (1995-2014). P99: 99th percentile of daily precipitation. TX35: number of days with mean temperature above 35oC. DF: drought frequency. [PLACEHOLDER FOR FINAL DRAFT: to be updated]

13.6.1.5.1. Risks from coastal, river and pluvial flooding

New studies increase confidence in AR5 statements that floods and flood damages will increase in coastal areas due to sea level rise and changing social and economic conditions (Mokrech et al., 2015) (Section 13.2). Except for areas affected by land uplift (e.g., in Scandinavia and parts of Scotland), it is projected that further adaptation will be required to maintain risks at the present level for most coastal cities and settlements (Haasnoot et al., 2013; Ranger et al., 2013; Malinin et al., 2018; Hinkel et al., 2019; Umgiesser, 2020).

There is *high agreement* that sea-level rise will become a major threat to urban beaches and coastal peri-urban settlements without adaptation by mid-21st century (Hinkel et al., 2013) (Cross-Chapter Box SLR in Chapter 3). Neglecting uncertainties on future sea-level rise (WGI AR5 Chapter 9), tides, waves, currents at the scale of the continental shelf, and precipitation and runoff at river-basins scales may mislead adaptation (Hinkel et al., 2019; Haasnoot et al., 2020b).

Strong urbanization, resulting to growth of impervious surfaces in urban areas of Western Central and Eastern Europe, can have comparable effects on the exposure of cities to pluvial flooding with some climate change scenarios (Thieken et al., 2016; Skougaard Kaspersen et al., 2017).

13.6.1.5.2 Risks from heatwaves, cold waves and drought

Heatwave days and long heatwaves increased in most capitals during 1998-2015 compared to 1980-1997 (Morabito et al., 2017). As a result, indoor overheating and reduced outdoor thermal comfort, often coupled with urban heat island, have already impacted European cities (see also Section 13.7.1). In the summer of 2018, many cities suffered from heatwaves attributed to climate change (Vogel et al., 2019). In 2010, Moscow suffered from a 44-day heatwave, the worst on record in Europe, with about 11,000 excess deaths (Russo et al., 2015; Shaposhnikov et al., 2015).

Heatwaves are likely to become a major threat not only for Mediterranean but also for Western Central and Eastern European cities, which will face the largest temperature increases (Russo et al., 2015; Guerreiro et al., 2018; Lorencova et al., 2018; Smid et al., 2019). Under RCP8.5-SSP3 and by 2050, about half of Europeans will be under very high heat stress in summer (Rohat et al., 2019). The urban heat island effect will further increase urban temperatures up to 6-10°C under RCP8.5 (Estrada et al., 2017). There is *high confidence* that overheating during summer in buildings with insufficient ventilation and/or solar protection will increase significantly (Jenkins et al., 2014a; Hamdy et al., 2017; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019; Shen et al., 2020). Highly insulated buildings according to present building standards across Europe will be more vulnerable to overheating than others, particularly under high warming levels, unless proper ventilation and other adaptation measures are applied (Williams et al., 2013; Virk et al., 2014; Mulville and Stravoravdis, 2016; Fosas et al., 2018; Ibrahim and Pelsmakers, 2018; Salem et al., 2019; Tian et al., 2020). Cities in northern and Western Central Europe are more vulnerable due to limited solar shading and fewer air conditions installed (Ward et al., 2016; Thomson et al., 2019). Cooling energy demand in Mediterranean buildings has been projected to increase by 81-104% by 2035 and by 91-244% after 2065 depending on climate change scenarios (Cellura et al., 2018), while increases of 31-73% by 2050 and by 165-323% by 2100 were estimated for buildings in Northern Europe (Dodoo and Gustavsson, 2016).

Cold waves under RCP8.5 will not represent an effective threat for European cities at the end of the century, and only a marginal hazard in mid-century (Smid et al., 2019).

Under RCP8.5 almost all cities would exceed the historical maximum 12-month drought severity index of the past 50-years (on drought risks see also Section 13.2) and 30% will have at least 30% probability of exceeding this maximum every month (Guerreiro et al., 2018), with potential adverse effects on the operation of municipal water services (Kingsborough et al., 2016). The combination of high temperatures, drought, and extreme winds, potentially coupled with insufficient preparedness and adaptation, may amplify the damage of wildfires in peri-urban environments.

13.6.1.5.3 Risks from thaw of permafrost

Increasing temperatures in Northern Europe and the Alps lead to accelerated degradation of permafrost, negatively affecting the stability of infrastructures (Stoffel et al., 2014; Beniston et al., 2018 trends, and future challenges; Duvillard et al., 2019). In the Caucasus, glacial mudflows due to permafrost degradation and modern tectonic processes pose a significant danger to the infrastructure of the mountain territory (Vaskov, 2016). In the last 30 years, the permafrost temperature in the European part of the Russian Arctic has increased by 0.5-2.0°C, and consequent damages in buildings, roads and pipelines, particularly in Vorkuta city, required significant expenditure for stabilizing soils (Porfiriev et al., 2017; Konnova and Lvova, 2019). Under RCP8.5, the bearing capacity for infrastructure in the permafrost region of the

European Russia could decrease by 32-75% by mid-century and by 95% by 2100, potentially affecting settlements in Murmansk, Arkhangelsk Oblast, Komi Republic and Nenets Autonomous Okrug (Shiklomanov et al., 2017; Streletskiy et al., 2019). Increasing number of cycles of freezing and thawing wall material, observed in the European part of Russia, leads to accelerated aging of building envelopes (Frolov et al., 2014).

13.6.2 Solution Space and Adaptation Options

Monetary assessments of future damages from climate extremes on critical infrastructures show rapidly escalating figures by 2080s (Figure 13.10), by an order of seven compared to the baseline (Forzieri et al., 2018), highlighting the need for adaptation.

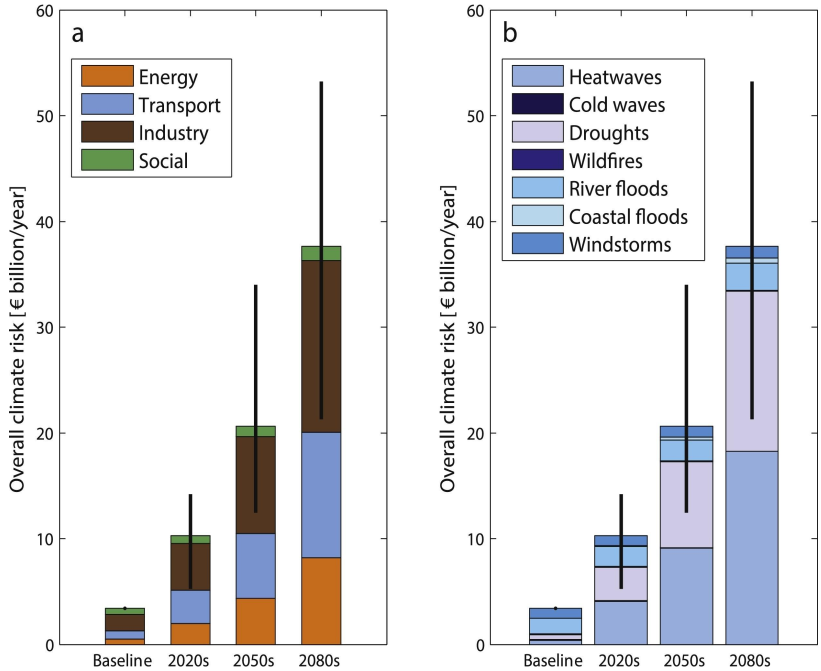


Figure 13.10: Overall climate hazard risk to critical infrastructures aggregated at European (EU+) level under the SRES A1B scenario (Forzieri et al., 2018). Baseline: 1981-2010. 2020s: 2011–2040. 2050s: 2041–2070. 2080s: 2071–2100.

13.6.2.1 Current status of adaptation

There is new evidence on increasing adaptation planning in cities, settlements and key infrastructure, but less on implemented adaptation (Table 13.8; Box 13.3).

Table 13.8 Present status of adaptation in cities, settlements and key infrastructure in Europe

	General commitments / Adaptation Plans	Implemented adaptation actions
Cities	➔ Increasing number of cities. ➔ Of 6900 European cities in the Covenant of Mayors for Climate & Energy, 1080 have set commitments for adaptation, 190 of these have submitted adaptation plans and 106 have their results monitored. ➔ Most urban adaptation plans include ecosystem-based measures (but often with insufficient baseline information and lack of convincing implementation actions).	➔ Large cities are in the process of implementation (e.g., Helsinki, Copenhagen, Rotterdam, Barcelona, Madrid, London). ➔ Many cities have implemented measures potentially supporting adaptation but not labelled as such. ➔ Current climate policies implemented at city-scale are primarily addressing mitigation and, to a lesser extent adaptation. ➔ Increasing use of NbS to address urban heating and the discontinuity of the urban water cycle due to surface sealing and limited infiltration.

	General commitments / Adaptation Plans	Implemented adaptation actions
Energy	➔ 29 countries (in place in 14 and in progress in 15). ➔ Few countries have considered specific adaptation actions (mostly preparatory) in their national or energy-specific risk assessments.	➔ 11 countries (actions implemented in 5 and in progress in 6) ➔ DSOs, electricity, and energy companies, focusing on adaptation of transmission lines, water cooling, dams for avoiding flooding during intense precipitation events, harbours to avoid flooding and secure fuel supply.
Tourism	➔ Legally binding consideration of climate change when constructing new tourism units (e.g., the 2016 French Mountain Act).	➔ 18-67% of ski slopes (67% in Austria, 39% in Switzerland, 18% in Bavaria-Germany, 20% in French Alps, 45% in Spain. ➔ Resorts implementing nocturnal skiing (e.g., Spain) and offering other snow-based activities. Transformation to all-year mountain resorts (e.g., 70% of Spanish ski resorts).
Transport	➔ Only 10 countries have started coordination activities or identified adaptation measures. ➔ An integrated, trans-modal approach to adaptation is lacking. ➔ Low mainstreaming of adaptation within transport planning and decision-making.	➔ Only in 5 countries. ➔ Majority of actions are preparatory. ➔ Actions mostly focus on infrastructure and much less on services.
	➔ Some action is undertaken in the public and private sector, e.g., revised manuals/guidelines/ protocols to consider climate change impacts and extreme events (e.g., Deutsche Bahn, Norwegian Public Roads Administration).	➔ Some public and private actors are moving faster: new railway drainage standards (Network Rail/ UK), prediction of adverse weather events (Spanish rail service operator), measures against coastal flooding (Copenhagen Metro), measures for sea level rise (Rotterdam port and France).
Banking and insurance	➔ Recommendation of the High Level (HLEG) Expert Group on Sustainable Finance that the European Commission endorses and implements the guidelines provided by the Task for on Climate-Related Financial Disclosure) ➔ Central banks and supervisors establish a Network for Greening the Financial System; several European central banks take a leading role in this network	➔ Implementation of HLEG recommendations as regulation by banking supervision bodies in UK, France, Netherlands, Norway ➔ Development of different tools (stress testing, scenario analysis, value at risk) by climate service providers

Green shading: adaptation is well-established, Orange shading: adaptation is advancing, Grey shading: low adaptation. Sources: a) Cities (Reckien et al., 2015; EEA, 2016b; Geneletti and Zardo, 2016; Davis et al., 2018; Gedikli and Balaban, 2018; Reckien et al., 2018b; CoM, 2019), b) Energy (EEA, 2019a), c) Tourism (Damm et al., 2017; Campos Rodrigues et al., 2018; Joye, 2018), d) Transport (Battiston et al., 2017; D'Orazio and Popoyan, 2019; de Bruin et al., 2020; Feridun and Güngör, 2020).

Although urban adaptation is well underway, many small and economically weak (i.e. with low GDP/capita) or vulnerable cities lack adaptation planning (Reckien et al., 2015; EEA, 2016b). Also, while almost all large northern and western municipalities report implemented actions at least in one sector, this is not the case for 32% of Mediterranean and eastern municipalities (Aguiar et al., 2018). In the UK, the requirement to compile urban adaptation plans has been a significant driver for their rapid development (Reckien et al., 2015). The availability of funding for adaptation is also crucial for plan development (see Section 13.11.2). Network membership (e.g., ICLEI, C40/Covenant of Mayors) is an important driver for city planning and transfer of best practices

Although large municipalities usually fund the implementation of their adaptation plans, smaller and less populated municipalities in Mediterranean and Eastern Europe depend on international/ national funding which is often limited. The proportion of cities with adaptation strategies is much lower in countries without or recently produced national adaptation policies (Heidrich et al., 2016). Evidence from cities also shows that only 29% of local adaptation plans are mainstreamed, which could reduce the effectiveness of implementing adaptation (Reckien et al., 2019).

13.6.2.2 Adaptation options as a function of who is adapting

Much adaptation for cities and key infrastructure in Europe is still driven by governments who play an important role in enabling and accelerating societal adaptation across sectors and levels (Section 13.11.2). At present, almost all European countries have included the energy sector into their national climate change impact, vulnerability and risk (CCIV) assessments and their National Adaptation Strategies or Plans (EEA, 2019a). Conflicts between actors in transport where different modes often compete for public funds, and political priorities for specific modes have been shown to influence implemented adaptation (Rotter et al., 2016).

Private sector adaptation is increasing (Section 13.11.3), though not in a uniform rate across all sectors. Large national and multinational companies, and companies regulated by mitigation policy are first movers in corporate adaptation (Averchenkova et al., 2016a; Schiemann and Sakhel, 2018), while small and medium sized enterprises often lack knowledge on climate risks and adaptation options (Herrmann and Guenther, 2017; Halkos et al., 2018).

Intra-community networking contributes in building community resilience and supporting individual adaptation, as in households undertaking adaptation measures to power outages (Ghanem et al., 2016).

13.6.2.3 Adaptation options as a function of impacts

Examples of adaptation options in Europe for reducing climate change risks are presented in Figure 13.11, and in detail in Table 13.A.3. An assessment of the feasibility and effectiveness of main adaptation options, based on literature, is presented in Table 13.9 (and details on input data in Table 13.A.4).

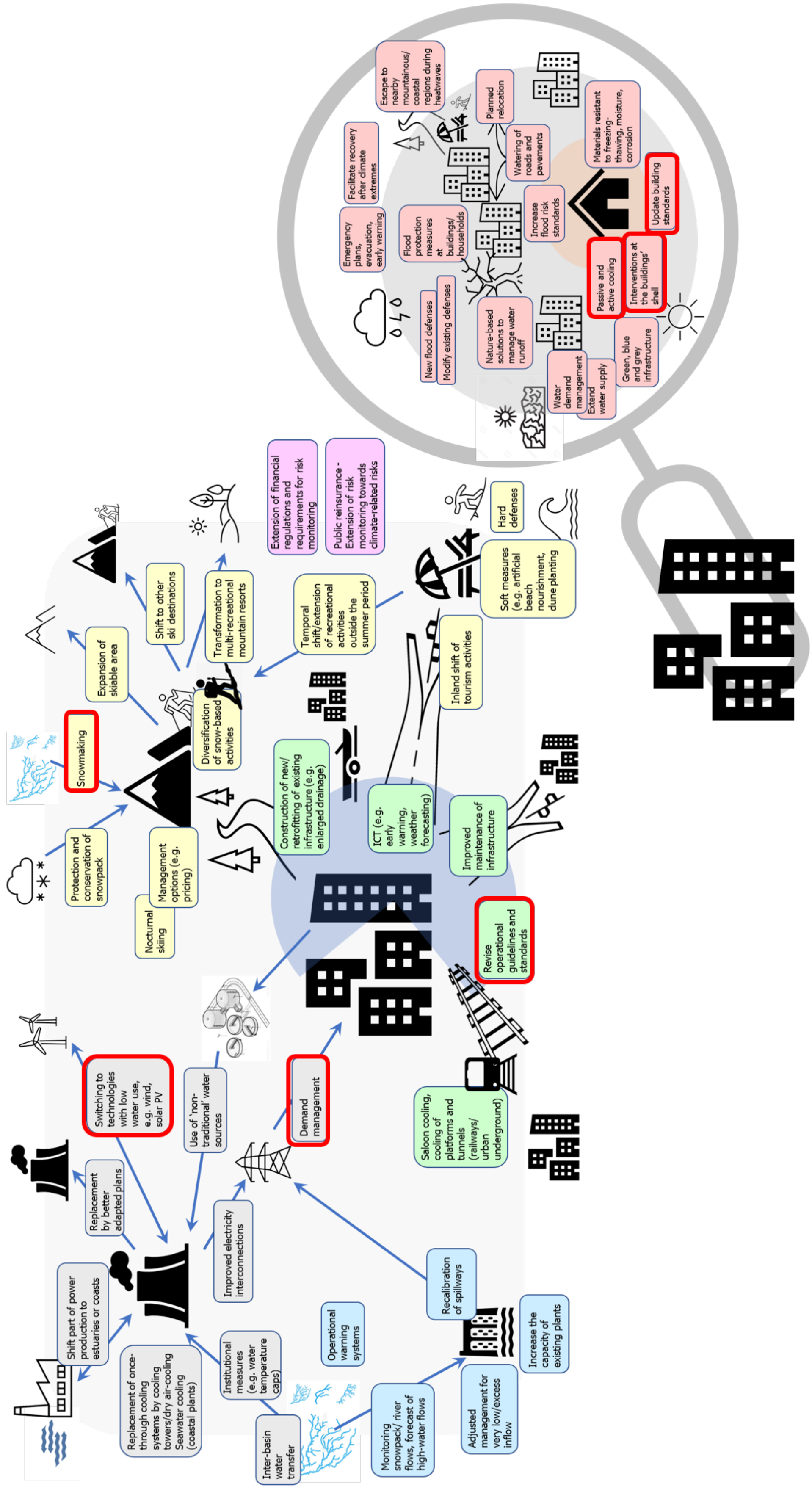
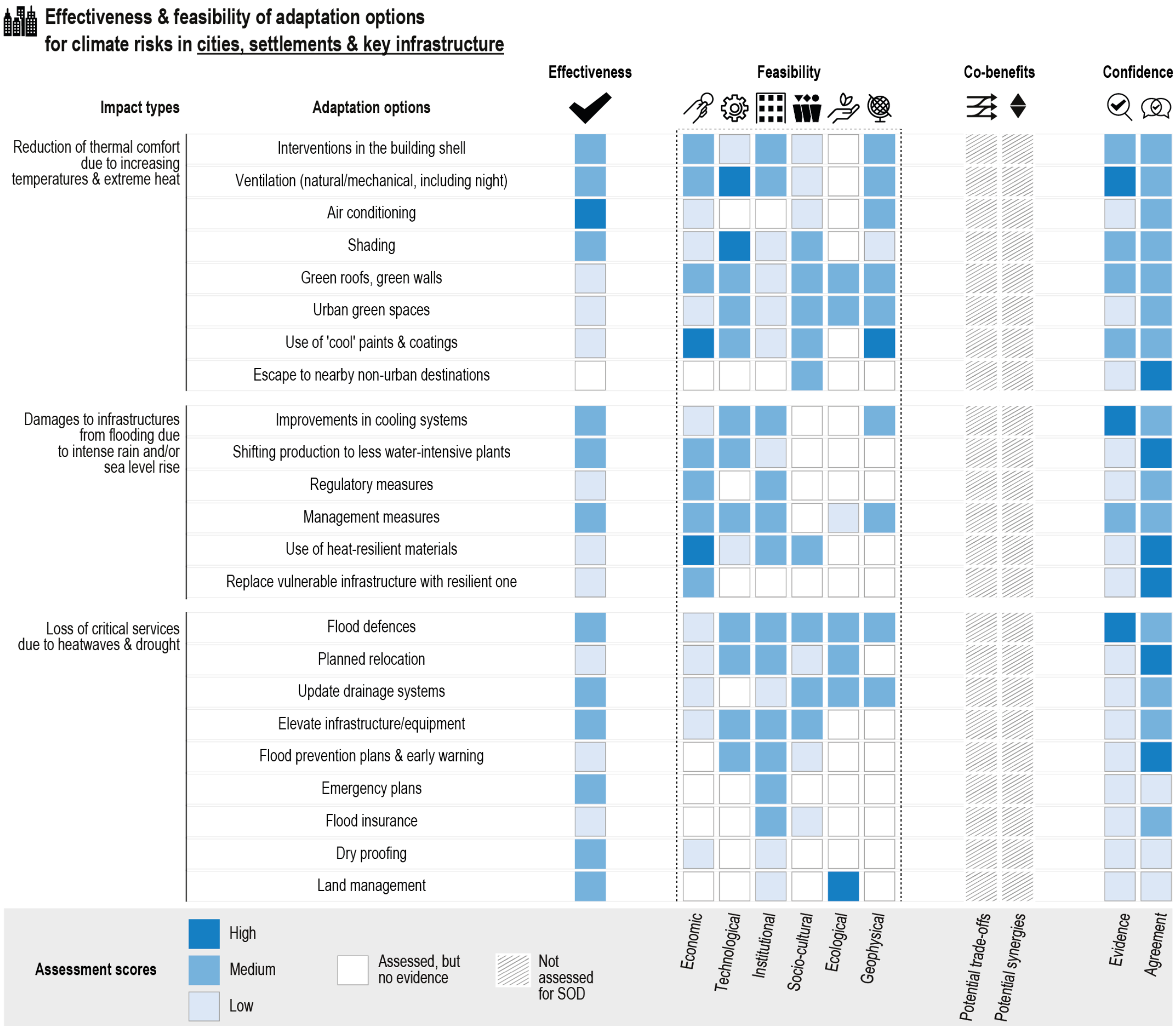


Figure 13.11: Interconnections between adaptation options for cities, settlements and key infrastructure in Europe, derived from relevant literature (presented in Table 13.A.13. 3). Red-bordered options indicate potential synergies and trade-offs with mitigation [PLACEHOLDER FOR FINAL DRAFT: to be updated].

Nature-based solutions (NbS) for urban stormwater management and heat mitigation represent an emerging adaptation option. For example, the NbS implemented in the Augustenborg district of Malmö, Sweden, to manage stormwater runoff (including multifunctional green spaces, ponds, wetlands and green roofs) resulted in capturing an estimated 90% of runoff from impervious surfaces, and reduced the total annual runoff volume from the district by about 20% compared to the conventional system (EEA, 2020). Urban green is associated with lower ambient air temperature and relatively higher thermal comfort during warm periods (Bowler et al., 2010; Oliveira et al., 2011; Cohen et al., 2012; Cameron et al., 2014). Both the scale and relative degree of NbS management or integration with 'engineered' solutions affect their vulnerability to climate change. Small-scale urban NbS are relatively less vulnerable due to increased capacity for intervention, while the relatively greater contact between stakeholders and urban NbS (compared with larger-scale, rural NbS) provides greater opportunity for human intervention to ensure the survival of urban NbS vegetation during droughts or heatwaves.

There is *medium confidence* that climate services support risk prevention in coastal and riverine cities, with stimulating regulations and bottom-up initiatives being set-up in various ways depending on each country (Cavelier et al., 2017; Le Cozannet et al., 2017; Reckien et al., 2018b). Other sectors (e.g., energy) have also started to explore their use. Still, climate services face many challenges (Section 13.11).

Table 13.9: Effectiveness and feasibility of the main adaptation options to climate change impacts and risks for cities, settlements and key infrastructure in Europe [PLACEHOLDER FOR FINAL DRAFT: to be updated]. The assessment steps are described in Table 13.A.3. Underlying data and references can be found in Table 13.A.4.



As shown, several options have a significant potential for reducing climate risks. Though, there are still gaps of knowledge on the social, environmental and geophysical dimension of feasibility for many options.

13.6.2.4 Adaptation limits, residual risks, incremental and transformative adaptation

Technical, environmental, economic and social factors pose limits to adaptation in Europe (Figure 13.12 and Table 13.A.5).

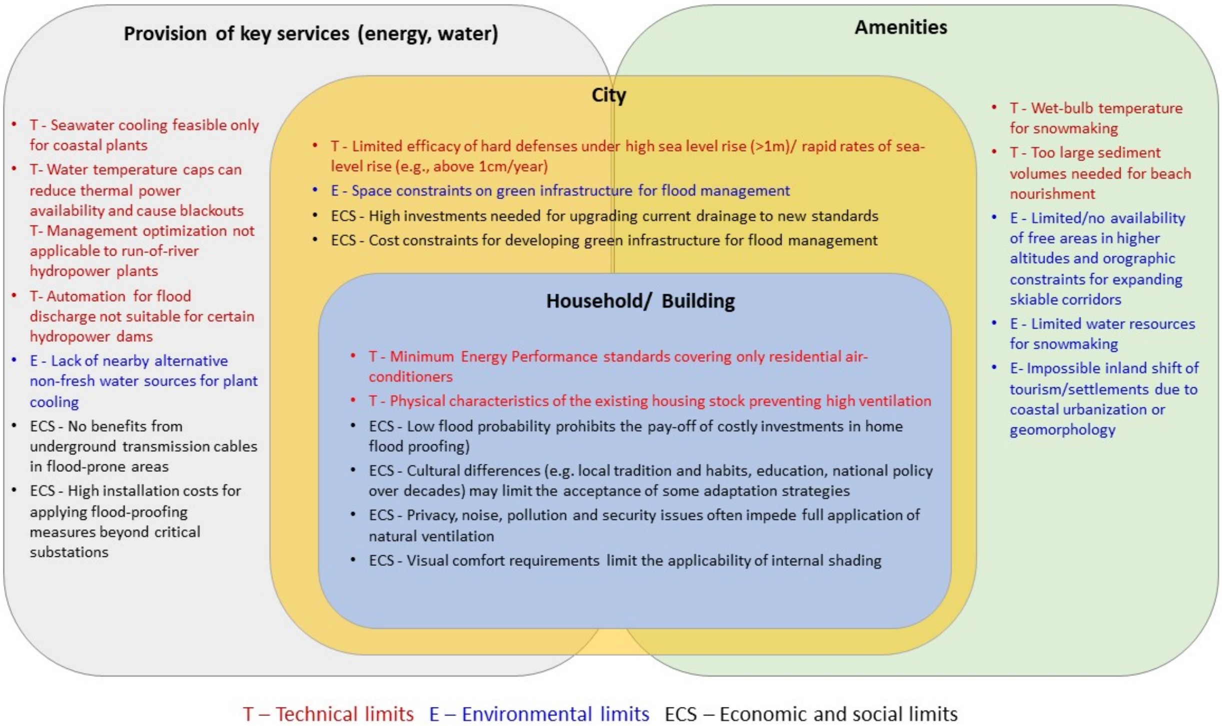


Figure 13.12: Examples of adaptation limits in cities, settlements and key infrastructure in Europe, reported in the relevant literature. [PLACEHOLDER FOR FINAL DRAFT: to be updated]

Regarding residual risks, there is *high confidence* that many adaptation measures will not be able to fully mitigate overheating in buildings under high warming (Tillson et al., 2013; Virk et al., 2014; Dodoo and Gustavsson, 2016; Mulville and Stravoravdis, 2016; Hamdy et al., 2017; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019), and the same is true for snowmaking beyond 3°C warming (Scott et al., 2019; Steiger et al., 2020; Steiger and Scott, 2020). There is some evidence on residual risks for hydropower (Gaudard et al., 2013; Ranzani et al., 2018), electricity transmission and demand (Bollinger and Dijkema, 2016; EEA, 2019a; Palkowski et al., 2019), urban subways (Jenkins et al., 2014b), and flood mitigation in cities (Skougaard Kaspersen et al., 2017; Umgiesser, 2020). Also, some adaptation actions in a sector may increase vulnerability in others. For example, shifting ski areas to higher elevations could cause a decline of the suitable area for birds in the Alps (Brambilla et al., 2016), and artificial beach nourishment can adversely impact marine environment as witnessed in Montenegro (Pranzini et al., 2015).

Examples of transformative adaptation in urban areas are observed (e.g., the Benthemplein water square, the Floating Pavilion in Rotterdam and the Hafencity flood proofing in Hamburg), but they often remain policy experiments, disconnected from formal decision making and planning (Jacob, 2015; Restemeyer et al., 2015; Restemeyer et al., 2018; Holscher et al., 2019). The active involvement of local stakeholders, public administration and politicians are drivers for community transformation, whereas lack of local resources and/or capacities are frequently reported barriers to change (Fünfgeld et al., 2019; Thaler et al., 2019).

13.6.2.5 Governance and insurance

Urban adaptation plans can contribute to enhance resilience. So far, their development is mandatory in the UK, France, and Denmark (Reckien et al., 2019). There is evidence that the development of urban adaptation planning is much more influenced by a city's population size, present adaptive capacity and GDP per capita than by anticipated climate risks (Reckien et al., 2015). There is also some evidence that a high organizational capacity in a municipality is not a necessary condition for forward-looking investment decisions (including climate change considerations) on urban water infrastructure, although enablers differ for small versus medium-to-large municipalities (Pot et al., 2019). There is large in-country variation in how cities are adapting (Lesnikowski et al., 2019b). In early adapter cities (e.g., Rotterdam), institutional arrangements provide for a coordination of climate, resilience and sustainability-related actions and collaboration between city departments, government levels, businesses, and rest stakeholders (Holscher et al., 2019). In other cities however, adaptation planners rarely consider collaborations with citizens, systematic monitoring and learning are lacking, and there are difficulties in departmental coordination and upscaling from pilot projects (Brink and Wamsler, 2018).

The level and type of collaboration between the public and private sector in managing climate risks varies across Europe. For example, in flood management, the private sector involvement in Rotterdam is much more pronounced and there are joint public–private responsibilities throughout most of the policy process due to the very large share of private ownership of land and real estate (Mees et al., 2014).

In large infrastructure networks, the lack of a leading and powerful body, with sufficient research resources targeted to climate change risk assessment, may limit adaptive capacity, as for example in railways (Rotter et al., 2016).

The insurance industry in Europe has developed tailored products for specific physical climate risks threatening cities, settlements and key infrastructure, such as risk-based flood insurance for homeowners. While risk-based insurance premiums can induce risk averting behaviour, they are potentially unaffordable to poor households and households living in high risk zones (Hudson, 2018). Considerable differences exist across European countries regarding the insurance system, and government funded compensation of damages (Keskitalo et al., 2014; Surminski et al., 2015; Hanger et al., 2018). A public discourse is emerging on whether society should bear the costs of flood risk insurance and management (Penning-Rowsell and Priest, 2015; Kaufmann et al., 2018). The availability of public assistance in some European countries may dis-incentivize private insurance uptake and private risk reductive behaviour (Poussin et al., 2013; Hanger et al., 2018; Pagano et al., 2018) (Section 13.11.3). For instance, improvements in structural flood protection can discourage homeowners from undertaking adaptation actions (O'Hare et al., 2016; Suykens et al., 2016; Hanger et al., 2018; Seebauer and Babcicky, 2018) (see also Section 13.11.3). When flood insurance is made conditional on flood protective behaviour, it can increase resilience (Surminski, 2018).

13.6.2.6 Links between adaptation and mitigation

Evidence from transport in Europe shows that adaptation actions do not consider enough long-term transition paths embedded in mitigation, while mitigation strategies are often not assessed under the future climate (Aparicio, 2017). Greenhouse gas emissions and fossil fuel consumption may increase the use of air-conditioning in European cities unless more efficient cooling technologies are applied (IEA, 2018), the escape of city residents to cooler locations during heatwaves (Juschten et al., 2019a), and the increasing snowmaking in European ski resorts (Scott et al., 2019). On the other hand, adaptation to overheating in buildings reduces cooling demand and consequently emissions from electricity production by fossil fuels. (Scott et al., 2019).

13.6.3 Knowledge Gaps

- A quantitative European-wide integrated assessment of future climate change risks on water and energy, including different socio-economic futures, is missing. Models capable of representing integrated policies for energy and water are lacking (Khan et al., 2016).
- Quantitative modelling of impacts on energy transmission and coastal energy infrastructure is limited (Cronin et al., 2018).
- Systematic collection of empirical data on the damage of transport infrastructure (e.g., railways) covering different European countries is missing, and indirect economic effects of interruptions of transport networks are understudied (Bubeck et al., 2019). Uncertainties associated with impacts of climate change on transport flows and indirect impacts (delays, economic losses).

- Interactions created by synchronous adaptation in ski tourism supply and demand are not fully known, while models do not yet include individual snowmaking capacity and need a higher time resolution (Steiger et al., 2019). A European-wide assessment of flooding risks on coastal tourism is missing. Many studies do not consider market characteristics (e.g., competitors) in assessing risks.
- Location-specific climate risks for firm assets, operations, finance and insurance is needed to inform adaptation actions (de Bruin et al., 2020; Feridun and Güngör, 2020; Monasterolo, 2020)
- Limited knowledge on sectoral risks from compound, concurrent, and consecutive climate extremes, as well as on cascading risks through transport, telecommunications, water, and banking and finance.
- Limited knowledge on how SSPs affect risks, and on adaptation tipping points.

13.7 Health, Wellbeing and the Changing Structure of Communities

13.7.1 Observed Impacts and Projected Risks

13.7.1.1 Mortality due to heat and other extreme events

Across western Europe, up to 70,000 heat-related deaths attributed to heat have occurred during the 2003 heatwave (Kjellstrom et al., 2016). The 2010 heatwave in eastern Europe resulted in 54,000 heat-related deaths (Barriopedro et al., 2011; Revich et al., 2019). Elderly, children, (pregnant) women, and socially isolated people are particularly exposed and vulnerable to heat-related risks, as are those people suffering from pre-existing medical conditions, including cardiovascular disease, kidney disorders, and respiratory diseases (Chapter 7, de'Donato et al., 2015; Sheridan and Allen, 2018). An aging population in Europe (13.1) will increase the pool of vulnerable individuals, resulting in higher risk of heat-related mortality (Montero et al., 2012; Carmona et al., 2016a; WHO, 2018).

Staying within 1.5°C warming could result in 30,000 annual deaths due to extreme heat, with up to three-fold the number with 3°C in 2100 (*high confidence*) (Roldán et al., 2015; Forzieri et al., 2017; Kendrovski et al., 2017; Naumann et al., 2020). The risk of heat stress, including mortality and discomfort, is dependent on socioeconomic developments (Rohat et al., 2019) (Figure 13.13). The number of heat-related respiratory hospital admissions is projected to increase from 11,000 (1981-2010) to 26,000 annually (2021-2050) (Astrom et al., 2013), particularly in the elderly (75+ years) population group in Mediterranean and Northern Europe (Michelozzi et al., 2009). Cold spells are projected to decrease across Europe, particularly in southern Europe (Lhotka and Kysely, 2015; Carmona et al., 2016a).

Over 70% of Europeans live in urban areas (13.6.1), where microclimates due to buildings and infrastructure and exacerbated climatic hazards impacts human health, including air pollution, heat island effect, and extreme heat spells (WHO, 2018). In large European cities, stabilizing climate warming at 1.5°C would decrease premature deaths by 15–22% in summer compared with stabilization at 2°C (Mitchell et al., 2018) (*high confidence*).

Although there is *robust evidence and high agreement* that risk consequences will inevitably be more pervasive and widespread in a warmer Europe, no adaptation and consequent heat habituation is improbable (Martinez et al., 2019). Evidence of higher heat tolerance is emerging across most European regions (Todd and Valleron, 2015; Åström Daniel et al., 2016 Sweden, 1901–2009; Follos et al., 2020). Future projections of mortality rates in Europe under the assumption of complete acclimatization suggest constant or even decreasing rates of mortality in spite of global warming (Astrom et al., 2017; Guo et al., 2018; Díaz et al., 2019).

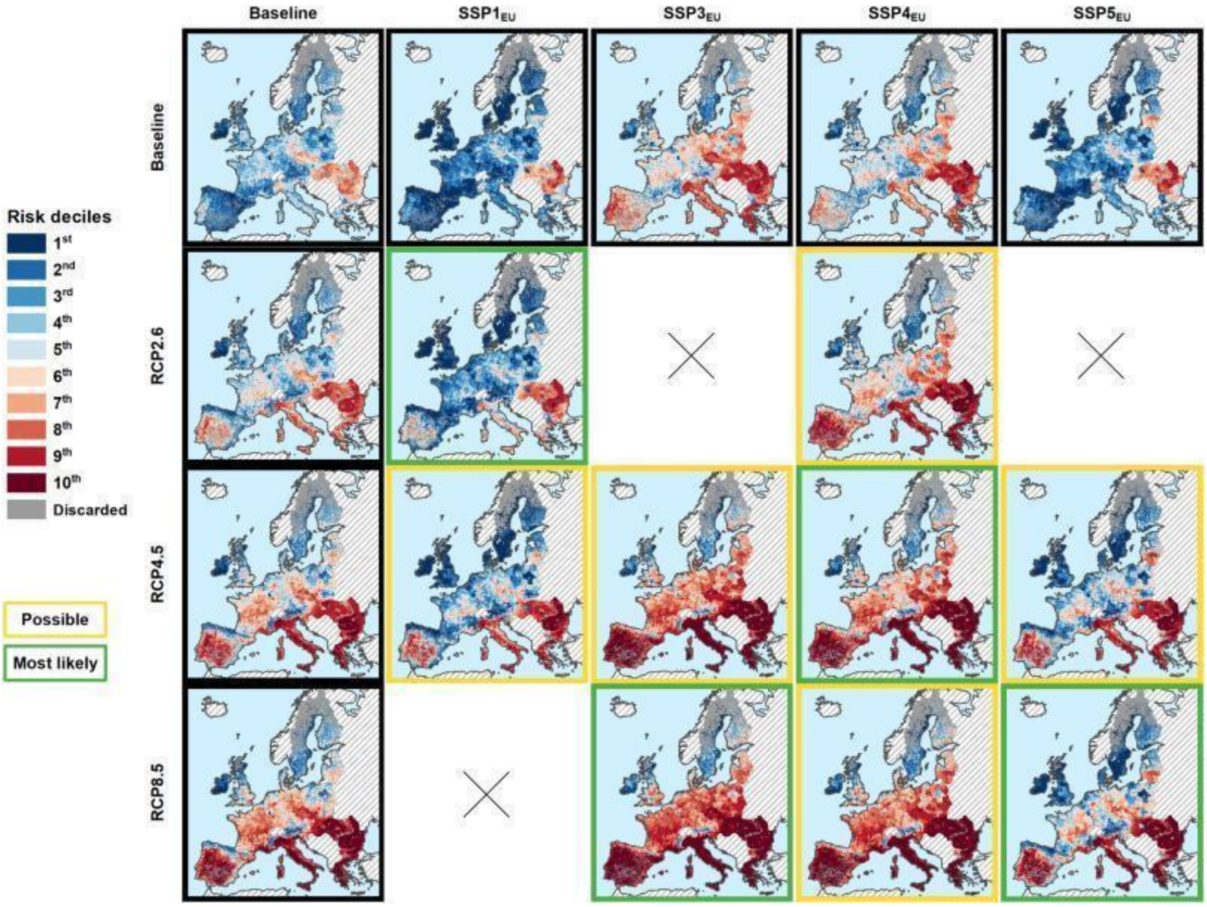


Figure 13.13: Scenario matrix for multi-model median heat stress risks under RCP 2.6, 4.5 and 8.5 and extended SSPs for Europe (EU28+) for the period 2040-2060 (baseline 1986-2005). The heat stress risk is calculated by geometric aggregation of the hazard (heat wave days), population vulnerability and exposure. Risk values are normalised using a z-score rescaling with a factor 10-shift. Details of the methodology are provided in (Rohat et al., 2019).

Other extreme events already result in major health risks across Europe. Between 2000 and 2014, for example, floods in Russia killed approximately 420 people, mainly older women (Belyakova et al., 2018). Fatalities associated with coastal flooding, wildfires, windstorms and river floods are expected to rise substantially by 2071-2100 compared to 1981-2010 (*medium confidence*) (Forzieri et al., 2017), with demographics, social and economic factors considered to be important (*medium confidence*)

13.7.1.2 Air quality

Air pollution is already one of the biggest public health concerns in Europe; in 2016 roughly 412,000 people died prematurely in due to long-term exposure to ambient PM2.5, 71 000 due to NO2, and more than 15,000 premature mortalities occurred due to near surface ozone (EEA, 2019b). Climate change could increase air pollution health effects (Jacob and Winner, 2009; Orru et al., 2017) (*high agreement, medium evidence*). Increases in temperature and changes in precipitation will impact future air quality due to increased risk of wildfires and related air pollution episodes. Projected increase in wildfires (13.3) and reduced air quality is expected to increase respiratory morbidity (Slezakova et al., 2013; de Rigo et al., 2017a). Data on the health impacts of wild-fires in Europe is currently limited, but examples of the summer of 2017 fires suggest that more than 100 people died prematurely in Portugal alone as a result of poor air-quality (Oliveira et al., 2020).

At 3 degrees warming could be 9,850 and 2,890 additional premature mortalities each year in Europe due to exposure to PM2.5 and O3, respectively (*medium confidence*) (Silva et al., 2017). Estimated annual premature mortalities due to exposure to near-surface ozone are projected to increase up to an 11% in central and southern Europe in 2050 and decrease up to an 9% in Northern Europe (under RCP4.5) (Orru et al., 2019) (*medium confidence*). Constant or lower emissions combined with to stricter regulations and new policy initiatives, might improve air quality in coming decades (*medium agreement, low evidence*). Aging population in Europe enhances the future air quality mortality burden by 3-13% in 2050 (Geels et al., 2015; Orru et al., 2019). Beside ambient air quality, projected increases in flood risk and heavy rainfall could decrease indoor air quality (13.6.1.5.2) due to dampness and mould, leading to increased negative health impacts, including allergy, asthma and rhinitis (EASAC, 2019c; EEA, 2019b).

13.7.1.2 Climate sensitive infectious diseases

Transmission of infectious diseases are determined by a range of social, economic, ecological, health care, and other factors, but the incidence, prevalence, and distribution are projected to shift in a changing climate (Chapter 7). Table 13.10 summarizes the observed impacts and projected risks of the main climate sensitive infectious diseases for the four European regions.

Lyme disease and tick-borne encephalitis (TBE) are frequently occurring vector borne disease and has been documented to expand from western Europe northwards to Sweden, Norway and the Russian Arctic (Jaenson et al., 2012; Jore et al., 2014; Tokarevich et al., 2017) and to higher elevations in Austria and the Czech Republic (Daniel et al., 2003; Heinz et al., 2015) (*medium confidence).* Potential habitat expansion of 3.8% across Europe is projected (Porretta et al., 2013; Boeckmann and Joyner, 2014). TBE and Lyme infections are anticipated to reduce in southern Europe (Semenza and Suk, 2018). The Asian tiger mosquito (Aedes albopictus) is present in many European countries and can transmit Dengue, Chikungunya and West Nile fever (Semenza and Suk, 2018). Europe experienced an exceptionally early and intense transmission season of West Nile fever during the 2018 heatwave (Haussig et al., 2018). Projections for Europe under the A1B scenario show the West Nile fever risk extending; for 2025 risk is projected to increase in Southern and South eastern Europe, with the risk areas expanding further northward by 2050 (*medium confidence*) (Semenza et al., 2016b).

Climate change is projected to affect the precipitation patterns and rain in early spring which can trigger water borne diseases such as campylobacteriosis outbreaks (Djennad et al., 2019; Lake et al., 2019 2008 to 2016) and warming has been linked with elevated incidence in different European countries (Yun et al., 2016; Lake et al., 2019). Under further warming, the number of months with risk of Vibrio transmission increases and the seasonal transmission window expands (Semenza et al., 2017)There is empirical evidence that warming increases risks gastrointestinal infections in humans(Semenza et al., 2017) (*medium confidence*).

Table 13.10: Overview of observed impacts and projected risks for climate sensitive infectious diseases across European regions. Table 13.A.6 provides an overview of supportive references. [PLACEHOLDER FOR FINAL DRAFT: to be updated]

		Confidence		NEU			EEU			MED			WCE		
		Evidence	Agreement	Obs.	1.5°C	3°C	Obs.	1.5°C	3°C	Obs.	1.5°C	3°C	Obs.	1.5°C	3°C
Vector borne diseases															
	Tick-borne encephalitis														
	Lyme borreliosis														
	West Nile fever														
	Dengue fever														
	Chikungua fever														
	Malaria														
	Zika														
Water borne diseases															
	Vibriosis														
	Legionella														
Food borne diseases															
	Salmonella														
	Campylobacter														

High risk
Medium risk
Low risk
Disease not established
No evidence
Not assessed for SOD

13.7.1.4. Allergies and pollen

The main drivers of allergies are predominantly non-climatic (increased urbanization, adoption of westernized lifestyles, social and genetic factors etc.,) but climate change strongly contributes to the spread of some allergenic plants, thus exacerbating existing and causing new allergies to humans across Europe (*high confidence*) (D'Amato et al., 2016; EASAC, 2019c). The prevalence of hay fever (*allergic rhinitis*), for example, is between 4% and 30% among European adults (Pawankar et al., 2013). The invasive common ragweed is a key species already causing major allergy in late summers (including hay fever and asthma), particularly in Hungary, Romania and parts of Russia (Ambelas Skjøth et al., 2019). Sensitization to ragweed is expected to increase from 33 to 77 million people by 2041–2060 (RCP 4.5, 8.5, resp.) (Lake et al., 2017).

Warming will result in an earlier start of the pollen season and extending it, but this differs across regions, species, traits and flowering periods (Ziello et al., 2012; Bock et al., 2014; Revich et al., 2019). For instance in different parts of Europe, the start of the birch season flowering have been shifted and extended up to two weeks earlier during recent decades (Biedermann et al., 2019). Airborne pollen concentrations are projected to increase across Europe (Ziello et al., 2012). In south-eastern Europe, where pollen already have a substantive impact, the pollen count could increase more than 3/3.5 times by 2041–2060 compared to 1986–2005 (RCP 4.5/8.5, resp.) and can become a more widespread health problem across Europe, particularly where it is currently uncommon (*medium agreement, low evidence*) (Lake et al., 2017).

13.7.1.5. Labour productivity and occupational health

Extreme heat and cold waves have been linked to an increased risk of occupational injuries, loss of productivity and economic damages (Martinez-Solanas et al., 2018). The sectors with a high percentage of high intensity outdoor work in Europe, mainly agriculture and construction, have the highest risk of increased injury and labour productivity losses, but also manufacturing and service sectors can be affected when air conditioning is not available (Gosling et al., 2018; Szewczyk et al., 2018; Dellink et al., 2019; Matsumoto, 2019; Orlov et al., 2019). A substantial reduction in work capacity and related labour productivity in 2085 is projected under RCP8.5 particularly in the Mediterranean, but also for other parts of Europe (Kjellstrom et al., 2016; Takakura et al., 2017; Gosling et al., 2018). For Europe and its regions, occupational heat stress is projected to contribute substantially to the total economic welfare loss due to climate change (section 13.10.2). Effects of other extreme events on labour productivity and occupational health is limited.

13.7.1.6. Food quality and nutrition

There is strong evidence that climate change will affect food quality (diversity of food, nutrient density, and food safety) and food access, although the risks for European citizens are significantly lower compared to other regions (Fanzo et al., 2018; IFPRI, 2018). Projected changes in crop and livestock production (13.5.1), particularly reduced access to fruits and vegetables and foods with lower nutritional quality, will impact already vulnerable groups (Swinburn et al., 2019). The effects of climate change on food quality and access varies based on wealth, livelihood, and nutrient requirements, with low income and more vulnerable societal groups in Europe most affected (IFPRI, 2018). Spikes in food prices due to changing growing conditions in Europe (13.5.1), increased competition for land (e.g., land-based climate change mitigation), and feedbacks from international markets, are expected to decrease access to affordable and nutritious food for European citizens (13.9.1) (EASAC, 2019c; Loopstra, 2020). Limited access to healthy and varied food could contribute to overweight and obesity which is an increasing health concern across European countries (Springmann et al., 2016). Increased rates of obesity and diabetes further exacerbate risks from heat related events (EASAC, 2019c).

13.7.1.7. Mental health and wellbeing

Extreme weather events can trigger post-traumatic stress disorder (PTSD), anxiety and depression; this is well-documented for flooding in Europe *(high confidence)*, but less for other extreme weather events. For example, in the UK, flooded residents suffered stress and identity loss from the flood event itself, but also from subsequent disputes with insurance and construction companies (Carroll et al., 2009; Greene et al., 2015). Residents displaced from their homes for at least one year due to 2013-2014 floods in England were significantly more likely to experience PTSD, depression and anxiety, with stronger effects in the absence of advance warning (Munro et al., 2017; Waite et al., 2017).

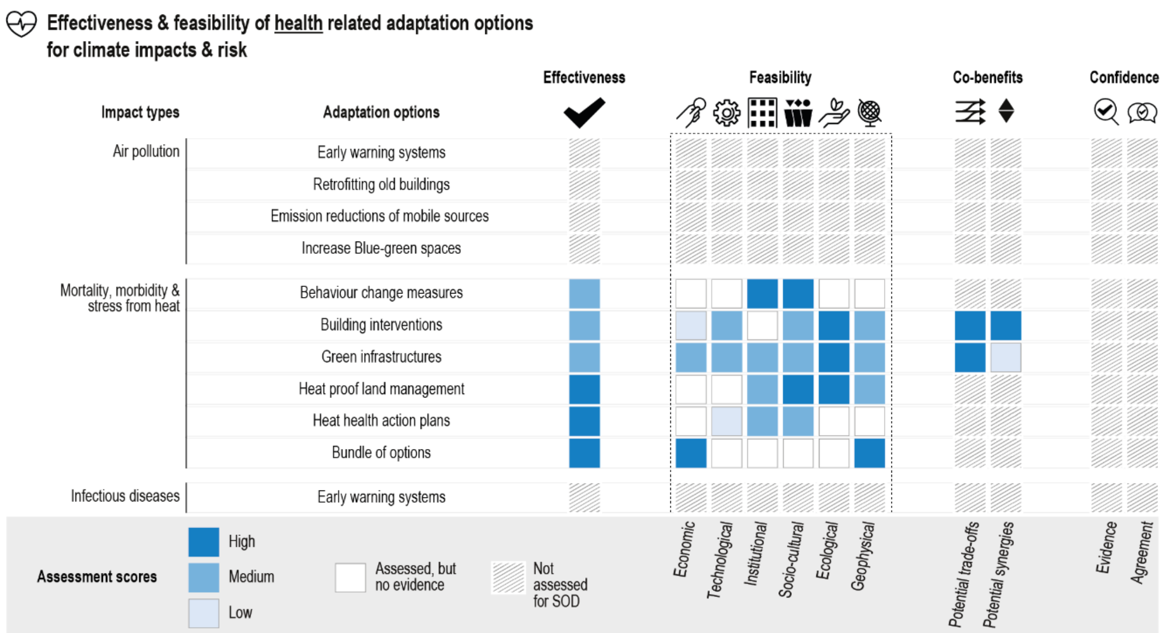
There is emerging evidence across Europe that young people may be experiencing anxiety about climate change, though it is unclear how widespread or severe this is (Hickman, 2019). In northern Italy, the number of daily emergency psychiatric visits and mean daily air temperature has been linked (Cervellin et al., 2014). During the heatwave in 2010, the number of suicides in Moscow increased two-fold (Revich et al., 2019).

13.7.2 Solution Space and Adaptation Options

Adaptation to health impacts has generally received less attention compared to other climate impacts across Europe (EASAC, 2019c). Progress on health adaptation can be observed. Between 2012 and 2017, at least 20 European countries instituted new governance mechanisms such as interdepartmental coordinating bodies for health adaptation and adopted health adaptation plans (Kendrovski and Schmoll, 2019). Progress on city level health adaptation is generally limited (Araos et al., 2016a), with most activities occurring in the Mediterranean region (Paz et al., 2016).

A range of health adaptation options have been implemented across European cities and regions. Table 13.11 presents the assessment of the feasibility and effectiveness of key health adaptation. It shows that substantial barriers complicate wide spread implementation of measures; studies on the implementation of new blue-green spaces in existing urban structures in for example Sweden (Wihlborg et al., 2019), UK (Carter et al., 2018), the Netherlands (Aalbers et al., 2019), point to important feasibility challenges (e.g., access to financial resources, societal opposition, competition for space) (*high confidence*). Lower perception of health risks has been observed amongst vulnerable groups which in conjunction with perceived high costs of protective measures act as barriers to implement health adaptation plans (van Loenhout et al., 2016; Macintyre et al., 2018; Martinez et al., 2019). Mental health has been given little attention with barriers including lack of funding, coordination, surveillance, and training (e.g., psychological first aid) (Hayes et al., 2018; Hayes and Poland, 2018). Existing health measures, such as monitoring and early warning systems play an important role in detecting and communicating emerging risks (Confalonieri et al., 2015; Linares et al., 2020) (*high confidence*). Stricter enforcement of existing health regulation and policy can have a positive effect in reducing risks (Berry et al., 2018).

Table 13.11: Effectiveness and feasibility of the main adaptation options to climate change impacts and risks for health in Europe [PLACEHOLDER FOR FINAL DRAFT: to be updated]. The assessment steps are described in Appendix 13.A. Underlying data and references supporting this assessment can be found in the Table 13.A.7.



There are still significant gaps in our understanding of the effectiveness of most options in reducing health risks, and the effectiveness is determined by many co-founding factors, including the extent of the risk, existing socio-political structure, and other adaptation options considered (*high agreement, medium evidence*). Successful examples include the implementation of heat wave plans (Schifano et al., 2012; van Loenhout and Guha-Sapir, 2016; de'Donato et al., 2018) and improvements in health services and infrastructure of homes (Vandentorren et al., 2006) (13.10.3.2). A study of nine European cities, for example, showed lower numbers of heat related deaths in Mediterranean cities, and attributed this to the implementation of heat prevention plans, a greater level of individual and household adaptation, and growing awareness of citizens about exposure to heat (de'Donato et al., 2015). Long-term national prevention programs in Northern Europe have been shown to reduce temperature related suicide (Helama et al., 2013). Combining multiple types of adaptation options into a consistent policy portfolio may have an amplifying effect in reducing risks (Lesnikowski et al., 2019a) (*medium confidence*) (Chapter 7).

Health adaptation actions have demonstrable synergies and trade-offs. For example, increasing green-blue spaces in Europe's densely populated areas can be effective in improving micro-climate, reducing the impact of heat waves, reducing air pollution, and improving mental health by increasing access to fresh air and green (restorative) environment (Gascon et al., 2015; Kondo et al., 2018). These can also have negative trade-offs and could lead to maladaptaton, such as creating new nesting grounds for carriers of vector-borne diseases, increase pollen and allergy (Kabisch et al., 2017), higher freshwater use for irrigation (Reyes-Paecke et al., 2019), and could lead to green gentrification (Yazar et al., 2019). Similarly, air conditioning and cooling devices are considered highly effective but have low economic and social feasibility and negative trade-offs due to increasing energy consumption which are particularly challenging for the poor (section 13.8.1, 13.8.3), enhancing the heat island effect, and increasing noise production (Fernandez Milan and Creutzig, 2015; Hunt et al., 2017; Macintyre et al., 2018).

The solution space for implementing health adaptation options is slowly expanding in Europe. Health adaptation can build on, and integrate into, established health system infrastructures. Health systems infrastructures differ significantly Europe, as are their existing capacities to deal with climate related extreme events (Austin et al., 2016; Austin et al., 2018; Orru et al., 2018; Watts et al., 2018; Austin et al., 2019; Martinez et al., 2019). Despite some progress, limited mainstreaming is observed, particularly due to limited societal pressure to change, confidence in existing health systems, and lack of awareness of link between human health and climate change (*medium confidence*) (Austin et al., 2016; WHO, 2018). Coordination of health adaptation actions across scales and between public sectors is needed to ensure timely and effective responses for a diversity of health impacts *(high confidence)* (Austin et al., 2018; Ebi et al., 2018). Key enabling conditions to extend the solution space have been documented, including increased role of national governments in facilitating knowledge sharing across scales, allocating dedicated financial resources, and dedicated knowledge and policy programs (Wolf et al., 2014; Akin et al., 2015; Curtis et al., 2017). Investing in public health care systems more broadly increases their capacity to respond to climate related extreme events (Cross-Chapter Box COVID in Chapter 7).

Nevertheless, there are limits to how much adaptation can take place and residual risk remain. These are predominantly discussed in the context of excess mortality and morbidity to heat extremes (Hanna and Tait, 2015; Martinez et al., 2019). Future heatwaves (13.7.1.1) are expected to stretch existing adaptation interventions well beyond levels observed in response to the observed events of 2003 and 2010, see 13.10.3.2 (Hanna and Tait, 2015). Increases in excess mortality from mid to end century (compared to 1971-2020) cannot be avoided for most European countries under all emission scenarios (Guo et al., 2018).

13.7.3 Knowledge Gaps

Literature on the link between public health, climate impacts, vulnerability and adaptation is skewed across Europe, with most studies focusing region specific impacts (e.g., flood injuries in western Europe, heatwaves in the Mediterranean region (Berrang-ford et al., Submitted). In general, attributing health impacts to climate change remains challenging, particularly for mental health, (mal)nutrition and food quality, wellbeing, and infectious diseases, where other socio-economic determinants play an important role. The connection between climate change and health risks under different socio-economic development pathways is hardly studied comprehensively for Europe, with some exceptions for extreme events (Section 13.7.1.1). SSP/RCP combinations seem to play an important role in better understanding projected risks.

Some climate related health issues are emerging but evidence is too limited for a robust assessment, for example evidence of the links between climate change and violence in Europe (Fountoulakis et al., 2016; Mares and Moffett, 2016; Sanz-Barbero et al., 2018; Koubi, 2019).

The solution space for public health adaptation in Europe, and the leavers for interventions, are hardly assessed. Although health adaptations are documented, these are particularly around mortality and injuries due to extreme events (predominantly floods and heat waves). There are very few studies assessing the barriers and enablers of health adaptations, nor systematically assess the effectiveness of (portfolio) of options. Limited insights in what works where hampers upscaling of insights across Europe and constrains the ability to evaluate whether investments in health adaptation have actually reduced risks.

13.8 Poverty, Livelihoods and Cultural Heritage

13.8.1 Observed Impacts and Projected Risks

13.8.1.1 Poverty

While AR5 found little evidence of climate change related poverty in Europe, the recent literature reports that poor households are affected more strongly by heat, drought and flooding events (*medium confidence*). Climate change is not the main driver of social inequality in Europe, but it can exacerbate existing risks to marginalized people (*medium confidence*) because of their higher exposure and sensitivity to flooding and heat, a higher dependence on food self-provisioning, and a lower adaptive capacity (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017).

Urban poor and ethnic minorities often settle in more vulnerable settlement zones, and are therefore impacted more e.g., by flooding with the subsequent recovery perpetuating exclusion (*medium confidence*) (Medd et al., 2015; Župarić-Iljić, 2017; Efendić, 2018; Fielding, 2018; Winsemius et al., 2018; Puđak, 2019; Inuit Circumpolar Council, 2020). Yet, in some western European residential waterside developments this pattern is reversed by flooding impacting high income residents more strongly (Walker and Burningham, 2011).

The health of the poor is also disproportionately affected during heat waves in the Mediterranean (Jouzel and Michelot, 2016) or when flooding leads to heavy metal contamination of agricultural land (Filijović and Đorđević, 2014). Women and the elderly are disproportionately affected by heat (Section 13.7.1).

Food self-provisioning is a widespread practice in parts of Northern, Eastern and Southern Europe (Aleynikov et al., 2014; Corcoran, 2014; Church et al., 2015; Mustonen and Huusari, 2020). While it strengthens resilience for disadvantaged households (Church et al., 2015; Boost and Meier, 2017; Promberger, 2017; Vávra et al., 2018; Ančić et al., 2019; Pungas, 2019), it can become at risk in regions with projected crop yield reductions (*high confidence*) (Hallegatte et al., 2016; Quiroga and Suárez, 2016; Myers et al., 2017; Inuit Circumpolar Council, 2020), and after devastation by extreme weather events (Filijović and Đorđević, 2014).

Energy poor households often live in thermally inefficient homes and cannot afford air conditioning to adapt to overheating in summer (Sanchez-Guevara et al., 2019; Thomson et al., 2019). While energy poverty is much more prevalent in southern and eastern Europe (Bouzarovski and Petrova, 2015; Pye et al., 2015; Atsalis et al., 2016; Monge-Barrio and Sánchez-Ostiz Gutiérrez, 2018), climate change will also exacerbate energy poverty in European regions where heating was so far the major share of energy costs (*medium confidence*) (Sanchez-Guevara et al., 2019; Randazzo et al., 2020).

13.8.1.2 Traditional Livelihoods and Displacement of People within Europe

Northern communities are particularly affected by climate change because of their dependence on cryosphere ecosystems they live in and use for livelihoods *(high confidence*) (Chapter 8, Cross-Chapter Paper 6, Hayashi, 2017; Huntington et al., 2017; Hock et al., 2019b; Meredith et al., 2019a; Inuit Circumpolar Council, 2020). Table 13.12 summarizes how these livelihoods and cultures are affected.

Impacts cascade due to lack of access to key ecosystems, lakes and rivers preventing traditional livelihoods and food security (see Box 13.2 for an example), as well as the capacity to maintain unique indigenous cultural systems. They contribute to the loss of cultural heritage (burial grounds, nomadic camp sites, graveyards, seasonal dwellings and routes). Capacity of already-marginalised indigenous and local communities will be further hindered by their limited representation in formal institutions (Arctic Council, 2013; Post et al., 2019; Mustonen and Huusari, 2020). Severe impacts may also affect indigenous mental health (Furberg et al., 2011) (Figure 13.14).

Table 13.12: Impacts to Cryosphere-Dependent Traditional Systems in the European Arctic

Geography	Observed Changes (Hazard, Exposure)	Vulnerability	Observed Impacts and Projected Risks	References
Russian Federation (Murmansk, Karelia, Archangelsk, Komi), Sweden	Increased forest fires since 2010 including 250km2 per year in Sweden	Vulnerable natural habitats, Sámi forests, boreal ecosystems under threat	200% increase in burned boreal forests	(Khabarov et al., 2016; Krikken et al., 2019; Mustonen and Shadrin, 2020)
Greenland, Finland, Sweden, NW Russia	Increased loss/flux of freshwater ice cover	Disruption of food systems, loss of key species	Collapse of food security, livelihood safety, access issues to freshwater fisheries	(Hanna et al., 2016; Abermann et al., 2017; Meredith et al., 2019b; Post et al., 2019; Ruan et al., 2019; Saros et al., 2019; Golledge, 2020; Inuit Circumpolar Council, 2020)
Greenland, NW Russia (Kara Sea, Nenets Aut. Area)	Unstable loss/flux of marine ice cover	Increased precipitation in tundra, Nenets herding strongly impacted, ice-dependent species potentially lost	Interlinked loss of food security, safety, access to marine ice	(Forbes et al., 2016; Hayashi, 2017; Huntington et al., 2017; Inuit Circumpolar Council, 2020)
Finland, Sweden, NW Russia	More frequent Rain-on-Snow events / autumn	Cascading loss of natural pastures and habitat of reindeer	Loss of natural pastures and food	(Arctic Council, 2013; Forbes et al., 2016; Mikhaylova, 2018)
Greenland	Changes to marine food web	Loss of Indigenous knowledge, food security	Further uncontrolled system changes	(Hayashi, 2017; Pecl et al., 2017; Hayashi and Walls, 2019; Inuit Circumpolar Council, 2020)
Greenland, Finland, Sweden, NW Russia	Loss of spring snow and ice	Loss of transport, access, safety and harvesting areas	Cultural and social impacts	(Arctic Council, 2013; Post et al., 2019; Mustonen and Huusari, 2020)
NW Russia (Nenets Autonomous Area, Archangelsk)	Increased coastal and catchment erosion	Clogging of spawning sites, loss of habitat	Loss of Indigenous land use and cultural sites	(Brattland and Mustonen, 2018)
Greenland, Finland, Sweden, NW Russia, Scotland	Diminishing freshwater lake ice in autumn	System shifts in freshwater aquatic habitats, loss of fish	Collapse of winter fisheries	(Post et al., 2019; Mustonen and Huusari, 2020; Mustonen et al., 2020)

Finland, Sweden	Fish lake death and fish death events due to warm water, 2018	Loss of populations locally that support key systems; Loss of Indigenous knowledge, food security	Loss of cold-dependent species; Loss of food and cultural well-being	(Mustonen et al., 2018)
Finland, NW Russia, Norway	Expansion of invasive Pink Salmon, 1970s to 2018	Proliferation of non-native species, loss of A. salmon	Competition with native salmon	(Mustonen et al., 2020)
Finland	Erosion of river banks, increased nutrients, algal blooms	Loss of water quality and cold-species habitats	Impacts to waterways and quality	(Mustonen et al., 2018)
Puruvesi, Finland	Loss of ice cover months by 50% 1968-2020	Algal blooms and loss of ice risks extinction of seals	Seining season and incomes halved, habitat and gear lost	(Mustonen, 2014; Mustonen and Huusari, 2020)
Nellim, Finland	Cultural and linguistic loss due to lack of access to traditional harvesting areas	Endangered ways of knowing lost	Established cultures under threat	(Frainer et al., 2020)
Nellim, Finland	Sámi women lack of access to ice	Gendered knowledge lost	Gendered impacts	(Frainer et al., 2020)

Climate impacts on the cryosphere interact with complex and compounding processes both at sea and on land creating inseparable links between temperature, ice formation and seasonal change, food chains and ecosystems (*high confidence*). Across Northern Europe, several observed changes illustrate this compounding nature. Mortality for Arctic Char associated with warmer waters in high-Arctic freshwater habitats (13.3.1) impacts Sámi cultural and linguistic well-being (Mustonen et al., 2018) (Frainer et al., 2020). Introduced Pacific Pink Salmon expands in range, affecting endemic species through competition reducing their abundance (Mustonen et al., 2020). Increased nutrient loading of rivers and rapid expansion of algae increase the risks for cold-dependent fish (Mustonen et al., 2018). The start of ice cover on lakes, e.g., lake Puruvesi (Finland), has changed from November to February (Mustonen, 2014; Mustonen and Huusari, 2020) which, combined with much earlier ice breakup, reduces fish harvest for important species by up to 50% and impacts on local safety, ecosystems, oral history maintenance and the local economy.

[START BOX 13.2 HERE]

Box 13.2: Sami Reindeer Herding in Sweden

Reindeer (Rangifer tarandus) are keystone species in northern landscapes (Vors and Boyce, 2009). Reindeer herding is a traditional, semi-nomadic livelihood of the Sami. Reindeer migrate between seasonal pastures that cover 55% of Sweden and are simultaneously used for multiple other purposes (Sandström et al., 2016). As an indigenous right, reindeer herding is protected by the UN Declaration on the Rights of Indigenous Peoples and several UN conventions.

Temperatures in Arctic and sub-Arctic regions have increased on average by 2°C over the last 30 years (*very high confidence*) (WGI AR6 Chapter 12). Future warming is expected to further increase winter precipitation (*high confidence*) (WGI AR6 Chapter 12) and extreme weather events such as rain-on-snow (ROS), creating a hard ice crust on the snow after refreezing (Bokhorst et al., 2016; Rasmus et al., 2018).

The documented and projected impacts on reindeer are complex and varied. Warming and CO_2 increase result in higher plant productivity (Section 13.3) changes in plant community composition, and higher parasite harassment; unstable ice conditions affect migration; extreme weather conditions during critical winter months, more frequent fires and changes in plant community composition reduce pasture quality (*medium confidence*) (Mallory and Boyce, 2018) (Figure 13.14). Warming and CO_2 increase result in higher plant productivity (Section 13.3) changes in plant community composition, and higher parasite harassment; unstable ice conditions affect migration; extreme weather conditions during critical winter months, more frequent fires and changes in plant community composition reduce pasture quality (*medium confidence*) (Mallory and Boyce, 2018) (Figure 13.14). High snow depth and ROS impede reindeer access to ground lichen in winter and delay spring green-up during critical calving period; both cause malnutrition and negative impacts on reindeer health, mortality, and reproductive success (*medium confidence*) (Hansen et al., 2014; Forbes et al., 2016; Mallory and Boyce, 2018). Lower slaughter weights and increased mortality reduce the income of herders (*high confidence*) (Tyler et al., 2007; Helle and Kojola, 2008).

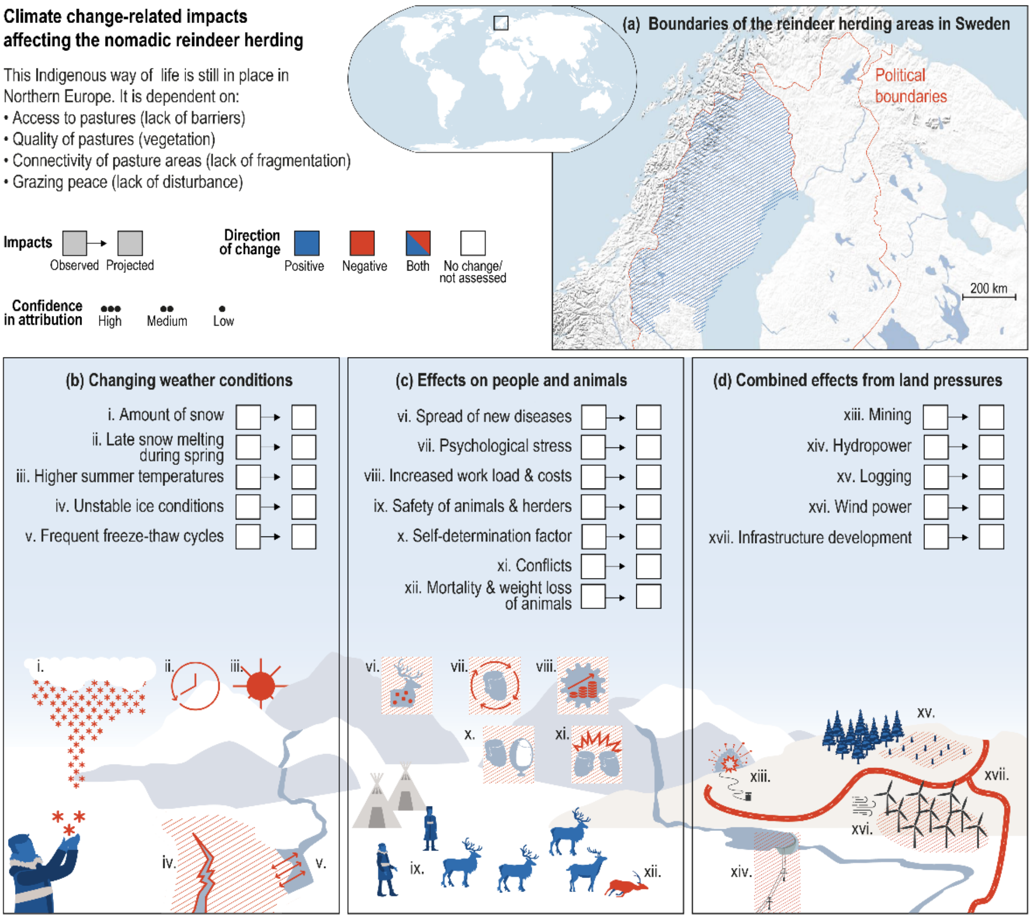


Figure 13.14: Climate change-related impacts affecting nomadic reindeer herding in Northern Europe [PLACEHOLDER FOR FINAL DRAFT: direction of change will be added for observed impacts and projects risks] See Table 13.A.8 for references.

Reindeer herding already autonomously adapts to changing conditions through flexible use of pastures and supplementary feeding (*high confidence*), reducing and thereby hiding some of the negative impacts of climate change (Uboni et al., 2016). However, adaptive herding practices have themselves added significant burden through increased workload, costs and stress (*high confidence*) (Furberg et al., 2011; Löf, 2013; Rosqvist et al., 2020). Supplementary feeding also increases risk for infectious diseases and implies culturally undesirable herding practices (*low confidence*) (Lawrence and Kløcker Larsen, 2019; Tryland et al., 2019).

Rapid land use change reduces the ability to adapt (*high confidence*) (Tyler, 2010; Löf, 2013). National and EU policies expand land uses for mining, wind energy and bioeconomy in the area, causing loss, fragmentation and degradation of pastures, increasing human disturbance, and reducing the adaptation space *(medium confidence)* (Kivinen et al., 2012; Skarin and Åhman, 2014; Kivinen, 2015; Skarin et al., 2015; Sandström et al., 2016; Beland Lindahl et al., 2017; Österlin and Raitio, 2020). The cumulative impacts of these land-uses on pastures are not adequately assessed or recognized in land use planning (Kløcker Larsen et al., 2017; Larsen et al., 2018). Herding communities face strong barriers to protecting their rights and halting further degradation of pastures (*medium confidence*) (Allard, 2018; Kløcker Rasmus and Raitio, 2019; Raitio et al., 2020). Attempts by herding communities to stop mining projects have led to conflicts with other actors, including racist hate speech (Persson et al., 2017; Beland Lindahl et al., 2018). Combined with land use conflicts climate impacts cause reduced psycho-social health and increase suicidal thoughts among herders *(low confidence)* (Kaiser et al., 2010; Furberg et al., 2011).

Reindeer herding is and will be significantly affected by climate change directly and indirectly (Figure 13.14) (Pape and Löffler, 2012; Andersson et al., 2015). However, the complexity of the herding system and its socio-political context result in *low confidence* for the precise nature of the impacts of 1.5°C and 3°C warming. Nonetheless, the cumulative effects of land use and climate change have already increased vulnerability and reduced the adaptive capacity of reindeer herding to the extent that its long-term sustainability is threatened (*medium confidence*) (Löf, 2013; Horstkotte et al., 2014; Kløcker Larsen et al., 2017) }.

Maintaining and improving the solution space to adapt reindeer herding is crucial for reducing existing impacts and projected risks of climate and land use change *(low confidence)* (Andersson et al., 2015; Turunen et al., 2016; AMAP, 2017; Hausner et al., 2020). Seasonality of habitat selection can buffer alpine reindeer pastoralism against climate variability (Altieri and Gedan, 2015). Lack of control over land use is the biggest and most urgent threat to the adaptive capacity of reindeer herding and the right of Sami to their culture (*high confidence*) (Pape and Löffler, 2012; Andersson et al., 2015; Larsen and Raitio, 2019).

[END BOX 13.2 HERE]

Displacement of people within Europe is predominantly triggered by economic disparities among European countries (Fischer and Pfaffermayr, 2018) (see section 13.9 for external migration). There is limited and inconclusive evidence for climate-driven impacts on these movements (Hoffmann et al., 2020). Climate-induced migration within Europe occurs in the aftermath of natural disasters and over short distances (Cattaneo et al., 2019). The unequal distribution of future climate risks and adaptive capacity across European regions may increase pressure for internal migration (Williges et al., 2017; Forzieri et al., 2018). For instance, projected sea-level rise (13.2) has the potential to result in abandonment of coastal settlements and inland migration in the UK, the Netherlands and the northern Mediterranean (Mulligan et al., 2014; Antonioli et al., 2017).

13.8.1.3 Cultural Heritage

Changes in rainfall patterns, sea-level rise, coastal erosion, humidity, higher temperature, loss of ice and permafrost, floods and exposure to extreme weather events pose a serious threat to preservation of cultural heritage in Europe (*high confidence*) (Haugen and Mattsson, 2011; Daire et al., 2012; Dupont and Van Eetvelde, 2013; Macalister, 2015; Phillips, 2015; Fatorić and Seekamp, 2017; Graham et al., 2017; Carroll and Aarrevaara, 2018; Sesana et al., 2018; Iosub et al., 2019; Daly et al., 2020). With higher warming levels, not only are building exteriors affected but also valuable collections are at risk from indoor climate changes (Leissner et al., 2015). Low-lying coastal European regions, such as the German Wadden Sea and more than 50 heritage sites along the Mediterranean (Box 13.1 Venice) and UK coastline, are under water-related threats (Reimann et al., 2018b; Walsh, 2018; Harkin et al., 2020) (Cross-Chapter Paper 4).

Disappearing cultural heritage can reduce incomes due to loss of tourism (Hall et al., 2016), as is the case for the Aletsch-Jungfrau glacier in the Swiss Alps or the glaciers of the Laponian Area in Scandinavia and in Greenland (Bjorst and Ren, 2015; Bosson et al., 2019). Intangible cultural heritage can be affected through socio-ecological interconnections with the ecosystems, such as place names, and lost traditional practices (Mustonen, 2018; Dastgerdi et al., 2019). Glacier retreat can create a sense of discomfort, displacement and anxiety in people (Section 13.7) (Albrecht et al., 2007; Brugger et al., 2013; Allison, 2015; Jurt et al., 2015).

13.8.2 Solution Space and Adaptation Options

As climate change is one of many drivers of poverty, improving the social position of the current poor and the vulnerable will also increase their resilience in meeting climate change impacts (Hallegatte and Rozenberg, 2017; Fronzek et al., 2019). Some adaptation actions have the potential to alleviate poverty, such as rooftop photovoltaics which provide electricity to households at lower cost (Romero Rodríguez et al., 2018) (see section 13.11 on trade-offs and synergies). However, adaptation action can also increase social inequalities, e.g., when practices of disaster recovery focus on high visibility areas and thereby amplify inequalities (D'Alisa and Kallis, 2016). Disaster management and risk communication reliant on new technologies can exclude older populations with lower educational attainment (Kešetović et al., 2017).

Regarding risks to northern traditional livelihoods and indigenous communities, small-scale adaptation is taking place, for example by ecological restoration of habitats (section 13.3) (Mustonen and Kontkanen, 2019). However, limited access to resources outside the jurisdictions of the communities limits the scope of community-based adaptation (Arctic Council, 2013; Mustonen et al., 2018; Meredith et al., 2019b). Indigenous knowledge, embedded e.g., in fishermen, farmers and navigators, can be a vehicle for detecting, monitoring and observing impacts (Arctic Council, 2013; Brattland and Mustonen, 2018; Madine et al., 2018; Meredith et al., 2019b). Up to now, climate-induced large scale migration within Europe is prevented by good governance and effective adaptation actions e.g., in the UK (Fielding, 2011; Mulligan et al., 2014).

European world heritage sites are in need of adaptation strategies to preserve key cultural assets (Haugen and Mattsson, 2011; Howard, 2013; Heathcote et al., 2017; Reimann et al., 2018b; Harkin et al., 2020). Current adaptation actions for climate change adaptation in the management of cultural heritage are underdeveloped (Phillips, 2015; Fernandes et al., 2017; Sesana et al., 2018; Daly et al., 2020). Lack of tailored knowledge and understanding of the impacts and how to translate these into adaptation measures constrains implementation and overarching policy guidance is largely absent (Sesana et al., 2018; Fatorić and Biesbroek, 2020; Sesana et al., 2020).

13.8.3 *Knowledge Gaps*

The understanding of the relation between social inequality, climate change impacts and adaptation, especially on different types of poverty (structural, temporal, permanent) and in respect to marginalised groups across different dimensions, such as sexual orientation, is in its infancy. It is unclear whether regional disparities across Europe and structural change amplify internal migration pressure. Indigenous and local knowledge sourcing is still relatively low for Europe and could provide a baseline for adaptation. For cultural heritage, there is also still a major knowledge gap on the range of adaptation options available, including its limits.

13.9 Interregional Impacts, Risks and Adaptation

This section addresses interregional risks between Europe and other parts of the world (not within Europe). Global risk pathways affecting sectors and supply chains relevant for European economies and societies involve (1) ecosystems, (2) people (e.g., through migration), (3) financial flows, and (4) trade, and these pathways ultimately impact security, health, wellbeing and food supply (Yokohata et al., 2019) (Cross-Chapter Box INTEREG in Chapter 16).

13.9.1 Consequences of Climate-change Driven Impacts, Risks and Adaptation Emerging in Other Parts of the World for Europe

Recent literature (Wenz and Levermann, 2016a; Hedlund et al., 2018; Benzie et al., 2019) strengthens the confidence in the AR5 statement from 2014 that "with increasing globalization, the impacts of climate change outside the European region are likely to have implications for countries within the region"(Kovats et al., 2014). The exposure of European countries to trans-European climate impact and risk pathways varies with their degree of globalization, position in the global supply chain, territorial settings and national policies (Berry et al., 2015; Hedlund et al., 2018; Benzie et al., 2019). There is *limited evidence* that Europe is more exposed to interregional risks than North America, and less than Africa and Asia, due to European countries' position in the global supply chain, their national policies, and links with territories outside Europe (see 1.9.3) (Hedlund et al., 2018).

There is *low confidence* in the sign and magnitude of climate change impacts for human inter-regional migration and violent conflicts (Gemenne, 2011; Buhaug et al., 2014; Topilin, 2016; Defrance et al., 2017; Gemenne and Blocher, 2017; Selby et al., 2017; Mach et al., 2019). Asylum applications might double for RCP8.5, but they might also decrease due to growing economic and regulatory limitations in the capacity of populations to migrate from Africa (Kelley et al., 2015; Missirian and Schlenker, 2017; Zickgraf, 2018; Borderon et al., 2019) (Cross-Chapter Box MIGRATE in Chapter 7).

Climate risks in the originating countries can be transmitted to European economies via trade networks (Figure 13.15(a)). Figure 13.15(b) illustrates that European agricultural imports exert a high water footprint in originating countries already today (Dolganova et al., 2019; Ercin et al., 2019), and some crop imports are highly vulnerable to future climate change (Brás et al., 2019; Chatzopoulos et al., 2020). Simultaneous breadbasket failures, and trade restrictions, such as after the 2010 drought in Russia, increase risks to food supply (*medium confidence*) (Fellmann et al., 2014; d'Amour et al., 2016; Gaupp et al., 2017; Gaupp et al., 2020). The European economy is also projected to be negatively affected by supply chain disruptions due to flooding destroying facilities, heatwaves and malaria reducing productivity in labor intensive industries and regions (13.7.1), and sea-level rise affecting ports and cities along coastlines (13.2.1) (*high confidence*) (Nicholls and Kebede, 2012; Challinor et al., 2016a; Wenz and Levermann, 2016b; Hedlund et al., 2018; Koks, 2018; Szewczyk et al., 2018; Willner et al., 2018; Knittel et al., 2020; Kulmer et al., 2020).

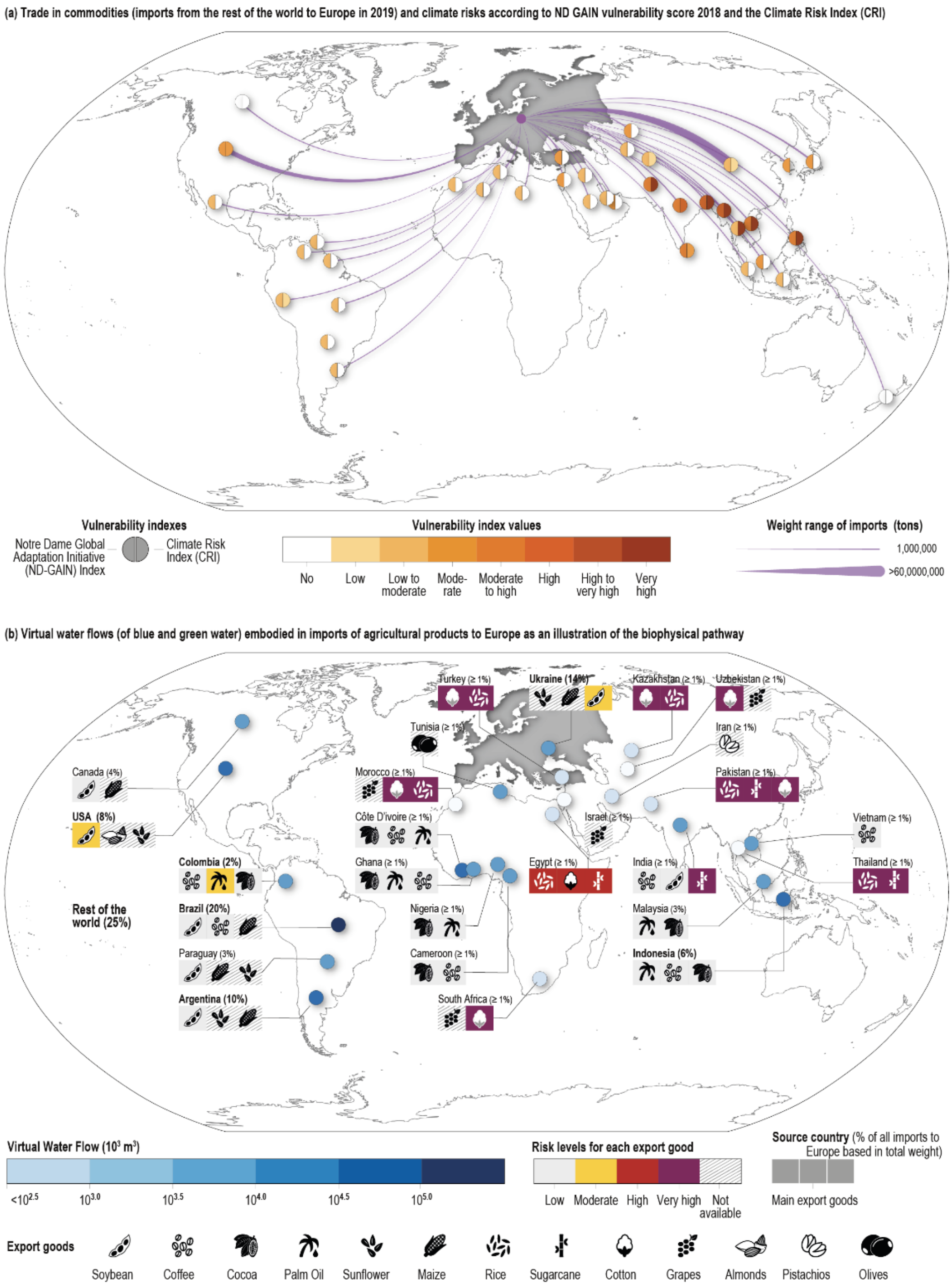


Figure 13.15: Trans-European climate risks in trade: imports of goods and virtual water embodied in agricultural imports. (a) import flows of goods to Europe in 2018 in 1,000 USD (UNCTAD, 2020) and climate change vulnerability of countries of origin, as measured by the ND GAIN exposure score (University of Notre, 2020) and the Climate Risk Index (Germanwatch, 2020); (b) virtual water flows embodied in agricultural imports to Europe in 2018 and the vulnerability to climate change of the most important crops in the originating countries (Dolganova et al., 2019; Ercin et al., 2019).

13.9.2 Interregional Consequences of Climate Risks and Adaptation Emerging from Europe

New literature published since AR5 suggests that climate risks in Europe can propagate worldwide in a 3°C (*medium confidence*). Key concerns include climate impacts on European agriculture threatening global food security (Berry et al., 2017; van der Velde et al., 2018) (Section 13.5.1) and the European demand limiting the adaptation potential for ecosystems in South-America, Africa and Asia (IPBES, 2018; Pendrill et al., 2019; Fuchs et al., 2020). Emerging literature suggests that unprevented coastal flood risks in western Europe could be amplified through the global financial system, and generate a systemic financial crisis

(Mandel et al., 2020a) (Figure 13.16). For 3°C of global warming and without adaptation, northern Atlantic flight routes and European ports are projected to be increasingly disrupted by changing winds, waves, and sea-level rise (Section 13.6.1.2) (Williams and Joshi, 2013; Irvine et al., 2016; Williams, 2016; Becker et al., 2018; Camus et al., 2019; Verschuur et al., 2020).

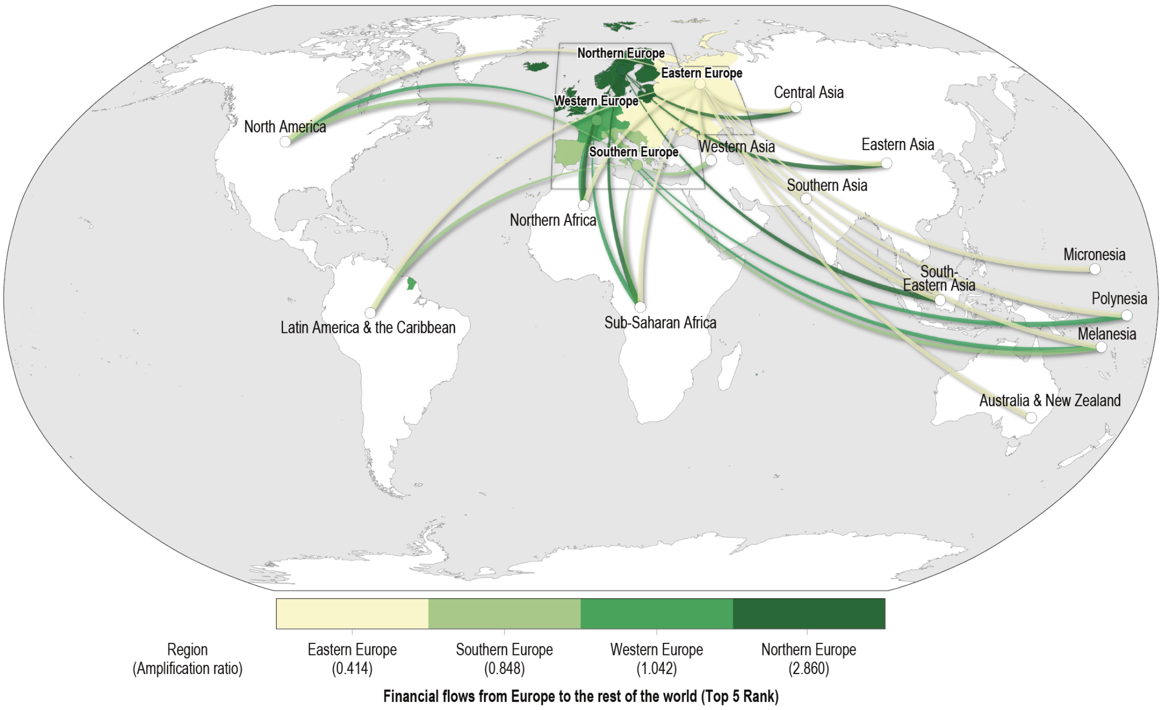


Figure 13.16: The transmission of flood risks via finance flows from Europe to the Rest of the World. The color of the European regions shows the global effect relative to the regional effect. Values larger than 1 indicate that there is spill over, values larger than 2 indicate that their spill over effect is stronger than the regional effect. The fluxes indicate the financial flows from European to other IPCC regions. [Provisional figure - location of Pacific countries will be revised] (Mandel et al., 2020a).

13.9.3 European Territories Outside Europe

European territories outside Europe are critically exposed to climate risks such as increased forest fires (Russian Siberia) (Sitnov et al., 2017), climate change-induced biodiversity losses and sea-level rise (UK, Spanish, Portuguese, French and Dutch overseas regions and territories) (Ferdinand, 2018; Sieber et al., 2018). Europe is projected to be affected by climate risks emerging from these territories, such as smoke and dust from Siberian forest fires (Sitnov et al., 2017), and, depending on European health-risk mitigation measures, dengue and other mosquito-transmitted diseases (13.7) (Schaffner and Mathis, 2014). Some marine protected areas (MPA) in European overseas territories are increasingly affected by changes originating in far-field upstream areas, which, in turn, are influenced by climate change, and ultimately undermines their ability to curb biodiversity losses and foster food security (Schaffner and Mathis, 2014; Robinson et al., 2017). (Robinson et al., 2017)Adaptation options and regulations developed for mainland Europe apply in these territories, despite *limited evidence* that they meet local and regional adaptation challenges and address the aspiration for social justice, promotion of local solutions and consideration of traditional knowledge (Schaffner and Mathis, 2014; Robinson et al., 2017; Sitnov et al., 2017; Ferdinand, 2018; Terorotua et al., 2020).

13.9.4 Solution Space and Adaptation Options

European countries can address interregional risks at the place of origin or destination, e.g., by developing local adaptation capacity in trading partner countries and in European territories outside Europe (Petit and Prudent, 2008; ADEME, 2014; Benzie and Persson, 2019; Adams et al., 2020; Terorotua et al., 2020), by providing international adaptation finance (Dzebo and Stripple, 2015; BMUB, 2017), by developing insurance mechanisms suitable for adaptation, or European climate services to support global adaptation (Linnerooth-Bayer and Mechler, 2015; Brasseur and Gallardo, 2016; Street, 2016; Cavelier et al., 2017; Le Cozannet et al., 2017) (Cross-Chapter Box INTEREG in Chapter 16). Along the supply chain, risks can be reduced by trade diversification and alternative sourcing (Benzie and Persson, 2019; Adams et al., 2020). Within Europe, risks can be reduced by integrating interregional climate risks into national adaptation strategies and plans and mainstreaming into EU policies (e.g., Common Agricultural Policy, trade agreements) (Benzie et al., 2019; Benzie and Persson, 2019; Adams et al., 2020). There is *high confidence* that the exposure of European countries to interregional risks can be reduced by international governance (Dzebo and Stripple, 2015; Cramer et al., 2018; Persson and Dzebo, 2019) (Cross-Chapter Paper 4), e.g., fulfilling the targets of environmental agreements such as the Convention for Biological Diversity (IPBES, 2018). There is emerging evidence that supporting adaptation outside Europe may generate economic co-benefits for Europe (Román et al., 2018), but there is also the potential risk that, for example, substituting suppliers may increase risk levels in the most vulnerable countries (Benzie et al., 2019; Adams et al., 2020).

13.10 Detection and Attribution, and Key Risks Across Sectors and Regions

13.10.1 Detection and Attribution of Impacts

Since AR5, scientific documentation of changes attributed to global warming have proliferated (*high confidence*). Ecosystem changes detected in previous assessments, such as earlier annual greening and onset of faunal reproduction processes, and relocation of species towards higher latitudes and altitudes, have been further documented and attributed to climate change (*high confidence*). The impacts of heat on human health, and productivity are already detectable now and have been attributed to climate change (*medium confidence*) (Figure 13.17). Formal attribution of impacts of compound events to anthropogenic climate change is just emerging. However, there is high agreement and medium evidence that particular events attributed to climate change have induced cascading impacts and other impact interactions (Smale et al., 2019; Vogel et al., 2019). The methodology of attribution is discussed in Chapter 16.2.

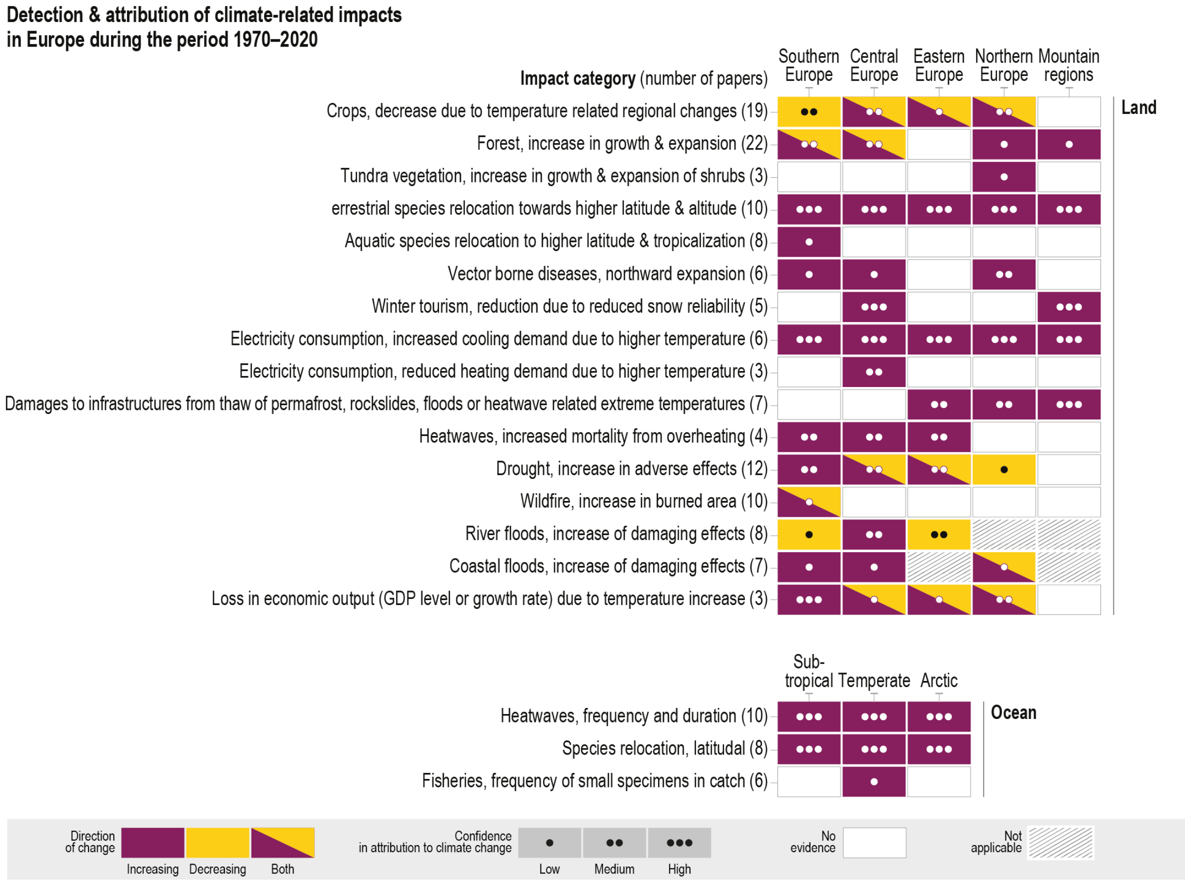


Figure 13.17: Detected changes and attribution (D&A) on land (top) and in the ocean (bottom). Assessment based on peer reviewed literature in this chapter that reported observed evidence with at least 90% significance and usually with 95% significance or more. The list of the assessed references is provided in Table 13.A.9.

13.10.2 Consequences of multiple climate impacts and risks for European economies

While not all impact categories can be measured in monetary values, macroeconomic loss (reduction on aggregate economic output or welfare) is a metric for comparing between impact categories, regions, and time periods. Macroeconomic assessments of multiple climate risks capture not only the direct losses within the affected systems, but also indirect effects due to cascading and interaction effects across sectors, as well as market and price responses. The total economic effect can be therefore considerably larger than the direct effect, e.g., for riverine flooding (Koks and Thissen, 2016).

At lower warming levels (up to approx. 0.8 °C above pre-industrial), macroeconomic losses were detected for southern Europe whereas gains were detected for northern Europe and there was mixed evidence for central and eastern Europe (Burke et al., 2015). In the recent decades (2000-2015), economic losses intensified in southern Europe (*high confidence*) and were also detected for parts of Central, Eastern and Northern Europe (*medium confidence*) (Table 13.13), with an estimated GDP loss of US$ 300 bn per year for Europe in total (Burke and Tanutama, 2019; Diffenbaugh and Burke, 2019b).

Under 1.5°C, a few sectors and regions experience economic gains (e.g., agriculture and energy supply in Northern Europe and Northern parts of Eastern Europe) (Pretis et al., 2018; Szewczyk et al., 2018; Kahn et al., 2019; Szewczyk et al., 2020), but the combined effect of multiple risks is negative for Southern Europe (*high confidence*) and for Europe in total (*medium confidence*) (Aaheim et al., 2017; Szewczyk et al., 2018; Szewczyk et al., 2020). Under 3°C warming, economic losses for Europe are multiple times larger than under 1.5°C (*medium confidence*) because almost all European regions show net losses and the losses are much higher in Southern Europe (*high confidence*) (Kalkuhl and Wenz, 2020). Despite net economic losses in almost all regions, regional disparities are intensified (*medium confidence*), amplifying existing economic disparities among European regions (Diffenbaugh and Burke, 2019b; Feyen et al., 2020). While the trend direction is uniform for MED and NEU, there are opposing trends within EEU and WCE due to the large spatial gradient.

When comparing across sectoral risks for 3°C warming, the highest contribution to macroeconomic damages originate in health, followed by agriculture, coastal flooding, labour productivity and riverine flooding (Table 13.13). In addition, drought and water scarcity lead to considerable macroeconomic costs. While risks for tourism and energy supply and demand may be substantial in parts of Europe like the Alps (Gonseth and Vielle, 2018), the evidence suggests that the total effect on the European scale is smaller. There is also emerging evidence that climate risks from regions outside Europe lead to considerable economic losses for Europe (Section 13.9). Several climate risks, such as loss of biodiversity and ecosystem services e.g., provided by forests, are not included in these macroeconomic assessments but have potentially also high societal costs.

Adaptation is found to effectively reduce macroeconomic costs but residual costs remain, particularly for warming of more than 3°C (*low evidence, medium agreement*) (De Cian et al., 2016 damage and adaptation; Bosello et al., 2018).

Table 13.13: Macroeconomic effects due to projected climate risks in multiple sectors, for 3°C relative to no additional warming; macroeconomic effects measured in GDP or welfare; decrease = GDP/welfare loss; increase = GDP/welfare gain. List of references in Table 13.A.10

Sectoral risks	n	MED	NEU	WCE	EEU	Europe
Agriculture	(6)	•••	••	••	••	•••
Coastal flooding	(8)	•••	•••	•••	•••	•••
River flooding	(5)	••	••	••	••	••
Health	(5)	•••	••	••	••	••
Labor productivity	(5)	••	••	••	••	••
Energy	(5)	••	••	••	••	••
Forestry	(2)	LE	LE	LE	LE	LE
Fisheries	(1)	LE	LE	LE	LE	LE
Drought / water scarcity	(5)	••	•	•	•	••
Tourism	(3)	••	•	•	•	•
Transport	(2)	LE	LE	LE	LE	LE
Trade	(3)	•	•	•	•	••
TOTAL	(7)	•••	•••	•••	••	•••

GDP Loss				GDP Gain		
very high (VD)	high (HD)	moderate (MD)	no (N)	moderate (MI)	high (HI)	very high (VI)

Confidence: high (•••), medium (••), low (•)

both (B) | limited evidence (LE)

13.10.3 Key Risks Assessment for Europe

The key risks are informed by a body of literature highlighting the complex and interacting nature of climate risks (Raymond et al., 2020; Zscheischler et al., 2020; Simpson et al., submitted). Consequences from key risks are amplified due to cumulative effects and feedbacks on human and ecosystems and their potential to cascade across sectors (Section 13.10.2) (*medium evidence, high agreement*) (Huber et al., 2014; Gallina et al., 2016; Gill and Malamud, 2016; Rosenzweig et al., 2017; Byers et al., 2018). Key risk consequences are summarised in Table 13.14 following the key risk approach in Section 16.5.2.1. The direction of change per region and aspects assessed are shown in Figure 13.18. The literature and data used are in Table 13.A.9.

Table 13.14: The table explains the (severe) risk consequences and geographical area they apply. A more detailed version is available in Chapter 16].

Key risk	Consequences that would be considered severe	Geographical area	Confidence in key risk identification
KR1: Risk of stress and mortality to people and to marine and freshwater ecosystems and loss of income from crop yields due to increasing temperatures and heat extremes	On average 40 times more heat-related deaths with 3°C warming (compared to present warming). By mid-century (2 C warming) up to 200 million people at high risk of heat stress (compared to 2 million for the period 1986-2005) with more than 50% of the population at risk of thermal discomfort. Large scale reorganisation of marine, terrestrial and freshwater ecosystems. Up to 30% loss in yields with highest losses in southern region. Up to 60% increase in the impacts of invasive species (e.g., bark beetles).	Europe (whole continent) but risk increases from Northern to Southern Europe	*High confidence* in the direction, *medium confidence* in the relative change
KR2: Risk of income loss from crops yields, fire and limited recovery of terrestrial ecosystems from compound heat and dry conditions	Reduced crop production; amplified risk of wildfires; abandonment of farmland; loss of fodder; considerable reduction of recovery capacity and large-scale reorganisation of ecosystems and biome-shift.	Southern and central Europe	*High confidence* (MED), *medium confidence* (WCE)
KR3: Risks of mortality and damage to coastal infrastructure and economic assets due to coastal and inland flooding	Expected Annual Damage (number of people) costs increase by a factor of at least 10 (at least 16), with large adaptation and mitigation. Local loss of marine and terrestrial ecosystems reduces or eliminate their ability to lessen the impacts.	Low-lying European coastal zones (lower concern in Scandinavia), some river floodplains and mountain areas	*High confidence*
KR4: Risk of water scarcity to multiple interconnected sectors	One-third to over one-half million people are exposed to moderate water scarcity in Southern regions by mid-century due to competing demands from agriculture, energy generation, domestic and municipal water consumption.	Southern Europe, Central and Eastern Europe	*High confidence* (Southern Europe), *medium confidence* (Central and Eastern Europe)

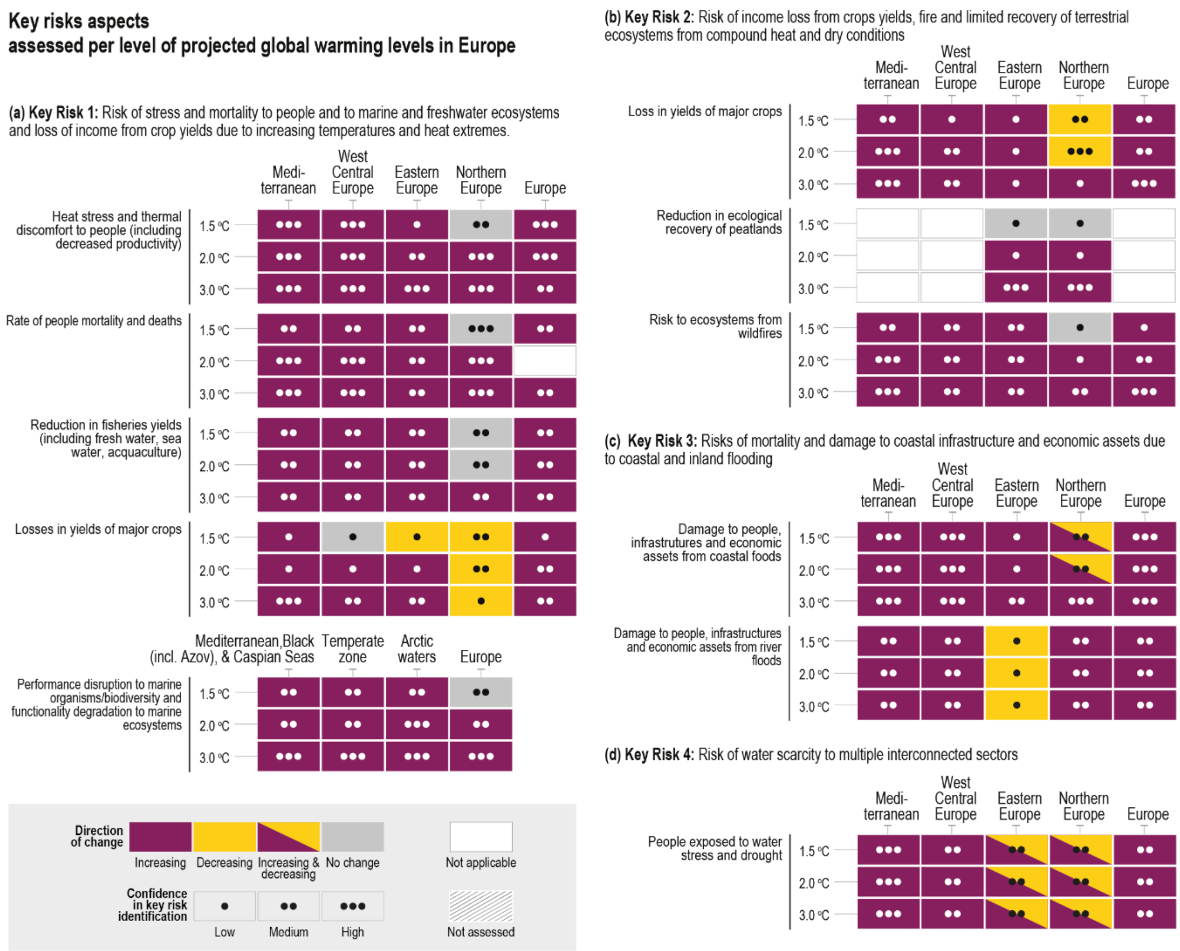


Figure 13.18: Regional synthesis of changes in consequences as "assessed aspects" associated with each key risk and for 1.5°C, 2°C and 3°C warming above pre-industrial. Further details in Table 13.A.9.

13.10.3.1 Risk of stress and mortality to people and to marine and freshwater ecosystems and loss of income from crop yields due to increasing temperatures and heat extremes

Heat related consequences to people manifest through an increase in the number of deaths, mortality rates, heat stress and exposure as well as reduction in thermal comfort and labour productivity (*high confidence*) (Table 13.11; Section 13.6.1.5.2; Section 13.7.1.1) (Forzieri et al., 2017; Gasparrini et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019; Casanueva et al., 2020). There is *medium evidence and agreement* that heat related fatalities will be 3-6 times higher at 3°C compared with 1.5°C (Forzieri et al., 2017; Naumann et al., 2020). For present and SSP1 conditions, the aggregate risk (i.e. across all assessed aspects) will remain moderate for warming levels up to 2°C (Figure 13.19(a)) (Gasparrini et al., 2017; Cellura et al., 2018; Guo et al., 2018; Rohat et al., 2019). Higher risk levels are reached for SSP3 and SSP4 conditions (mapping a medium to high vulnerability and exposure, see Figure 13.19(a)) (*robust evidence, moderate agreement*) (Hunt et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019). Negative consequences will be the highest in southern Europe, where their magnitude is also expected to increase more rapidly (Forzieri et al., 2017; Gasparrini et al., 2017; Cellura et al., 2018; Guo et al., 2018; Díaz et al., 2019; Rohat et al., 2019). Central, eastern and northern Europe will also experience accelerating negative consequences beyond 1.5°C (Guo et al., 2018; Revich et al., 2019).

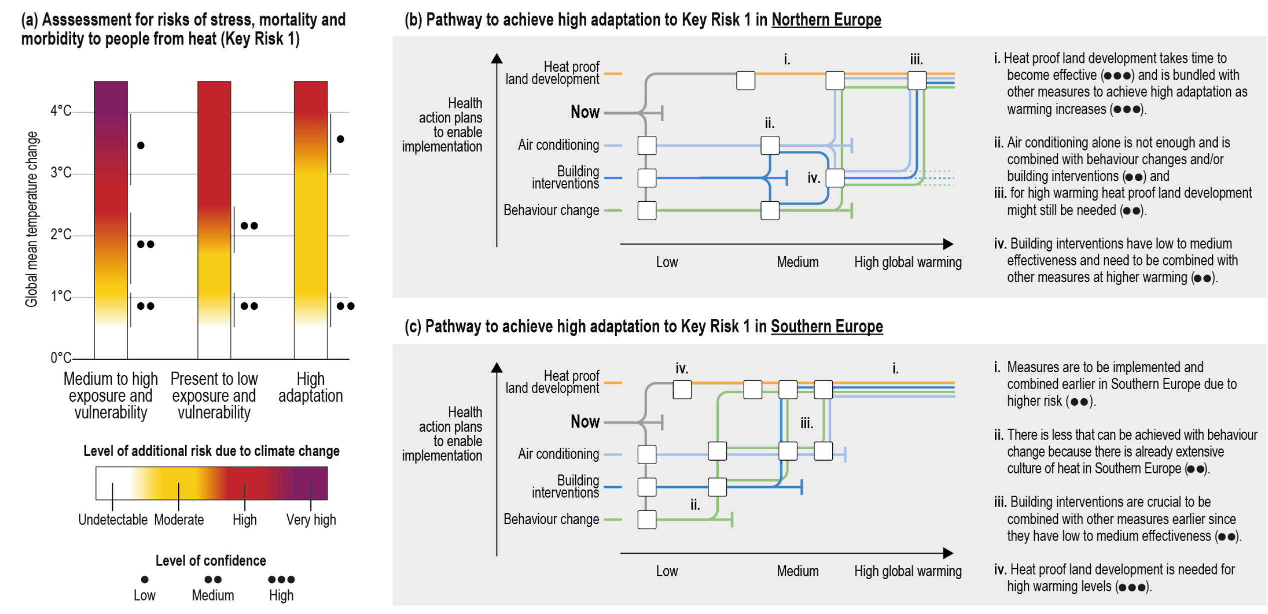
The effectiveness of adaptation measures depends on local context (*high confidence*) (Figure 13.19(b)). For example, natural ventilation is considered an effective, low cost and highly feasible measure for northern Europe (Ibrahim and Pelsmakers, 2018), but the effectiveness is generally lower for southern Europe (Table 13.9, Section 13.6.2) (*medium agreement, robust evidence*). Other measures are highly effective across Europe irrespective of warming levels, including air conditioning and urban planning (*high confidence*)

(Sections 13.6.2 and 13.7.2) (Jenkins et al., 2014b; Donner et al., 2015; Dodoo and Gustavsson, 2016; Astrom et al., 2017; Dino and Meral Akgül, 2019; Venter et al., 2020)], although air conditioning increasingly faces feasibility constraints (Tables 13.9 and 13.11). Building interventions have low to medium effectiveness independent of the region (Tables 13.9 and 13.11). Many behavioural changes such as personal and home protection have already been implemented and a culture of heat exists in southern Europe (Section 13.7.2, Martinez et al., 2019). To reach higher adaptation, measures combining low-medium-high effective actions are needed (Figure 13.19(b)), many of which are more systems transformative (Chapter 16) (e.g., heat proof land management) and remain effective at higher warming levels (*medium confidence*) (Díaz et al., 2019). These system transformations have long lead times, therefore requiring timely start of implementation including regions that are not yet experiencing high heat stress (*high agreement, medium evidence*).

Adaptation limits are in general discussed in the context of heat tolerance and heat habituation for humans recognising that adaptation has the potential to increase the thresholds of heat tolerance with *robust evidence and moderate agreement* that this process has happened already for people - albeit at different speeds - in almost all European regions (Section 13.7.1.1). However, it is uncertain how far heat tolerance can be enhanced and the conditions that will make it possible for warming of 3°C and beyond (Figure 13.19(a), Section 13.7.2)(Hanna and Tait, 2015).

The assessment of KR1 extends to natural systems and ecosystems. Warming impacts the physiology, phenology and ecology of species and populations resulting in changes in timing of development, migration northwards and upwards, desynchronization of species interactions, especially at the range limits, with cascading and cumulative impacts through ecosystems and food webs (Sections 13.3 and 13.4, *high confidence*). Stressful thermal and drought events impacting species on sea and land are increasing already, particularly in coastal areas of the Mediterranean Sea, the Balkans, and the western area of the Caspian Sea (Section 13.3; (Kärcher et al., 2019); Cross-Chapter Paper 4). In both land and the oceans, warming is currently within the current tolerance envelope of many species (Henson et al., 2017) resulting in migration, especially at the boundaries of ecological regions, but only rarely in documented local extinctions (Sections 13.3 and 13.4) (Smale, 2020). Land and marine heatwaves are projected to intensify, especially in the Mediterranean (Darmaraki et al., 2019b) (Section 13.4, Cross-Chapter Paper 4, WGI AR6 Chapter 9), projecting mass mortalities of vulnerable species and species extinction, altering the provision of important ecosystem goods and services, such as carbon sequestration, habitat generation and socioeconomic value (Marbà and Duarte, 2010).

Autonomous adaptation of species via migration in response to climate change is well documented in contemporary, historical and geological records (Figure 13.18, Chapter 2, Cross-Chapter Box PALEO in Chapter 1). However, the projected rate of environmental change can exceed migration potential, which would lead to evolutionary adaptation or increased extinction risk (Chapters 2 and 3). A reduction of non-climatic stressors, such as nutrient loads, resource extraction, habitat fragmentation or pesticides on land, are considered important adaptation options to increase the resilience to climate-change impacts (Ramírez et al., 2018) (Sections 13.3 and 13.4; *high confidence*). A major governance tool to reduce other impacts is the establishment of networks of protected areas (Sections 13.3.2 and 13.4.2) which are particularly suited to facilitate migration of species following their preferred temperature (*high confidence*), as well as a cost-effective adaptation strategy with multiple additional co-benefits (Roberts et al., 2017). Relocation of species, such as replanting, and restoration and rewilding (Section 13.3) are measures in areas where habitats have been lost. However, statutory policies around rewilding are lacking in Europe (Jones and Comfort, 2020). If these multiple adaptation tools are implemented too late or not sufficiently to effectively cope with rapid change, the genetic manipulation of species to gain higher tolerance against climatic stressors (assisted evolution) has been suggested as an adaptation tool (Filbee-Dexter and Smajdor, 2019). However, statutory policies around rewilding are lacking in Europe (Jones and Comfort, 2020).



(c) KR1: Example of a figure for marine and land ecosystems to be further developed

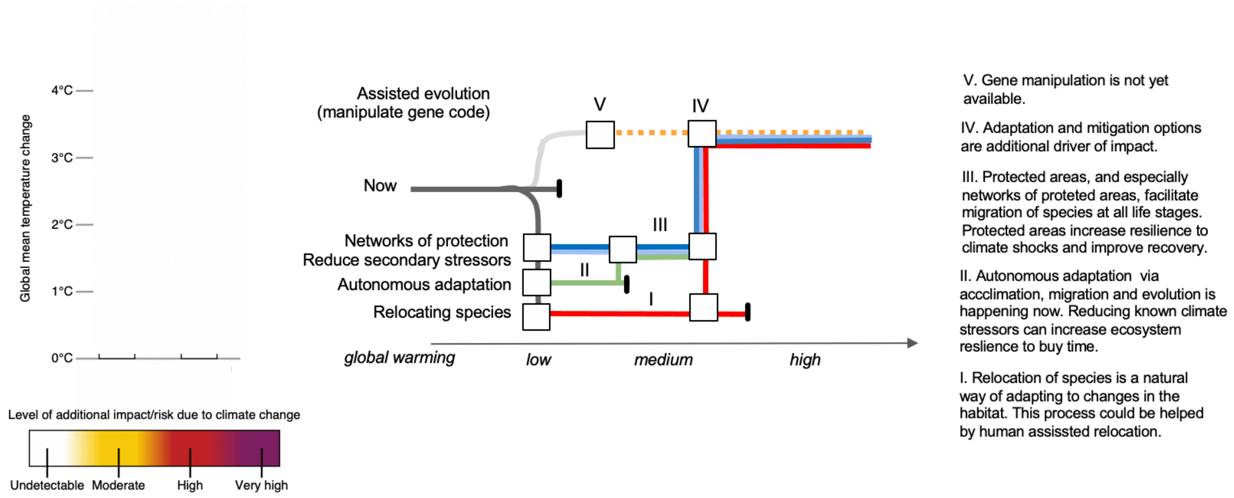


Figure 13.19: Panel (a) shows the burning embers for KR1 (human health) for two vulnerability and exposure conditions and for a high adaptation scenario, which refers to the adaptation to maintain current level of risk up to about 3°C. Panel (b) shows the illustrative adaptation pathways to achieve high adaptation for two regions based on the assessment of adaptation effectiveness (Section 13.10.3.1; Table 13.9; Table 13.11; (Haasnoot et al., 2020a)). Grey shading represents long lead time and dotted lines signal reduced effectiveness. The squares mean that the options are transferred to another pathway and the black bars that the pathways have reached a tipping point. Main key messages from the effectiveness assessment are shown on the right sides with corresponding confidence level and informed by the feasibility and effectiveness assessment. [Bottom panel (c) will show a similar figure but for ecosystems. [PLACEHOLDER FOR FINAL DRAFT: risk levels (left) will be inserted; pathways (right) have not been fully assessed and will be finalised]. The literature and data associated with these figures can be found in Table 13.A.7 and Table 13.A.9.

13.10.3.2 Risk of income loss from crops yields, fire and limited recovery of terrestrial ecosystems from compound heat and dry conditions

KR2 is already considered severe due to repetitive crop failure in the last decade in WCE and Russia (Section 13.5.1). There is *high confidence* that heat extremes compounded by drying conditions and strong winds have produced already widespread impacts across Europe (Hao et al., 2018; Pfleiderer et al., 2019; Vogel et al., 2019). Heatwaves and droughts have impacted the health of people and livestock (Sections 13.5.2, 13.6 and 13.7.1); agriculture (Section 13.5.1), limiting water resources (Section 13.2, Section 13.10.3.4) and impacting ecosystem function (Sections 13.3 and 13.4). There is *high confidence* that climate change will increase the likelihood of concurrent extremely dry and hot warm seasons with higher risks for Central Europe, Eastern Europe (particularly north-western Russia) and Southern Europe leading to enhanced risk of wildfires, crop failure and decrease in pasture quality (Section 13.5.1) (AR6 WGI Chapter 11, Zscheischler and Seneviratne, 2017; Sedlmeier et al., 2018).

Winter crops are projected to be less vulnerable due to earlier harvest. Yield loss in the EU28 in response to 3-4℃ warming of 10% are projected, and regionally gains at low warming (Webber et al., 2018) though some studies suggest significant losses (Toreti et al., 2019a). In contrast, maize, a summer crop, is irrigated already today in the MED (13.5.2). Future compound heat and drought events are projected to lead to maize yield losses in MED, WCE and EEU, locally resulting in total loss in southern Europe, averaging at 15% across the EU28 (Webber et al., 2018). In Southern Europe, increased heat and drought stress and reduced irrigation are projected to lead to abandonment of farmland as profitability of the land for agriculture decreases (Holman et al., 2017).

More intense and longer droughts, potentially coupled to heatwaves, can lead to a substantial desiccation of vegetation and drying of soils *(high confidence*). These will increase the conditions enabling fire, its rate of spread and thereby reduce suppression opportunities, as was evidenced in past heat waves in southern Europe (Section 13.2.1.2) (Ruffault et al., 2017). Projected increases in fire-hazard days for EEU vary regionally between 20 and 50% (Frolov et al., 2014). Burned area is projected to increase by a factor 2 for low end warming and 4 for 3°C-4°C (Wu et al., 2015a). Attempts at quantifying future risks from compound heat and drought events are scarce, though physiological responses of land plants (Chapter 2; Section 13.3) and crop (Chapter 4, Section 13.5.1) are well documented and impacts already detected for recent events in eastern Europe and central Europe in the last decade (Section 13.5.1, 13.10.1).

Autonomous adaptation of farmers to changing environments has happened for centuries. Adaptation solutions in the context of heat and drought-risk management include irrigation, the use of protective vegetative cover, mixed farming practices, change of crop and animal species, timing of planting but an integrated assessment of feasibility and effectiveness of combined adaptation options is lacking for many crops and regions (*high confidence*, Section 13.5.2). KR2 can be significantly reduced for crop production if the canopy temperature is reduced with irrigation and the drought impact removed (*high confidence*) (Webber et al., 2018); Section 13.5.2]. As KR4 points out clearly though, water will be distributed across many needs limiting its availability to agriculture which is currently the main user of water in many regions of Europe. Heat impacts on agriculture can be reduced via climate control for livestock and irrigation for crops at the cost of increasing the demand on energy and the investment in infrastructure (Section 13.5.2) (*medium confidence*). Without these adaptation options loss in the agricultural sector is projected, with an increase of risk from north to south with higher risk for those crops growing later in the season such as maize (*high confidence*). Under high-end scenarios, heat and drought extremes could become more frequent and widespread as early as mid-century (Toreti et al., 2019a).

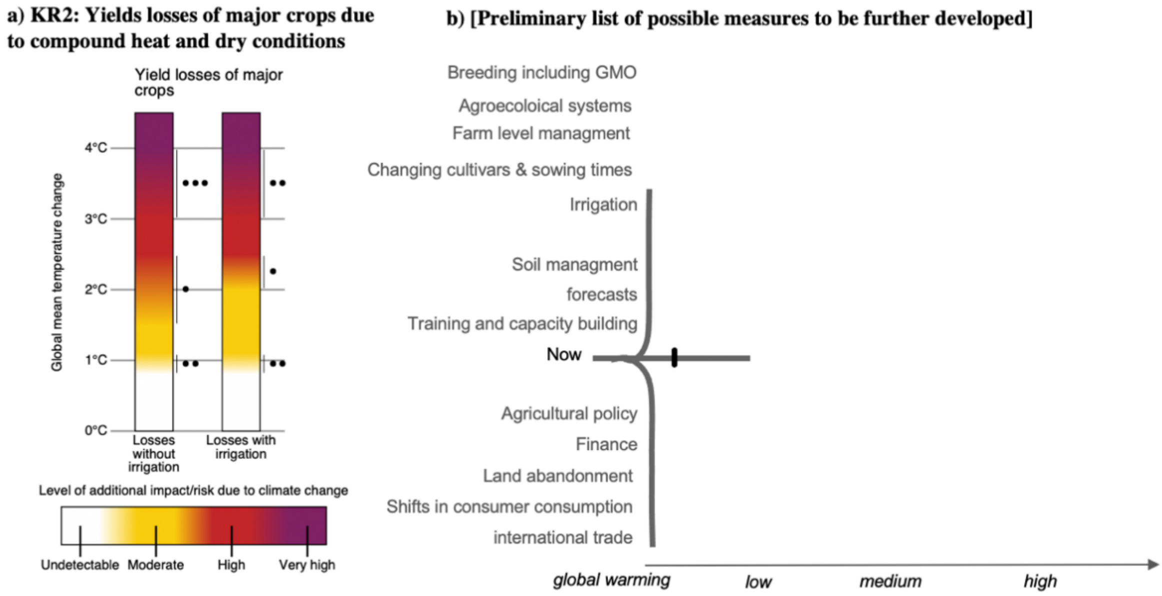


Figure 13.20: Panel (a) shows the burning ember diagram for KR2 [PLACEHOLDER FOR FINAL DRAFT: we have looked mainly at losses without and with irrigation. In the final draft we will amalgamate the burning ember with evidence from additional adaptation options to make it equivalent to Figure 13.19. We will also populate currently missing pathways (b)]

*13.10.3.3 Risks to people, economies and infrastructures d*ue to flood hazards

Damage and losses to people and infrastructure due to coastal and river floods are projected to increase substantially in Europe (*high confidence*) (Section 13.2.1.2) (Alfieri et al., 2015a; Alfieri et al., 2015b; Alfieri et al., 2016; Forzieri et al., 2017; Alfieri et al., 2018; Dottori et al., 2018; Guerreiro et al., 2018; Jacob et al., 2018; Vousdoukas et al., 2018a; Vousdoukas et al., 2018b; Vousdoukas et al., 2020a; Haasnoot et al., submitted). Damage and losses to people and infrastructure due to coastal and river floods are projected to increase substantially in Europe (*high confidence*) (Section 13.2.1) (Alfieri et al., 2015a; Alfieri et al., 2015b; Alfieri et al., 2016; Forzieri et al., 2017; Alfieri et al., 2018; Dottori et al., 2018; Guerreiro et al., 2018; Jacob et al., 2018; Vousdoukas et al., 2018a; Vousdoukas et al., 2018b; Vousdoukas et al., 2020a; Haasnoot et al., submitted).

Above 3°C, climate change may account for a doubling of damage costs and people affected from river flood (Alfieri et al., 2018). Depending on future greenhouse gas emissions, coastal flood damages may increase by a factor of 100 to 1000 without further adaptation (Vousdoukas et al., 2020a). While there is *high confidence* in the sign of projected trends, there is *low confidence* in quantitative economic assessments of flood impacts in Europe due to the uncertainties of current global flood models (see AR6 WGI Chapter 9). The human exposure to coastal hazards is projected to increase by 20% or 50% for SSP1 and SSP5 by the end of the century (*low evidence*) (Merkens et al., 2016; Reimann et al., 2018a). Future human exposure to river flood hazards for SSP5 might increase in northern and western Europe and in Russia (l*ow agreemen*t) (Jongman et al., 2012; Jones and O'Neill, 2016; Dottori et al., 2018). Vulnerability to flood hazards has decreased in WCE and NEU in the last decades due to improved flood risk prevention, but there is *low agreement* that this trend can compensate the projected increase in flood hazards (Jongman et al., 2015; Alfieri et al., 2018).

KR3 trends in flood risks are projected to increase considerably under scenarios of no to low adaptation both in terms of fatalities and economic losses (Figure 13.21). However, damage from coastal floods can be reduced by more than 80% with economically efficient adaptation (Vousdoukas et al., 2020a) Adaptation approaches, their timing and effectiveness are assessed in Section 13.2 and visualised in Figure 13.21 for urban and rural archetypes (Haasnoot et al., 2019).

Adaptation approaches include (1) reducing exposure (retreat/relocation/managed realignment); (2) reducing vulnerability (accommodation) and (3) reducing the hazard (nature-based or engineering based protections) (AR6 SROCC Chapter 4; Section 13.2; Cross-Chapter Box SLR in Chapter 3). Nature based solutions are increasingly considered and implemented across Europe (Pranzini et al., 2015), but their effectiveness is not guaranteed above 2.5° of global warming and for high rates of sea level rise (Gattuso et al., 2015; Kirwan et al., 2016) (Section 13.2.2).

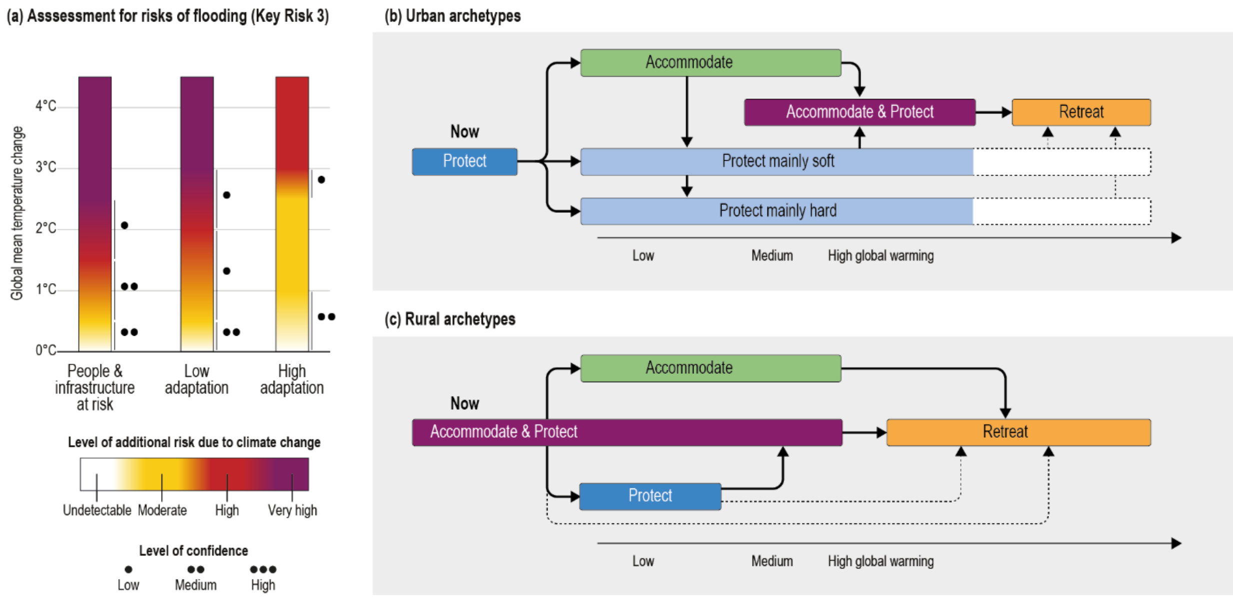


Figure 13.21: KR3 flood risk assessments. Panel A: magnitude of exposure to KR3 and associated risks with and without adaptation; Panel B: plausible adaptation pathways to sea-level rise (Table 13.A.9; Table 13.2) [PLACEHOLDER FOR FINAL DRAFT: Panel B will be further developed].

Figure 13.21 does not include emerging reasons for concern in Europe, such as observed and projected increases of extreme rainfall events (van Oldenborgh et al., 2016; Philip et al., 2018; Myhre et al., 2019), observed increases of synchronous river floods (Berghuijs et al., 2019), projected compound flood hazards in lower river watersheds, due to a seasonal shift of extreme rainfall events toward the autumn and winter storm surge season in particular in the Mediterranean and Northern Europe (Arnbjerg-Nielsen et al., 2015; Bevacqua et al., 2019). Climate risks in Europe are projected to become even more substantial with ice-sheets collapse (Thieblemont et al., 2019) as well as beyond 2100 (Clark et al., 2016) (Cross-Chapter Box SLR in Chapter 3) (*limited evidence, high agreement*). Above 3 meters of sea-level rise, the location and size of coastal infrastructures such as the Thames estuary needs to be reconsidered (Ranger et al., 2013).

13.10.3.4 Risk of water scarcity to multiple interconnected sectors

Drought and water scarcity affect a number of highly connected sectors in Europe, from public water supply to agriculture and livestock farming, energy (hydropower and cooling of thermal power plants) and industry (e.g., shipping) (Blauhut et al., 2015; Stahl et al., 2016; Bisselink et al., 2020; Cammalleri et al., 2020). Across Europe, drought is generally impacting agriculture and livestock farming more than public water supply (Stahl et al., 2016). Similarly, water quality will be negatively affected by climate change further enhancing the risks of water stress to multiple sectors (Section 13.2.1.4). In the EU and UK together, around 3.3 million people and € 75 billion of economic activity are currently exposed to severe water scarcity (Stahl et al., 2016; Bisselink et al., 2020). Around 90% of drought damage and population exposed to water scarcity are located in Southern Europe (*high confidence*) (Section 13.2, 13.3 and 13.5) but there is emerging evidence of damages due to drought and water scarcity also in parts of Central and Eastern Europe (*medium confidence*).

With 1.5°C warming, in Southern Europe the number of days with water scarcity and drought will increase slightly (Schleussner et al., 2016; Naumann et al., 2018). In Central and Eastern Europe, there is no clear trend in the number of days with water scarcity and drought (Schleussner et al., 2016; Naumann et al., 2018).

With warming of 3°C and beyond, water scarcity will become much more severe in already water scarce regions in Southern Europe (*high confidence*) and will expand to currently non water scarce regions in Central and Eastern Europe (*medium confidence*) (Section 13.2.1.2) (Naumann et al., 2018; Harrison et al., 2019; Koutroulis et al., 2019; Bisselink et al., 2020; Cammalleri et al., 2020; Spinoni et al., 2020). One third to over a half of the population in Southern Europe will be exposed to moderate water scarcity with 3°C and SSP5 by end of the century (Byers et al., 2018; Arnell et al., 2019). In Central and Eastern Europe, around 10% of the population will be exposed to water stress (Byers et al., 2018; Arnell et al., 2019).

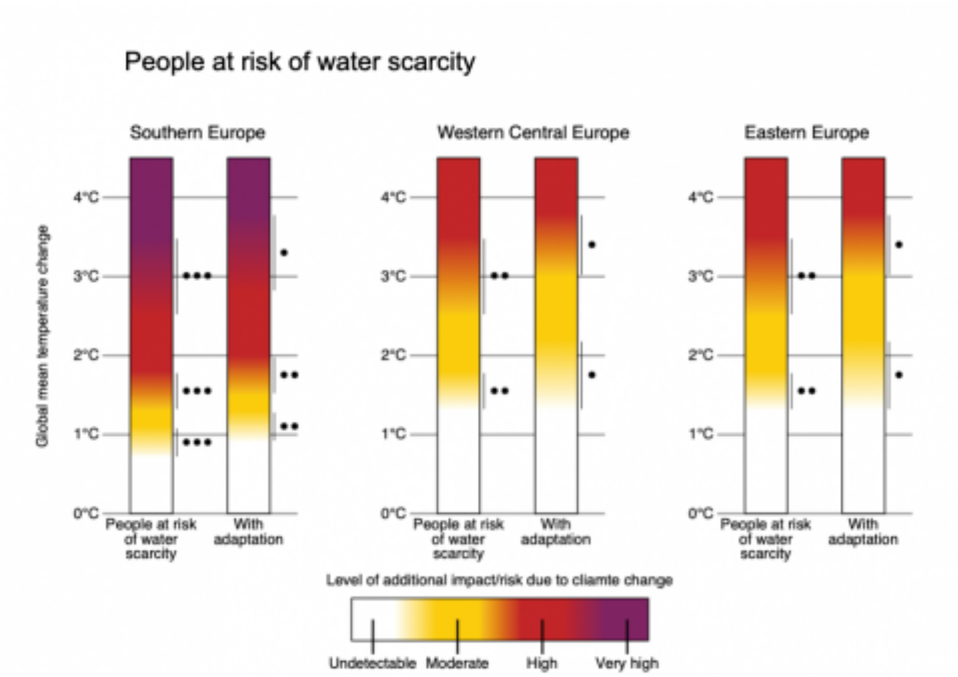


Figure 13.22: Burning ember diagrams for the risk of water scarcity to people in MED, WCE and EEU [PLACEHOLDER FOR FINAL DRAFT: references will be added; a panel on adaptation pathways will be added] (see Table 13.A.9).

Socioeconomic change contributes to risk levels, e.g., when a larger share of population settles in drought affected regions, or if the share of agriculture in GDP declines and therefore risk levels are lower (*high confidence*). For Europe in total, risk of water stress is higher under SSP5 and SSP3 than under SSP1 (*low confidence*) (Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019). Heat extremes will significantly increase the energy demand for cooling, while concurrent droughts will reduce the hydropower potential and river flows, and together with higher temperatures- will impose water-cooling constraints on thermoelectric power generation (Section 13.6.1.1).

To reduce the effects of drought and water scarcity, adaptation measures both at the supply and demand have been suggested (Section 13.2.2) (Garnier and Holman, 2019; Hagenlocher et al., 2019). There is only limited evidence on the effectiveness of different adaptation options in reducing risk of cross-sectoral water scarcity. While water trading is found to allocate water more efficiently across sectors and therefore reduce the economywide costs of water scarcity (Roson and Damania, 2017), this might have negative side effects for public water supply, the manufacturing sector and neighbouring countries (Wimmer et al., 2014; Koopman et al., 2017; Teotónio et al., 2020) (Section 13.9.2). To address the trade-offs among sectors, collaborative and integrated policies are needed that consider the trade-offs and synergies across sectors (Venghaus and Hake, 2018 energy and water resources). For example, sustainable water management is found effective in reducing future water scarcity, but there is a potential trade-off with food availability and employment (*low confidence*) (Papadimitriou et al., 2019).

13.10.4 Knowledge gaps

There is *low to medium confidence* that adaptation will be effective to reduce the risk severity for warming of and beyond 3°C and in particular in regions where multiple key risks show high to very high risk levels. Therefore, residual risks cannot be completely excluded even under scenarios of high adaptation, although there is only very *limited evidence* on their extent and timing. There is *limited evidence* on the effectiveness of specific adaptation options at different levels of warming that also include consideration of lead and lifetimes and in particular for KR1, KR2, and KR4. A Pan-European understanding of the emerging reasons for concern listed in Section 13.10.3.3 is lacking in the literature available today. Estimates of macroeconomic losses underestimate the full costs of climate change as available models neglect systemic risks, tipping points and limits to adaptation (Koks et al., 2019a; van Ginkel et al., 2020). Efforts to extend the SSP narratives to Europe can contribute to a more disaggregated understanding of risk severity for different vulnerability and exposure conditions (Figure 13.13). However, the evidence remains limited to only few examples (Rohat et al., 2018; Kok et al., 2019; Pedde et al., 2019; Rohat et al., 2019).

13.11 Adaptation Decision-making Across Sectors and Regions

13.11.1 Adaptation Responses across Europe

Observed and projected climate change impacts are recorded across Europe's sectors, vulnerable groups, and regions (Section 13.10.1). Coordinated policy responses are necessary to prevent inefficient and costly action (Clar, 2019), balance under- and over-reaction to climate risks (Peters et al., 2017; Biesbroek and Candel, 2019), prevent redistributing vulnerability (Atteridge and Remling, 2018), ensure timely implementation, and avoid unintended and maladaptive actions (Magnan et al., 2016) (*high confidence*). Since AR5, progress has been made to increase coordinated adaptation actions, but so far this is limited to a few sectors (mostly water management and agriculture) and European countries and regions (mostly MED, WCE depending on impact) (Lesnikowski et al., 2016; Biesbroek and Delaney, 2020) (*high confidence*) (Section 13.11.2). Despite evidence of emerging bottom-up (e.g., citizens and business initiatives) and top-down initiatives (e.g., governmental plans and instruments to ensure action), there are considerable barriers to implementing and mainstreaming responses (Runhaar et al., 2018) (*high confidence*). The implementation gap identified in AR5 (Chambwera et al., 2014), i.e. the gap between defined goals and ambitions and actual implemented actions on the ground (Dupuis and Knoepfel, 2013), continues to persist in Europe (Aguiar et al., 2018; Russel et al., 2020) with critical challenges including: difficulty translating abstract policy strategies into concrete action, insufficient policy instruments to ensure timely implementation, lack of awareness of key stakeholders to implement actions, and limited leadership on climate action (Aguiar et al., 2018; Howlett et al., 2019).

In the following subsections, building on our sectoral analysis in previous sections, we look across European sectors, vulnerable groups, and regions to assess how climate change impacts are being responded to in general by state (Section 13.11.2) and non-state (Section 13.11.3) actors, and their synergies and dependencies. Sections 13.11.3 assess if and how system transformations have emerged and implications for the SDGs and climate resilient development pathways (CRDPs).

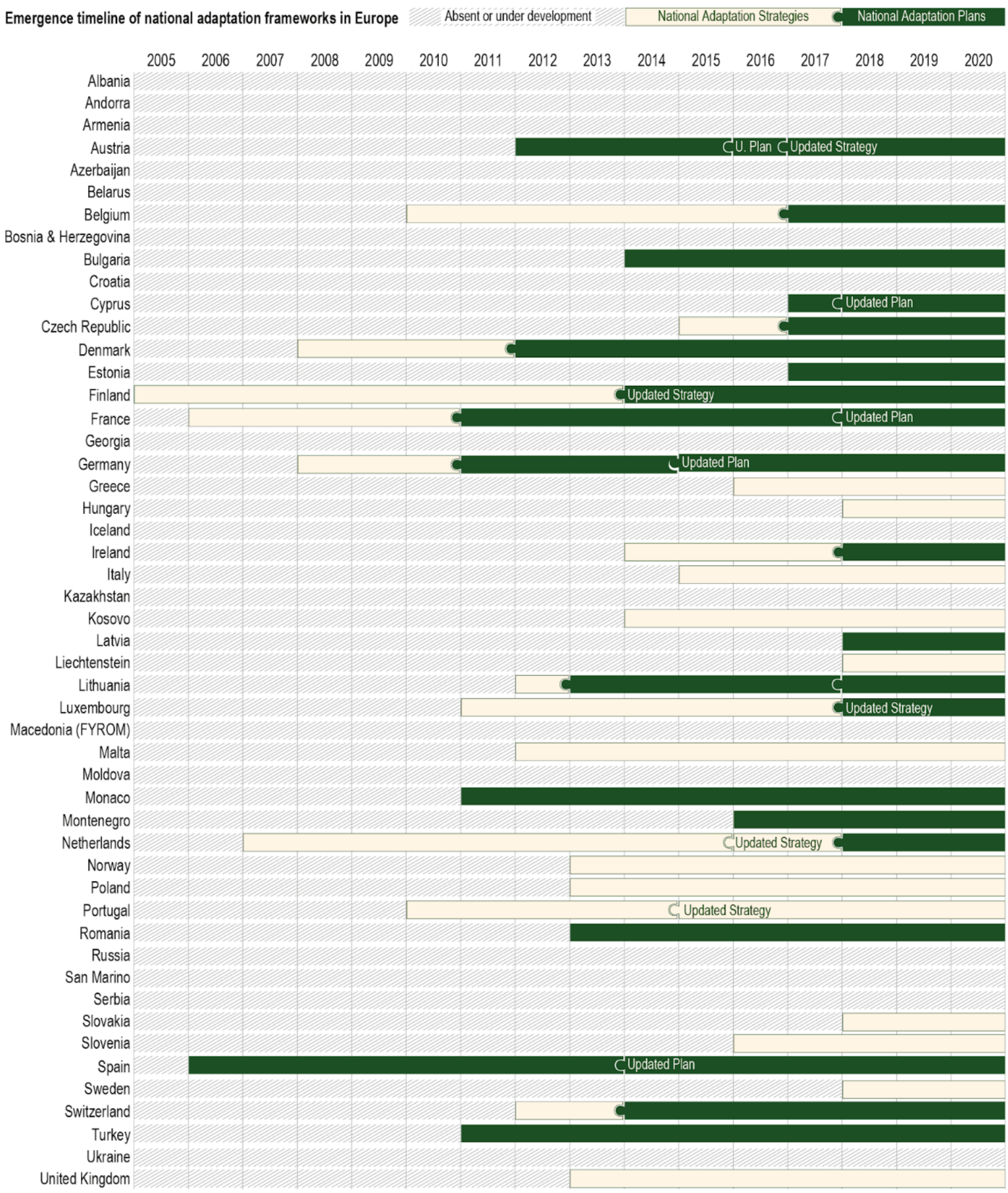
13.11.2 Policy Responses, Options and Pathways

European countries are increasingly planning to adapt to observed impacts and projected climate risks (Lesnikowski et al., 2016; Russel et al., 2020) (*high confidence*). Whereas in 2009, only nine countries had developed a National Adaptation Strategy (NAS) (Biesbroek et al., 2010; EEA, 2014b), in 2018, 25 EU Member States have done so (Table 13.15). Several countries have revised their strategies building on previous strategies (Klostermann et al., 2018). In some contexts, mostly Western Europe, national and sectoral adaptation plans have been developed to implement NAS (*high confidence*). Progress is also observed locally with an increasing number of European cities planning for climate risks (Aguiar et al., 2018; Reckien et al., 2018a; Grafakos et al., 2020) (Section 13.6.2.1; Box 13.3, Chapter 6). European countries where national adaptation frameworks are absent or under development (Table 13.15), do show evidence of actions across sectors and levels (Pietrapertosa et al., 2018), suggesting that, while adaptation plans can contribute to enhancing resilience, they are not necessary for advancing adaptation (*medium confidence*).

What drives sectors and regions to plan for adaptation and extend the adaptation solution space differs across Europe. Recurring drivers include: experienced climatic events, improved climatic information, societal pressures to act, projected economic and societal costs of climate change, participation in (city) networks, and changes in national and European policies and legislation (*medium evidence, high agreement*) (EEA, 2014b; Massey et al., 2014; Reckien et al., 2018b). The availability of public resources (human, knowledge, and financial) appears important for proactive adaptation (Termeer et al., 2012; Sanderson et al., 2018), while adaptation is also strongly dependent on economic and social development (global assessment: (Araos et al., 2016b); for Europe: (Sanderson et al., 2018) (*high confidence*). How adaptation is governed differs substantially across Europe. This difference can partly be explained by the political and social systems in which adaptation is mainstreamed (Biesbroek et al., 2018; Clar and Steurer, 2019; Lesnikowski et al., 2020). Mainstreaming adaptation options with existing institutional and political systems increases chances of successful adaptation compared to seeking one-size fits all solutions (*medium evidence, high agreement*) (Lesnikowski et al., 2020).

The scope of climate risks included in European adaptation policies and plans is generally broad, with some focusing on few main risks and others considering a broad range (EEA, 2018b). Systemic and cascading risks (see also Section 13.10) are often recognized, but most conventional risk assessment methods that inform adaptation planning are ill-equipped to deal with these effects (Adger et al., 2018). For example, transboundary risks emerging in regions outside of Europe are considered only by a few countries such as the UK and Germany (Section 13.9.3). European climate change adaptation strategies and national policies are generally weak on gender, LGBTQI, and other social equity issues (Boeckmann and Zeeb, 2014; Allwood, 2020). Adaptation policies and plans are generally considered as a technical exercise rather than a political process (Remling, 2018).

Table 13.15: Adoption of National Adaptation Plans and Strategies in Europe based on Grantham database and (EEA, 2018b) [to be updated for Final Draft]



Adaptive planning and decision making are still limited across Europe (*high confidence*). Many near-term investment decisions have long-term consequences, and planning and implementation can take up to decades, particularly for critical infrastructure planning in Europe. Consequently, there are calls to expand the planning horizons and consider long-term uncertainties to prevent lock-in to decision pathways, seize opportunities and synergies from other investments (e.g., socio-economic developments and energy transitions) and consider the range of possible impacts (e.g. Marchau, 2019; Oppenheimer et al., 2019; Haasnoot et al., 2020a). Extending planning horizons to beyond 2100, however, increases deep uncertainties to decision-makers as a result of unclear future socio-economic and climatic changes. For adaptation to sea level rise along Europe's coast, for example, there are already considerable uncertainties during this century (WGI AR6 Chapter 9). Prominent examples of adaptive plans include the city of London (Ranger et al., 2013; Kingsborough et al., 2016; Hall et al., 2019) and the Netherlands to reduce impacts of flooding and preserve fresh water resources under uncertain climate change (Van Alphen, 2016; Bloemen et al., 2019). Flexible strategies are increasingly considered by European countries (e.g. Stive et al., 2013; Kreibich et al., 2015; Bubeck et al., 2017; Haasnoot et al., 2019).

Monitoring adaptation action can help to adjust planning (Hermans et al., 2017; Haasnoot et al., 2018). In the Netherlands, a comprehensive monitoring system has been put in place to evaluate implementation effectiveness and determine appropriate pace (Hermans et al., 2017; Haasnoot et al., 2018; Bloemen et al., 2019). Signals for adaptation have been used to decide when to implement adaptation options or adjust plans.

Climate services to support adaptation decision-making of governments and businesses across Europe have rapidly increased since AR5, partly as a result of EU investments in creating a climate services market (*high confidence*) (Street, 2016; Soares and Buontempo, 2019). These services are increasingly used; however, their success is hardly systematically evaluated (EEA, 2018b). Barriers to use include: lack of perceived usefulness of climate information to organisations and expertise to use the information, and the mismatch between needs and type of information made available (*high evidence, medium agreement*) (Cavelier et al., 2017; Bruno Soares et al., 2018; Christel et al., 2018). Adaptation support platforms also face challenges regarding updating, training and engagement with users (EEA, 2015; Palutikof et al., 2019). High-end scenarios are often not considered in climate change adaptation planning due to a lack of perceived usability, missing socio-economic information, constraining institutional settings, and conflicting decision-making timeframes (*medium confidence*) (Lourenco et al., 2019). Such scenarios are often seen as having a low probability of occurrence, resulting in inaction or incremental rather than transformative adaptation responses to projected climate risks (Dunn et al., 2017). In addition to scientific knowledge, indigenous and local knowledges can demonstrate autonomous response space (Huntington et al., 2017) as is the case with indigenous-led ecosystem restoration in the European Arctic (Brattland and Mustonen, 2018).

Dedicated financial resources for the implementation of NAS and plans are a key enabling factor for successful adaptation (*high confidence*) (Russel et al., 2020) (Chapter 17). Yet, only 14 EU countries have announced such budget allocations in their plans and strategies; and even if budget numbers are available, they are difficult to compare (Leitner et al., 2020). Current adaptation spending varies greatly across European countries, partly reflecting national adaptation priorities or financing sources targeting investment projects (López-Dóriga et al., 2020; Russel et al., 2020).European government budgets are also burdened by climate change damages today, particularly after huge flooding events, limiting anticipatory action (Penning-Rowsell and Priest, 2015; Miskic et al., 2017; Schinko et al., 2017; Slavíková et al., 2020). National adaptation funding in MED, CEU and NEU is complemented by EU funding (European Structural and Investment Funds (ESIF), Horizon 2020, and LIFE). While the EU spending target on climate action increased from 20% in 2016-2020 to 25% in 2021-2016, most spending is going into mitigation, not adaptation (Berkhout et al., 2015; Hanger et al., 2015; Leitner et al., 2020).

With higher warming levels, financing needs are likely to increase (*medium confidence*) (Mochizuki et al., 2018; Bachner et al., 2019; Parrado et al., 2020); governments can address this higher need by cutting other expenditures, increasing taxes, or by increasing the fiscal deficit (Miskic et al., 2017; Mochizuki et al., 2018; Bachner and Bednar-Friedl, 2019). Yet, the requirement for fiscal consolidation that will be needed after the COVID-19 pandemic (Cross-Chapter Box COVID in Chapter 7) may also lead to a cessation of adaptation spending, as evidenced by the expenditure drop in coastal protection in Spain after the financial crisis 2008 (López-Dóriga et al., 2020). Governments can shift the financial burden to beneficiaries of adaptation, as e.g., suggested for coastal protection and riverine flooding (Jongman et al., 2014; Penning-Rowsell and Priest, 2015; Bisaro and Hinkel, 2018). There is also an increase in financial mechanisms to accelerate private adaptation actions, including adaptation loans, subsidies, direct investments, and novel public-private arrangements. For example, the European Investment Bank created a finance facility to support European regions through loans to implement adaptation projects (Leitner et al., 2020).

13.11.3 Societal Responses, Options and Pathways

13.11.3.1 Private-sector

Within the private sector, there tends to be a preference for 'soft' (e.g., knowledge generation) than 'hard' (e.g., infrastructure) adaptation measures (Goldstein et al., 2019), in contrast to government-led responses typically favouring hard measures (Pranzini et al., 2015). However, there also remains diversity across sectors and organisations in the degree and type of adaptation response, as discussed earlier (Trawöger, 2014; Dannevig and Hovelsrud, 2016; Ray et al., 2017; Ricart et al., 2018). Whereas some sectors such as flood management, insurance and energy (Gasbarro and Pinkse, 2016; Wouter Botzen et al., 2019) have generally made moderate progress on adaptation planning across Europe, there are key vulnerable economic sectors that are in earlier stages, including aviation (Burbidge, 2015), ports and shipping (Becker et al., 2018;

Ng et al., 2018), and ICT (EEA, 2018b) (*high confidence*). There is also some evidence of 'short-sighted' adaptation or maladaptation; for example, in winter tourism there is a preference for technical and reactive solutions (e.g., artificial snow) that will not be sufficient under high levels of warming (Section 13.6.1.4).

Where adaptation is considered by companies, it is typically triggered either by the experience of extreme weather events that led to business disruptions (McKnight and Linnenluecke, 2019) or is included into corporate risk management in response to regulatory, shareholder or customer pressure (Averchenkova et al., 2016b; Gasbarro et al., 2017); see also Section 13.6). Even if companies experience extreme weather events or stakeholder pressure, they may not adapt because they underestimate their vulnerability (Pinkse and Gasbarro, 2019). For example, analysis of Greek firms found barriers to adaptation included both external (e.g., lack of support/guidance) and internal factors (e.g., few resources, managerial perceptions (Halkos et al., 2018). Similarly, a survey of diverse German SMEs found corporate knowledge and incentives predicted adaptation (Herrmann and Guenther, 2017). Lack of knowledge, psychological distance (feeling climate change is not a salient risk), and lack of social learning or collaboration, appear to be barriers to private-sector adaptation (Dinca et al., 2014; André et al., 2017; Romagosa and Pons, 2017; Esteve et al., 2018; Luís et al., 2018; Ng et al., 2018) (Section 13.16.2.2). There remains little research on private-sector awareness of or responses to cascading or compound risks associated with climate change (Miller and Pescaroli, 2018; Pescaroli, 2018).

13.11.3.2 Communities, households and citizens

Planned behavioural adaptation remains limited amongst European households (*high confidence*); with few examples that can be considered transformative (e.g., structural, long-term, collective; (Wilson et al., 2020) (*medium confidence*). One Swedish survey of householders at risk of extreme weather events (e.g., floods, storms) found evidence of some organisational measures (e.g., bringing possessions inside prior to a storm, preparing for power cuts with candles, etc.) but very few households took any other (technical, social, nature-based, or economic) measures (Brink and Wamsler, 2019). Similarly, few at risk of flooding are taking action (Stojanov et al., 2015) (Section 13.4); for example, little public take-up of available municipal support for individual adaptation in Germany (Wamsler, 2016). Water efficiency measures in anticipation of, or response to, drought are also limited (Bryan et al., 2019), although water reuse in Mediterranean and some other EU (e.g., UK, Netherlands) countries is increasing (Aparicio, 2017). Amongst the adaptation responses recorded, few are perceived as opportunities (Taylor et al., 2014; Simonet and Fatorić, 2016). More European research is needed on public responses to risks other than flooding, heat stress and drought, such as vector-borne disease (van Valkengoed and Steg, 2019) (Section 13.7).

Perceived personal responsibility for tackling climate change remains low across the EU (Figure 13.23) and partly explains why household adaptation remains limited (*high confidence*) (Taylor et al., 2014; van Valkengoed and Steg, 2019), despite risk perception apparently growing (Figure 13.23: Eurobarometer, 2017; cf. (Capstick et al., 2015; Poppel et al., 2015; BEIS, 2019). Householders' risk perception and concern about climate change fluctuates in response to media coverage and significant weather or socio-political events (*high confidence*) (Capstick et al., 2015). On average across Europe, and particularly in relation to gradual change, non-experts continue to under-estimate climate change risks compared to experts *(medium confidence*) (Taylor et al., 2014). There is strong support for adaptation policy (e.g., building flood defences), within the UK, France, Norway and Germany (Doran et al., 2018). Yet, public adaptation can undermine motivation for householders to take adaptation measures in the case of flood protection (Section 13.2), with perceived efficacy of action a strong predictor of adaptation (*high confidence)* (Moser, 2014; van Valkengoed and Steg, 2019). However, there are also structural and economic barriers to household adaptation due to lack of policy incentives or regulations. For example, water-saving devices in homes could halve consumption, but lack of economic benefits to householders are barriers to adoption; while lack of standards may explain low levels of water reuse in Europe (EEA, 2017b). Conversely, water meters and higher tariffs have been found to reduce water consumption (EEA, 2017b; Bryan et al., 2019).

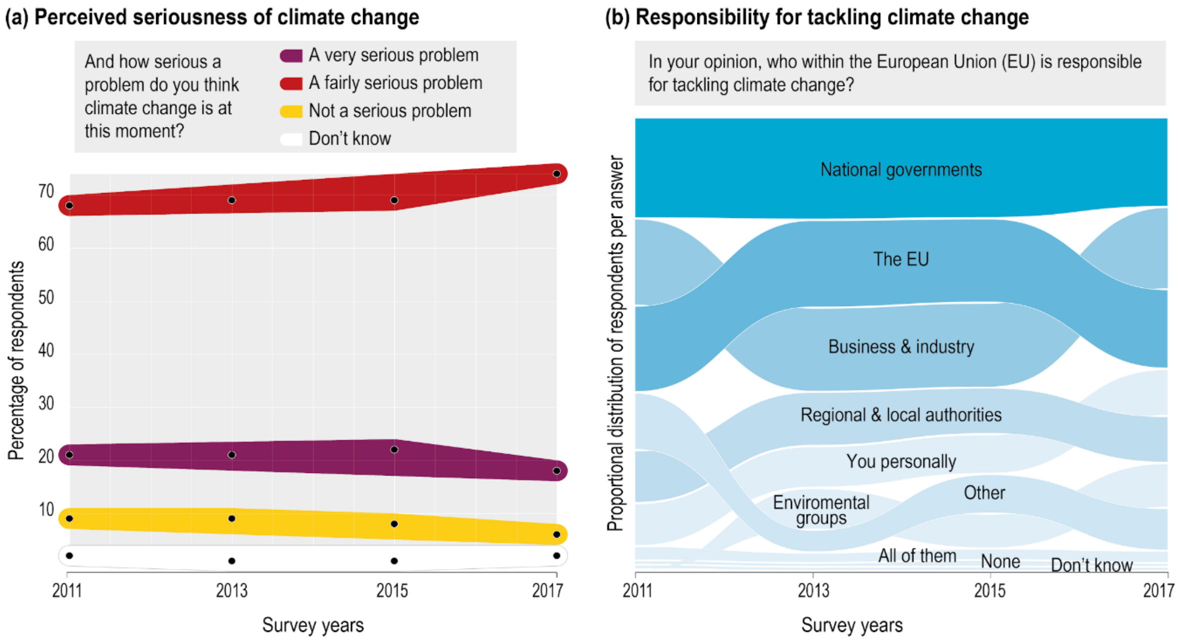


Figure 13.23: Trends in perceived climate change risks and responsibility for tackling climate change across EU-28 (EuropeanCommission, 2017)

As well as temporal trends in climate change risk perception, the literature since AR5 continues to show much heterogeneity (both within and between nations) amongst householders in respect of risk perception (*high confidence)*. Higher climate change risk perceptions observed in Spain, Portugal, Iceland, and Germany (Figure 13.2); at individual level, women, younger age groups, more educated, left-leaning, and those with more 'self-transcendent' values perceive more negative impacts from climate change, although the strength of these relationships varies across European nations (Clayton et al., 2015; Doran et al., 2018; Poortinga et al., 2019). Stronger evidence exists since AR5 that experience of extreme weather events can shape climate change risk perceptions, if these events are attributed to climate change or evoke negative emotions (*high confidence*) (Clayton et al., 2015; Demski et al., 2017; Ogunbode et al., 2019). Proximity to climate hazards does not predict adaptation responses in a straightforward way: in Portugal, those living by the coast were more likely to attribute local natural hazards to climate change and to take some adaptive measures (Luís et al., 2017); while coastal residents in flood-prone regions of France and Germany were more resistant to relocation, due to higher place attachment (Rey-Valette et al., 2019; Seebauer and Winkler, 2020); cf. (Adger et al., 2013; van Valkengoed and Steg, 2019). Migration from threatened regions is also discussed in Section 13.8.1.

13.11.4 Adaptation, Transformation and Sustainable Development Goals

Transformation is the implementation of far-reaching and rapid systemic change, including both adaptation and mitigation options (de Coninck et al., 2018) that enhance multilevel governance and institutional capabilities, and enables lifestyle/behavioural change and technology innovation. Adaptation responses across European regions and sectors, where they exist at all, can be considered much more often incremental than transformative, with possible exceptions including the Netherlands and some cities (Box 13.3) (*medium confidence*). Transformative options may be better able to exploit new opportunities and co-benefits (EEA, 2019a) (Box 13.3) (Cross-Chapter Box TRANSFORM in Chapter 18). System transformations towards more adaptive and climate resilient systems are often the result of responses to crises which create windows of opportunity for system changes (Johannessen et al., 2019) (cf. Chapter 18). This includes financial crises (e.g., Malmö) and the COVID-19 pandemic which have disrupted the status quo and accelerated innovation (e.g., Milan; Box 13.3, Cross-Chapter Box COVID in Chapter 7).

[START BOX 13.3 HERE]

Box 13.3: Climate Resilient Development Pathways in European Cities

Climate resilient development (CRD) in European cities offers synergies and co-benefits from integrating adaptation and mitigation with environmental, social and economic sustainability (Geneletti and Zardo, 2016; Grafakos et al., 2020). Climate networks (e.g., Covenant of Mayors), funding (e.g., Climate-KIC), research programs (e.g., H2020), European and national legislation, and international treaties contribute to the prioritisation of climate action in European cities (Heidrich et al., 2016; Reckien et al., 2018b). Engagement in climate networks, the identification of co-benefits, and the presence of national policies lead to more ambitious and integrated climate planning and action (Heidrich et al., 2016; CDP, 2020). Nevertheless, mitigation and adaptation remain largely siloed and sectoral (Heidrich et al., 2016; Reckien et al., 2018a; Grafakos et al., 2020). An assessment of the integration of mitigation and adaptation in urban climate change action plans in Europe found only 147 cases in a representative sample of 885 (Grafakos et al., 2020).

In European cities, CRD is most evident in the areas of green infrastructure, energy efficient buildings and construction, and active and low-carbon transport (Pasimeni et al., 2019; Grafakos et al., 2020). Nature-based solutions (NbS) often integrate adaptation and mitigation in sustainable urban developments and are associated with increasing natural and social capital in urban communities, improving health and wellbeing, and raising property prices (Geneletti and Zardo, 2016; Pasimeni et al., 2019; Grafakos et al., 2020; The Ignition, 2020). Barriers to CRD in European cities include limitations in: funding, local capacity, guidance documents and quantified information on costs, co-benefits and trade-offs (Grafakos et al., 2020). Pilot projects are used to initiate CRD transitions (Nagorny-Koring and Nochta, 2018). Malmö (Sweden) and Milan (Italy) illustrate the strategies and challenges of two European cities implementing CRDP.

Malmö (population 315,000): Since the 1990s, Malmö has been transitioning toward an environmentally, economically and socially sustainable city, investing in eco-districts and adopting ambitious adaptation and mitigation targets. The city has focused on energy efficient buildings and construction, collective and low carbon transportation, and green spaces and infrastructure (Anderson, 2014; Malmo, 2018). Malmö has leveraged creative implementation mechanisms, including a "climate contract" between the city, the energy distributor and the water and waste utility to co-develop the climate-smart district, Hyllie (Isaksson and Heikkinen, 2018; Kanters and Wall, 2018; Parks, 2019). Flagship districts play a central role in the city's transition, in the wider adoption of CRD and in securing implementation partners (Isaksson and Heikkinen, 2018; Stripple and Bulkeley, 2019). The city has also leveraged their status as a CRD leader to attract investment. The private sector views CRD as profitable, due to the high demand and competitive value of these developments (Holgersen and Malm, 2015). Malmö adopted the SDGs as local goals and the city's Comprehensive Plan is evaluated on these, e.g., considering gender in the use, access and safety of public spaces, and emphasizing development that facilitates climate resilient lifestyles (Malmo, 2018). Monitoring achievement of goals provides critical feedback and accountability. Malmö also engages stakeholders in planning and implementation, via dialogue with residents, collaboration with universities and partnerships with industry and service providers (Kanters and Wall, 2018; Parks, 2019).

Milan (population 1.4M): Milan is taking a CRD approach to regeneration and new developments (Comune di, 2019). From 2020, new buildings must be carbon neutral and reconstructions must reduce the existing land footprint by at least 10%. The Climate and Air Plan (CAP) and the city's Master Plan (Comune di, 2019) focus on low-carbon, inclusive and equitable development. The CAP is directed at municipal and private assets, and individual to city-scale actions. In 2020, Milan released a revised Adaptation Plan and the Open Streets project to ensure synergies between the COVID-19 response and longer-term CRD. Examples include strengthening neighborhood-scale disaster response and opening streets for walking and cycling (Comune di, 2020). Milan emphasizes institutionalization of CRD via a dedicated resilience department, and through active participation in climate networks and projects that support learning and exchange. Climate network commitments are cited in the city's Master Plan and CAP guidelines as driving more ambitious deadlines and emissions targets (Comune di, 2019).

[END BOX 13.3 HERE]

Considerable barriers exist that prevent system changes from taking place, including institutional and behavioural lock-ins such as administrative routines, certain types of legislation, and dominant paradigms of problem solving (Johannessen et al., 2019; Roberts and Geels, 2019) (*high confidence*). Breaking through these lock-ins requires substantive (political) will, (un)learning of practices, resources, and perseverance. Trade-offs exist between the depth, scope, and pace of change in transforming from one system to another, suggesting that designing system transformations is a careful balancing act (Termeer et al., 2017). Aspiring quick, in-depth and comprehensive transformational changes might create a consensus frame to work towards; but it might not offer concrete perspectives to act on the ground. Taking small steps and quick-wins offer an alternative pathway (Termeer and Dewulf, 2018).

Adaptation responses can also be understood in terms of their trade-offs and synergies with SDGs (Papadimitriou et al., 2019; Bogdanovich and Lipka, 2020). In terms of synergies, analysis of the Russian NAP found that successful completion of its first phase could lead to significant progress towards 15 of the 17 goals (Bogdanovich and Lipka, 2020). European water adaptation (e.g., flood protection) can similarly support freshwater provision; and water-secured environments support socio-economic growth (Sadoff et al., 2015) since people and assets tend to accumulate in areas protected from flooding, reducing the incentive for autonomous adaptation (de Moel et al., 2011; Hartmann and Spit, 2016). In health, behavioural measures to reduce mental health impacts (e.g., gardening, active travel) can have broader health benefits (SDG 3) as well as help reduce emissions (Section 13.7; SDGs 7 and 13). Conversely, growing use of air conditioning for humans and livestock represents a potential trade-off between adaptation and mitigation (Sections 13.5,13.6, 13.7, 13.10). As noted in Section 13.8, addressing poverty (SDG 1) - including energy poverty (SDG 7) and hunger (SDG 2) - and inequalities (SDG 10) - including gender inequality (SDG 5) - improves resilience to climate impacts for those groups that are disproportionately affected (women, low-income and marginalised groups). Also, more inclusive and fair decision-making can enhance resilience (SDG 16; Section 13.4.4); although adaptation measures may also lead to resource conflicts (SDG 16; Section 13.7). Climate adaptation, particularly nature-based solutions, also supports ecosystem health (SDGs 14 and 15) (Dzebo et al., 2019). Economic trade-offs appear to be more common across adaptation strategies, for example reduced employment arising from land use change measures (Papadimitriou et al., 2019). Figure 13.24 summarises the synergies between adaptation and SDGs as identified by 861 European cities in 2019; particularly prominent are reported biodiversity and health benefits most often arising from social (e.g., informational) and structural (e.g., technological/engineering) measures. Beyond the urban context, biodiversity co-benefits from agro-ecology are also recognised (Section 13.5). Sustainable behaviour change measures have been found to be particularly likely to lead to synergies with SDGs (Papadimitriou et al., 2019).

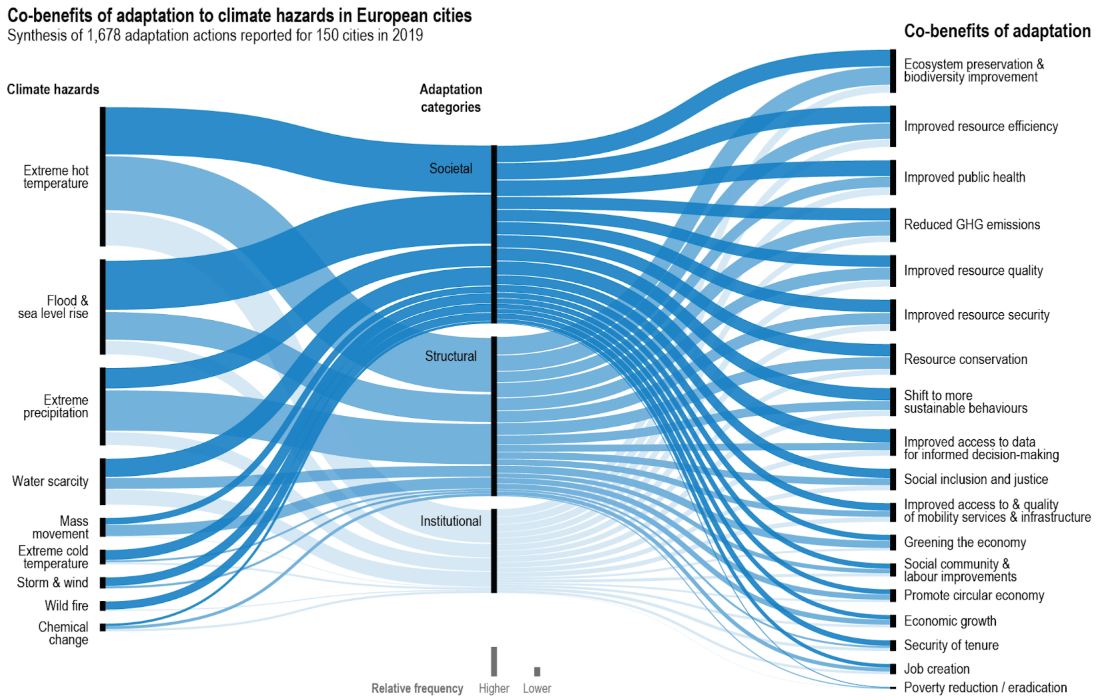


Figure 13.24: Co-benefits for SDGs from adaptation actions (as categorised by AR5 into 'social', 'structural' and 'institutional' measures) taken by European cities in response to climate hazards (using data reported by 861 European cities in 2019, CDP, 2019).

Frequently Asked Questions

FAQ 13.1: How will climate change increase social inequalities across Europe?

The poor and those practising traditional livelihoods are particularly exposed and vulnerable to climate change. They rely more often on food-self provisioning and settle in flood-prone areas. They also often lack the financial resources or the rights to successfully adapt to climate-driven changes. Yet, good practice examples demonstrate that adaptation can reduce inequalities.

Social inequalities in Europe arise from disparities in income, gender, ethnicity, age, as well as other social categorisations, and intersectionality. In the European Union, about a fifth of the population (109 million people) at present lives under conditions of poverty or social exclusion. Moreover, poverty is unequally distributed across Europe, with higher poverty levels in Eastern Europe.

The poor and those practising traditional livelihoods are particularly vulnerable and exposed to climate risks. Many depend on food self-provisioning from lakes, forests and the land. With higher temperatures, the availability of these sources of food is likely to be reduced in southern Europe, but also in the European Arctic where e.g., semi-migratory reindeer herding is a way of life among Indigenous and traditional communities (Komi, Saami, Nenets). Poorer households often settle in flood-prone areas and are therefore more exposed to flooding. Almost 15% of the EU population (in some countries more than 25%) cannot meet their needs for specific health care-related services for financial reasons. Low-income groups are also more exposed to climate risks through the type of work they do. Age is another factor affecting vulnerability, with the oldest and youngest in society often more at risk.

In addition to being more exposed to climate risks, socially vulnerable groups are also less able to adapt to these risks, because of financial and institutional barriers. More than 20% of people in southern and Eastern Europe live in dwellings that cannot be cooled to comfortable levels during summer and are thus particularly vulnerable to risks from increasing heatwave days in European cities. They may also lack the means to protect against flooding or heat, e.g., when they are renters but not owners of their dwellings or when they are already face energy poverty. Risk-based insurance premiums, which are intended to help people reduce climate risks, are potentially unaffordable for poor households. The ability to adapt is also often limited for indigenous people, as they often lack the rights and governance to resources, particularly when in competition with economic interests such as resource mining, oil and gas, and expansion of bioenergy (forestry).

Adaptation actions by the state can both increase and decrease social inequalities. For example, there is evidence that state support following extreme weather events was not well balanced between social groups. The installation of new or restoration of existing green spaces may increase land prices and rents because of a higher attractiveness of the areas, leading to potential displacement of population groups who cannot afford these higher prices. On the other hand, rewilding and restoration of ecosystems can improve the access of less privileged people to ecosystem services and goods, such as the availability of freshwater. At city level, there are examples of good practice in climate-resilient development that consider social equity; for example, Malmö (Sweden) integrates a gender-inclusive perspective in its sustainable urban planning, including designing public spaces and transit to ensure women, disabled people and other vulnerable groups can access and feel safe using these amenities (see Box 13.3).

FAQ 13.2: What are the limits of adaptation for ecosystems in Europe?

All over Europe, land, freshwater and ocean organisms and ecosystems are facing unprecedented pressures from human activities. Climate change is rapidly becoming an additional and, in the future, even primary threat to organism performance and ecosystem biodiversity and functionality. Ongoing and particularly projected future changes are too strong and happen too fast for many organisms and ecosystems to adapt. Reinforced environmental conservation and adaptation policies can slow and potentially stop and even reverse biodiversity and ecosystem declines.

Ecosystem degradation and biodiversity loss have been evident across Europe since 1950, mainly due to land use and overfishing. However, climate-change hazards are becoming further key threats. The unprecedented pace of the change in environmental conditions has already surpassed the natural adaptation capability of most species, communities and ecosystems in Europe. For instance, the space available for some land ecosystems is shrinking, especially in northern and Alpine regions, due to warming and permafrost melting. Across Europe, heatwaves and droughts and their knock-on impacts (e.g., wildfires) add further acute pressures. In the Mediterranean Sea, plants and animals cannot shift northward to evade warming risks and are declining due to marine heatwaves. Food-web dynamics of European ecosystems are disrupted as climate change alters the timing of biological processes, such as spawning and migration, and ecosystem composition. Moreover, it fosters the immigration of invasive species that compete with–and can even out-compete–the native flora and fauna.

In a future with further and even stronger warming, climate change and its many direct and indirect impacts will become increasingly more important threats. A number of species and ecosystems are projected to be already at high risk in a 2°C warmer world, including fin fishes and lake and river ecosystems. In an even warmer world of +3°C, many European ecosystems, such as coastal wetlands, peatlands, and forests, are projected to be at much higher risk than in a 2°C warmer world. For example, Mediterranean seagrass meadows will very likely become functionally extinct due to more, longer and more severe marine heat waves by 2050. Several wetland and forest plants and animals will be at high risk to be replaced by invasive species that are better adapted to increasingly dryer conditions, especially in boreal and Arctic ecosystems. Current protection and adaptation measures, such as Marine Protected Areas or the European Water and Marine Strategy Framework Directives, have some positive effects for European ecosystems. However, these policies are not sufficient to effectively curb overall ecosystem decline, and they will certainly not be for the projected higher risks in a more than 2°C warmer world at the end of the 21st century. In general, solutions that include actions to mitigate climate change (such as greenhouse gas emission reduction and carbon extraction), strengthened conservation measures, nature-based adaptations and international cooperation are projected to more effectively reduce risks for European ecosystems and biodiversity.
Not all climate-change adaptation options are necessarily beneficial to ecosystems: for example, ‘hard’ coastal protection measures (building seawalls, breakwaters and similar infrastructure) in response to sea-level rise reduce the space available for coastal ecosystems. Nature-based solutions, such as the restoration of wetlands, peatlands and forests, serve both ecosystem protection and climate-change mitigation through strengthening carbon sequestration. But those measures can also have side-effect risks and trade-offs, such as increased methane release from larger wetland areas and albedo change due to large-scale tree planting.

FAQ 13.3: How can people adapt at individual and community level to heat waves in Europe?

Heatwaves will become more frequent, intense and will last longer. A range of adaptation measures are available for communities and individuals to prepare for and deal with heat waves. Individual and collective measures are needed to reduce the impact when a heatwave strikes.

Heat waves will affect the people in different ways, and risks are higher for the elderly and people with pre-existing health conditions. By 2050, about half of the European population may be exposed to high or to very high risk of heat stress during summer, not only in Mediterranean but also in western central and eastern Europe. Climate change is an important driver, and the proportion of people at risk will also increase due to an ageing population. The severity of projected heat related risks will be higher in southern Europe and particularly in large cities due to the urban heat island effect. Eastern and central Europe are very likely to be faced with growing risks for heat waves in the coming decades.

There is already a 'culture of heat' in southern Europe where the general public is highly aware of the risks of heat waves. Consequently, over the past decades, governments and citizens have implemented a range of adaptation responses to reduce the impacts of heat waves. There are limits to how much adaptation can occur, however, therefore additional and transformative actions are needed in some places to prevent future impacts.

The parts of Europe where heat waves are relatively new phenomena, a culture of heat is also emerging. Although public awareness tends to be lower when compared with southern Europe, the institutional capacity is expanding, for example through the elaboration of public health interventions in Northern Europe and the heat health action plans and warning in Central Europe.

Preparing for heat waves is an important first step. Experiences in southern Europe but also more recent from central Europe show that creating and implementing national or regional early warning and information systems, heat wave plans and guidelines, and raising public awareness through campaigns are successful responses governments can take to prepare people for heat waves. Anecdotal evidence suggests such measures contributed to reduced mortality rates in southern and central Europe.

At city or municipal level, preparing for heat waves can take several forms, sometimes requiring systemic transformations. For example, green-blue spaces such as recreational parks and ponds in cities have shown to reduce the average temperature in cities dramatically. Across Europe, several cities have started to invest in green-blue spaces as there are also several environmental, social and health co-benefits. Other measures such as use of cool materials in asphalt, increasing reflectivity, green roofs, and building construction measures are being considered in urban planning for mitigating heat risks.

People too can prepare themselves, for example using ventilation and energy efficient air-conditioners in their homes, installing green roofs and green facades in their buildings, and by using renewables which can lower fossil-fuel based electricity consumption and risk of power outages during heat wave events.
During extreme heat events targeted information to people and social care providers is critical, particularly to those most vulnerable. Governments and NGOs play an important role in informing people what best to do and coordination between vital emergency and health services is critical. Important actions individuals can take to protect themselves from heat are (Figure FAQ 13.3): I) decreasing exposure to high temperatures (e.g., avoid outdoor during hottest times of the day, access cool areas, wear protective and appropriate (cotton) clothing); II) keep hydrated (e.g., drink enough proper fluids, avoid alcohol, etc), III) be sensitive to the symptoms of heat illness (dizziness, heavy sweating, fatigue, cool and moist skin with goosebumps when in heat, etc.).

Once the heat wave has ended, it is important to take stock and evaluate: what worked well and why? What can be improved when the next heat wave strikes? Governments can for example evaluate whether the early warning systems provided timely and useful information, whether coordination among different departments, organisations and stakeholders went well, or assess the effectiveness of measures taken using outcome indicators such as the estimated number of lives saved as results of the measures implemented. Sharing these lessons learned within a city or region is critical to allow changes to be made and linking to city networks can be a powerful tool to gain access to lessons from other cities. Individuals too can evaluate, asking questions such as whether their responses were appropriate, investments needed to be better prepared, or key lessons about what (not) to do when the next heat wave strikes.

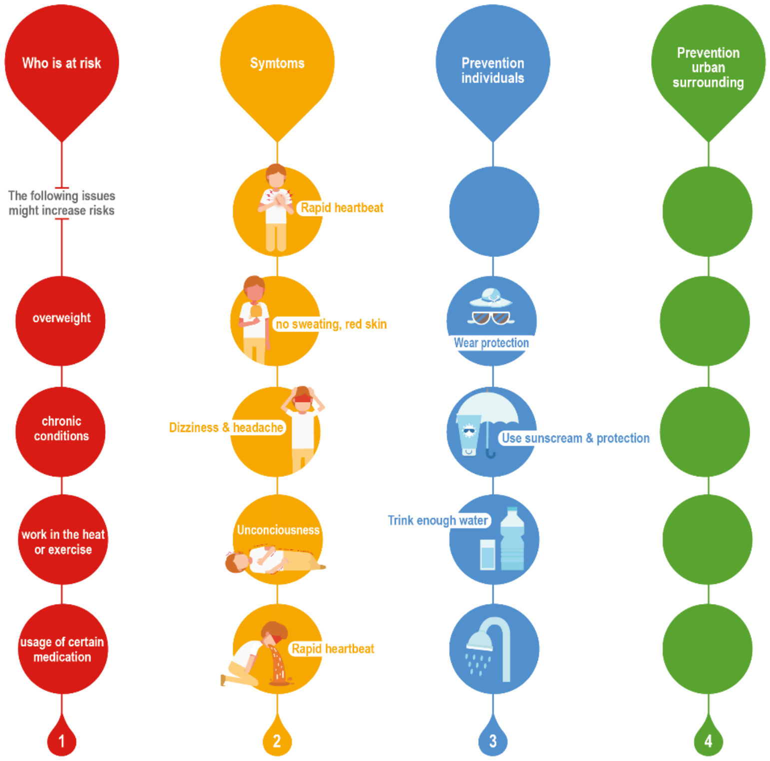


Figure FAQ 13.3: Range of risk signals and adaptation measures available at community and individual level to prepare for and take action in response to heat waves (Based on:WHO, 2015).

FAQ 13.4: What opportunities does climate change generate for human and natural systems in Europe?

Climate change impacts vary across European regions and with time, and not all its impacts pose challenges and threats to natural communities and human society but some offer opportunities instead. A slower climate change (facilitated by a drastic reduction of greenhouse gas emissions termed mitigation) as well as a forward looking/future oriented approach, as followed by some of the European countries, gives more time to innovate, plan, and implement measures and thus to seize opportunities.

Opportunities of climate change can be 1) positive effects of climate change, mainly warming, for specific sectors and regions such as agriculture in northern Europe, 2) co-benefits of measures reducing climate-change speed and impact, which will improve air quality, mental health and wellbeing, and 3) opportunities for large-scale transitions and transformations of our society through new policy initiatives in response to the COVID crisis, such as the European New Green Deal and Building Back Better.

Warming and change in snow and rainfall patterns are projected to have large impacts in the more southern part of Europe and those areas with extensive snow and ice cover. Therefore, opportunities derived from climate change benefits are primarily in northern regions increasing inequalities across Europe. Positive effects of climate change are fewer than negative impacts. Positive impacts are limited to some aspects of agriculture, forestry, tourism, and energy sectors. In the food sector, these are driven by the northward movement of food production zones, increases in plant growth due to CO_2 fertilisation, and reduction of heating costs for livestock. In the energy sector, such positive effects include increased hydropower potential in northern Europe and wind energy in the southwestern Mediterranean, and reduced energy demand for heating across all Europe. Climatic conditions for tourist activities during spring and autumn are projected to improve in most of European locations. Fewer cold waves will reduce risks on infrastructure particularly by the end of the century.

Adapting to climate change creates opportunities for the entire European region. For example, societal participation in designing flood risk management will increase inclusivity, legitimacy, and effectiveness. Nature-based approaches to adaptation can make cities and settlements more liveable, increase the resilience of agriculture, and protect biodiversity.

Opportunities emerge to mainstream adaptation into large socio-economic transformations. These transformations include investments for energy transition and COVID19 recovery to implement adaptation measures. Under new environmental (e.g., warmer) conditions, additionally, new measures are becoming feasible. All of these measures are backed by the increasing societal support across many European nations and especially young people for climate responses. Transformative climate solutions to achieve sustainability may be accelerated through larger system changes of, for example behaviour, energy, food or transport, to better exploit new opportunities and co-benefits.

Large-scale infrastructure projects and major changes in governance highlight that transformative actions in vulnerable places and social groups take a long time to establish and at present are largely not mainstreamed within decision-making. At the same time, some opportunities for transformation and choices for options will be reduced or become more difficult and costly if timely decision making is postponed.

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Appendix 13.A: Supplementary Material

[PLACEHOLDER FOR FINAL DRAFT: Supplementary Material will include additional supplementary tables on the observed impacts and projected risks as well as for the feasibility and effectiveness assessments.]

13.A.1 Supplementary Material "Point of Departure" (13.1)

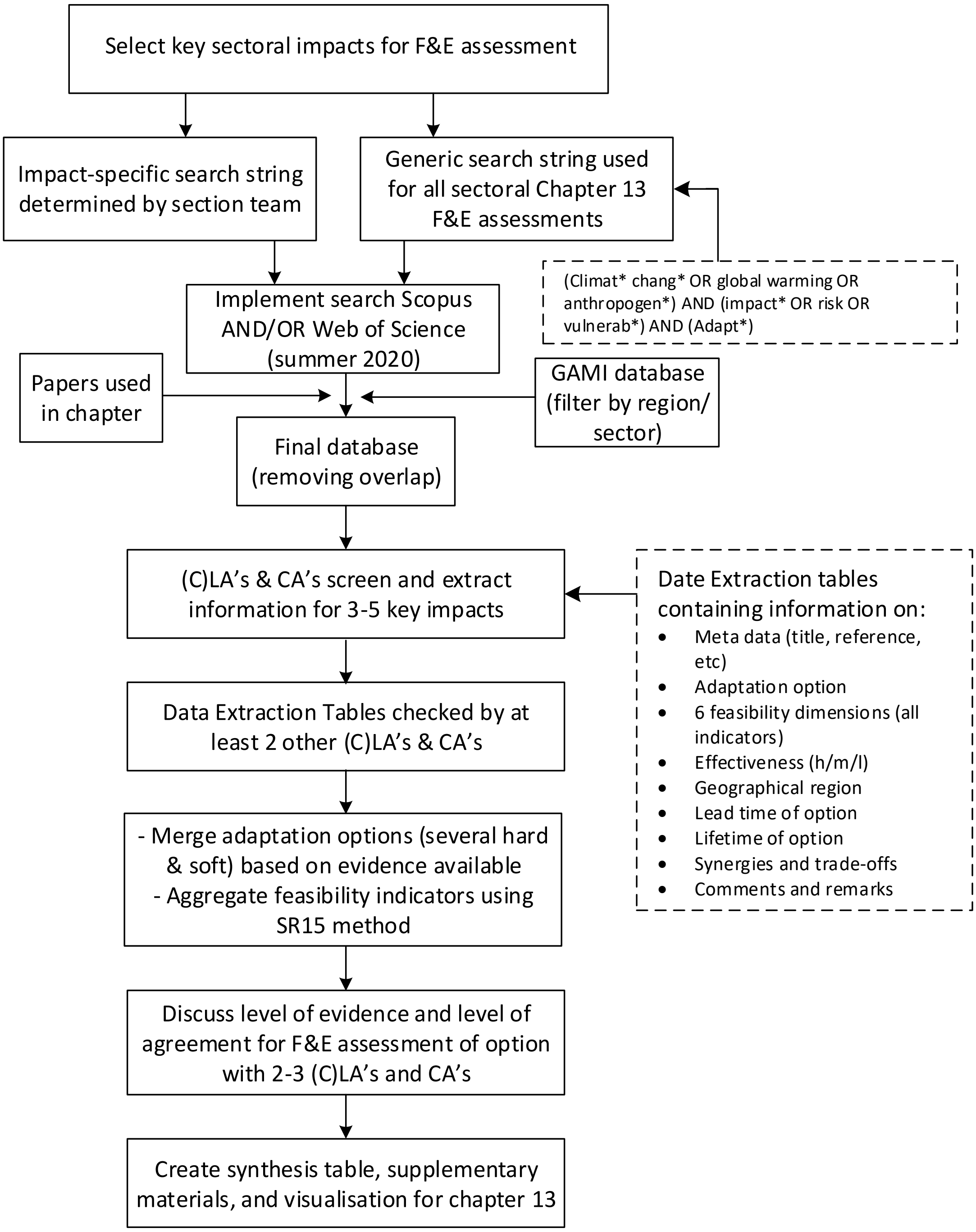

Figure 13.A.1: General workflow for assessing feasibility and effectiveness of adaptation options. Approach is based on (Singh et al., 2020). Not all tables have been completed. [PLACEHOLDER FOR FINAL DRAFT: to be updated]

13.A.2 Supplementary Material "Terrestrial and Freshwater Ecosystems and their Services" (13.3)

Table 13.A.1: Summary of key impacts and risks for terrestrial and marine ecosystems [PLACEHOLDER FOR FINAL DRAFT: reported trends are preliminary]. A. Reduced habitat availability and biodiversity; B. Local extinctions; C. Range shifts; D. Invasions of non-native species; E. Shifts in community composition; F1. Non-gradual, abrupt biome shifts (critical transitions); F2. Large-scale gradual biome shifts; G. Changes in phenology and reproductive success; H.

Foodweb disruptions; I. Changes in Productivity; J. Incidence of fire; K. Vegetation die-back, mortality events, population collapse; L. Emergence of trade-offs limiting adaptation options and solution space; M. Changes in regulating ecosystem services (carbon capture);

Impacts/Risks	Description of projected risks and affected system	References
	Predicted patterns of biodiversity changes qualitatively differ among taxonomic groups and usually show strong declines under RCP 8.5	(Radinger et al., 2016; Ruiz-Navarro et al., 2016; Dyderski et al., 2018; Miličić et al., 2018; Buras and Menzel, 2019; Di Marco et al., 2019; Harrison et al., 2019; Jarić et al., 2019; Soroye et al., 2020).
	Over the period 2061–2080, modelling predicts different types of responses of European forest tree species under RCP 2.6, RCP 4.5, and RPC 8.5 scenarios. For most temperate tree species, the suitable habitat area is projected to decrease (*medium confidence*), including some conifer and pioneer species (e.g., Betula pendula, Larix decidua, Picea abies, and Pinus sylvestris). For some though, habitat gain may proximately balance habitat loss (e.g., Abies alba, Fagus sylvatica, Fraxinus excelsior, Quercus robur, and Quercus petraea).	(Dyderski et al., 2018).
	Shifts in species distributions are predicted for the coming decades for multiple taxonomic groups showing a wide range of species-specific responses	(Levinsky et al., 2007; Hof et al., 2012; Kovats et al., 2014; Aguirre-Gutiérrez et al., 2017; Dullinger et al., 2017; Sáenz-Romero et al., 2017; Dyderski et al., 2018; Howard et al., 2018; Buras and Menzel, 2019; Milić et al., 2019; Schwager and Berg, 2019).
	Range retractions have been predicted for alpine ecosystems in isolated mountain ranges, and expansions in mediterranean and dryland ecosystems in southern Europe	(Kovats et al., 2014; Barredo et al., 2016; Guiot and Cramer, 2016; Lefebvre et al., 2019; Schwager and Berg, 2019).
	Climatically suitable habitats for peatlands may decrease in warmer climates in Northern Europe	(Swindles et al., 2019)
	In birds, by 2070 the breeding and non-breeding ranges of major migrant bird species may shift in response to all major RCP scenarios.	(Howard et al., 2018).
	While large decreases in the survival and growth of temperate oak trees are predicted for southern edge populations, demographic rates in the northern limits may not be strongly impacted.	(Sáenz-Romero et al., 2017).
J. Incidence of fire	From 1985–2014 total annual burned area in western Europe decreased, stabilized in 2015–2016 and increased in 2017. In a warmer climate, more severe droughts with high fire risk, an expansion of the fire-prone area, and longer fire seasons are projected across Europe. Risks of wildfires with extreme pyroconvections, i.e. strong and deep convection events within a fire plume, may also increase with climate change in Europe	(Costa Alcubierre et al., 2011; Dury et al., 2011; Frolov et al., 2014; Jacob et al., 2014; Khabarov et al., 2016; Lehtonen et al., 2016; Turco et al., 2016; de Rigo et al., 2017a; Castellnou and et, 2018; Turco et al., 2018b; San-Miguel-Ayanz et al., 2019; Resco de Dios, 2020).
J. Incidence of fire	Decreasing trends in the Mediterranean region have been reported in the total burned area between 1985 and 2011 and in the annual number of fires, which are partly explained by increased efforts in fire management and prevention. Since 2015 dangerous fires have occurred in mid autumn in Southern Europe. The risk of large fires and summer burned area is projected to largely increase in the Mediterranean basin. The estimate for summer burned areas in Mediterranean Europe under 1.5, 2 and	(Turco et al., 2014; Turco et al., 2016; Castellnou and et, 2018; Turco et al., 2018a; Michetti and Pinar, 2019; Resco de Dios, 2020).

	3°C warming is projected to increase from 40 to 100% across the scenarios.	
J. Incidence of fire	Burnt area in the Russian Federation has been significantly increasing since the 2000s. Large-scale wildfires, with areas burnt exceeding 2.000 ha, increased in number over recent years in Russia, highlighting the need for improved fire risk management and monitoring.	(Ponomarev et al., 2015; Filipchuk et al., 2018)
J. Incidence of fire	While fires were concentrated in southern and eastern Europe in the past, areas in northern Europe have recently suffered from unprecedented forest fires.	(Ponomarev et al., 2015; Lebedinskii et al., 2019; San-Miguel-Ayanz et al., 2019; Torzhkov et al., 2019).
	Larger extinction risks are expected in endemic, non-generalist and dispersal-limited taxa.	(Urban, 2015)
	Under RCP8.5, population extinctions of widespread drought-sensitive insects might occur as early as 2050 in North Europe.	(Oliver et al., 2015)
	Projected climate change impacts on ecosystem services are affected by strong and often dominant effects of changes in land use and management	(Schröter et al., 2005a; Polce et al., 2016; Verhagen et al., 2018).

Table 13.A.2: Adaptation options for European land ecosystems to address risks listed in Table 13.3 [PLACEHOLDER FOR FINAL DRAFT: adaptation options will be grouped by risk; range of adaptation options will be expanded to increase balance between risks covered; some measures will be collapsed]. A. Reduced habitat availability and biodiversity; B. Local extinctions; C. Range shifts; D. Invasions of non-native species; E. Shifts in community composition; F1. Non-gradual, abrupt biome shifts (critical transitions); F2. Large-scale gradual biome shifts; G. Changes in phenology and reproductive success; H. Foodweb disruptions; I. Changes in Productivity; J. Incidence of fire; K. Vegetation die-back, mortality events, population collapse; L. Emergence of trade-offs limiting adaptation options and solution space; M. Changes in regulating ecosystem services (carbon capture)

Risks	**Community/ System affected**	**Adaptation option**	**References**
		Promotion of mixed-species stands	(Vilà et al., 2007; Gamfeldt et al., 2013; Pretzsch et al., 2013; Ruiz-Benito et al., 2014; Guyot et al., 2016; Jactel et al., 2017; Ratcliffe et al., 2017)
		Forest and habitat restoration practices	(Kolström, 2011; Habel et al., 2019a; Lewis et al., 2019)
		Use of drought and/or fire-resistant provenances	(Gil et al., 2009; Hlásny et al., 2014; Calvo et al., 2016)
		Assisted species migration	(Willis et al., 2009; Williams and Dumroese, 2013; Brooker et al., 2018)
		Enhancing and managing tree recruitment and forest resilience using thinning and prescribed burning	(Tardós et al., 2019)
		Reducing tree density through thinning	(D'Amato et al., 2013; Giuggiola et al., 2013; Elkin et al., 2015; Giuggiola et al., 2016; Aldea et al., 2017; Ameztegui et al., 2017; Del Río et al., 2017; Gleason et al., 2017)
		Randomizing tree spatial patterns in thinning practices	(Giuggiola et al., 2016; Lechuga et al., 2017)
		Increasing the equitability or diversity of tree size classes in thinning practices	(Kolström, 2011), (Bouriaud et al., 2013; Giuggiola et al., 2016; Lechuga et al., 2017)
		Reducing forest understory cover by thorough mechanical treatments	(Kolström, 2011; Vilà-Cabrera et al., 2018)
		Implementing green infrastructure modelling platforms projecting land use changes into the near future	(Maes et al., 2015)

	Promoting participatory forest management planning processes and local self-governance mechanisms	(Andersson, 2006; Bouriaud et al., 2013; Bouriaud et al., 2015)
	Improving current networks of protected areas and corridors, covering altitudinal gradients and integrating climatic microrefugia areas	(Keeley et al., 2018; Habel et al., 2019a; Müller et al., 2020)
	Rewilding as a vehicle of adapting to the rapid climate impacts	(Kuuluvainen, 1994; Kuuluvainen, 2009; Mustonen, 2017; Pohjanmies et al., 2017; Brattland and Mustonen, 2018; Mustonen, 2018; Mustonen and Kontkanen, 2019)
	Adaptation options for freshwater and coastal land ecosystems include hydrological and land use planning at basin scale, complemented with local restoration and conservation practices	(Bruno et al., 2014; Carrizo et al., 2017; Cañedo-Argüelles et al., 2019; Vaughan and Gotelli, 2019)
	Preservation of the natural flow variability of rivers and streams	(Cid et al., 2017; Menció and Boix, 2018)
	Ameliorating sea-live rise impacts on land installing coastal protection elements, such as breakwaters, seawalls, dykes, surge barriers and submerged breakwaters	(Tomasicchio, 1996; Lamberti and Zanuttigh, 2005; Iskander et al., 2007; Sancho-García et al., 2013; Becchi et al., 2014; Tsoukala et al., 2015; Bouvier et al., 2017)
	Using beach and shore nourishment practices, dune restoration, and coastal restoration	(Hanson et al., 2002; Aragonés et al., 2015; Danovaro et al., 2018)
	Applying geotextiles	(Balouin et al., 2015)
	Managing irrigation canals for conservation and adaptation	(Aspe et al., 2016)
	Peatland rewetting and restoration as a key tool for climate-change adaptation and mitigation. In Europe, many peatland areas are under agricultural and forestry usage, requiring active land use and management planning. Saving extant peatlands, rewetting peatland areas and restoring temperate and boreal agricultural peatlands have been assessed as key practices.	(Kasimir et al., 2018; Gunther et al., 2020; Ojanen and Minkkinen, 2020)
J. Incidence of fire	Management of fuel to reduce fire intensity and the extent of large fires	(Agee and Skinner, 2005; Loepfe et al., 2010; Pausas and Paula, 2012; Regos et al., 2014)
J. Incidence of fire	Using prescribed burning for reducing the risk of high intensity fire and fuel load management	(Piñol et al., 2005; Piñol et al., 2007; Fernandes et al., 2013; Fernandes et al., 2016; Khabarov et al., 2016; Fernandes, 2018; Vilà-Cabrera et al., 2018; Duane et al., 2019)
J. Incidence of fire	Incentivizing and planning residential development to withstand inevitable wildfire	(Schoennagel et al., 2017; Samara et al., 2018)
J. Incidence of fire	Managing and planning landscape matrix schemes to reduce fire risk	(Loepfe et al., 2010; Moreira et al., 2011; de Rigo et al., 2017a; Erdős et al., 2018)
J. Incidence of fire	Improved fire suppression capacities and strategies	(Piñol et al., 2005; Brotons et al., 2013; Khabarov et al., 2016; Regos et al., 2016; Cramer et al., 2018; Turco et al., 2018a)
J. Incidence of fire	Using forest types and agricultural fields as fire breaks	(Khabarov et al., 2016; de Rigo et al., 2017a)
J. Incidence of fire	Reducing fire risk by promoting biomass extraction for energy purposes	(Evans and Finkral, 2009; Pausas and Paula, 2012; Regos et al., 2016)
J. Incidence of fire	Combining forest thinning, slash management and prescribed burning techniques	(Keeley et al., 2011; Fernandes, 2018; Piqué and Domènech, 2018; Samara et al., 2018)

13.A.3 Supplementary Material "Cities, Settlements and Key Infrastructure" (13.6)

Table 13.A.3: Examples of adaptation options for reducing sectoral climate change risks

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Thermoelectric power	Reduction/ Interruption of operation due to water cooling constraints	Replacement of once-through cooling by cooling towers - Dry air-cooling - Seawater cooling (for coastal plants) - Replacement by new better adapted plants (Behrens et al., 2017; EEA, 2019a; IAEA, 2019)	The choice of electricity producers between options is guided mainly by the economics of adaptation technologies, and less by the supply of information on future climate change (Bogmans et al., 2017). Costs for retrofitting cooling are site-specific and increase with the distance to water bodies, needs for additional structures and the plant's age (Sieber, 2013). Dry cooling for new plants is 3–4 times higher than wet recirculating system and 4–5.5 times higher than once-through cooling (IAEA, 2019), and could result in 10% efficiency losses (EEA, 2019a).
		Switching to alternative generation technologies with low water use, e.g., wind, solar PV (Porfiriev et al., 2017; EEA, 2019a)	Fragmentation of energy and water policy frameworks make cohesive energy and water management difficult (Byers et al., 2015; Behrens et al., 2017). Ignoring the impact of climate-induced water constraints may increase significantly the energy system costs (Khan et al., 2016).
		Inter-basin water transfer (Koch et al., 2014)	
		Use of 'non-traditional' water sources (e.g., recirculation of water from oil and gas fields or coal mines, treated wastewater from nearby cities) (Sieber, 2013)	Near-by sources of 'non-traditional' waters may not exist or may be of insufficient capacity.
		Shift part of power production to estuaries or coasts (Byers et al., 2015)	Its implementation to high-demand areas could bring significant nationwide water reductions (Byers et al., 2015), provided that recipient plants can undertake the extra production.
		Improved electricity interconnections (Behrens et al., 2017)	High investment costs.
		Demand management measures to reduce the economic losses during power curtailment	Can be an effective option, particularly under low climate change scenarios (Hanski et al., 2018).
		Institutional measures (e.g., water temperature cap, heat load plan, contract between environmental regulator and electricity producers).	The efficiency of institutional adaptation options may differ depending on the increase of heat waves intensity, frequency or both (Eisenack, 2016).
Hydropower	Reduced production due to lower streamflow	Adjusted hydropower management (Gaudard et al., 2013; EEA, 2019a).	By optimizing the hydraulic head and the turbine schedule with respect to the prices could reduce power losses up to 35% (Gaudard et al., 2013).
	Increased risk of damage from flooding	Adjusted hydropower management (Ranzani et al., 2018; EEA, 2019a)	Adaptive strategies in the management of reservoirs could reduce (but not avoid) revenue losses (Ranzani et al., 2018)
		Recalibration of spillways, e.g., through PKW, concrete or metal fuse gates	Recalibration systems have been implemented successfully in hydropower facilities in Europe and outside Europe (EEA, 2019a).
		Increase the capacity of existing hydropower plants (i.e. increase installed turbine capacity, increase reservoir storage)	This option has been implemented in some northern European hydropower plants (EEA, 2016a)
		Hydropower operational warning systems, monitoring of snowpack and river flows, forecast of high water flows	Hydropower forecasting faces key challenges related to integration of state-of-the-art weather services, data assimilation schemes, links between forecast quality and

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
			value, and enhancement of risk-based decision-making (Boucher and Ramos, 2018).
Electricity transmission and distribution	Power outages due to damages of transmission lines and power stations from extreme winds, storm surges, floods and very high temperatures	Construction of new substations and overhead lines (providing additional paths to transfer power in case of a transmission line failures) - Improve old overhead lines and substations (Fu et al., 2018).	Efficiency increases when construction of new lines and stations occurs to decentralized power systems, while improvement of existing lines and stations is less efficient (Fu et al., 2018). The contribution of substations' refurbishment in building flood resilience depends on the degree of protection of critical substations which may not necessarily be the most vulnerable to high water levels (Bollinger and Dijkema, 2016). The willingness-to-pay (WTP) to avoid power outage is higher for older people, females and urban residents; risk perceptions are greatly influenced by current regional temperatures; and under strong warming the WTP increases in summer and decreases in winter in all countries, particularly in the north (Cohen et al., 2018a). Experience with previous power cuts significantly enables resilience (Ghanem et al., 2016; Cohen et al., 2018a).
		Vegetation management	New technologies (e.g., Lidar) allow to reduce the need for time-consuming and labour-intensive traditional verification and to provide reliable input for guiding tree trimming. Though, their implementation may require significant changes of management practices at utility level.
		Turn, partially or totally, overhead lines into underground cables (Wang et al., 2016; Ciasca et al., 2017).	High installation cost Potentially long implementation time, depending on the area covered and the length of cables (EEA, 2019a). Selective undergrounding of line sections exposed to higher risk or harder to access can be a cost-effective adaptation strategy (Wang et al., 2016). For new lines, potentially long permitting processes and public opposition (Wang et al., 2016; Ciasca et al., 2017).
		Locate assets above flood level, flood barriers, relocate assets (Bollinger and Dijkema, 2016; Wang et al., 2016; Thacker et al., 2018)	High investment costs for existing assets (Wang et al., 2016). Long implementation time (EEA, 2020). TSOs often prefer to combine investments in flood defences with major renovations or refurbishments to substations, and consequently prioritization often occurs based on factors unrelated to a substation's criticality (e.g., on its age) (Bollinger and Dijkema, 2016; Wang et al., 2016). Assets' relocation is almost always not cost beneficial (Thacker et al., 2018).
		Distribution circuit segregation and automation (Wang et al., 2016).	
		Increase the height of poles supporting power lines, install conductors with hotter operating limits, use of 'low-sag' conductors (EEA, 2019a).	Legal requirements on minimum pole height support adaptation (EEA, 2019a).
	Reliability problems in electricity networks due to increased peak load for cooling	Strict efficiency standards for cooling equipment (EEA, 2019a; Palkowski et al., 2019).	Reliability can be increased through measures reducing cooling demand, such as improved building design, water cooling technologies for thermoelectric generation that do not use electricity (e.g., heat-driven absorption cooling), or direct utilisation of cooling water where available (EEA, 2019a).
		Increase transmission capacity, including international linkages	
		Increase backup capacity	
Transport	Reduction/ interruption of transportation due to damaged infrastructure and/or traffic	Broad range of options (EEA, 2014a; Frolov et al., 2014; Burbidge, 2015; Stamos et al., 2015; van Slobbe et al., 2016; Bachner, 2017):	Particularly in road transport, measures have also economy-wide feedback effects which must be considered when assessing adaptation benefits (Bachner, 2017). Nevertheless, as it is difficult to quantify the benefits and costs of adaptation measures in transport, cost-benefit analyses need to be performed on a case study level (Doll et al., 2014).

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
	disruption as a result of intense rain, flooding and heatwaves	a) Infrastructure construction/retrofitting (e.g., enlargement of drainage systems, measures to reduce slippery roads, raise links above flood level)	As 'soft' adaptation options (e.g., ICT) have already been implemented to a large extent in railways, investments in advanced protection systems (e.g., tunnels, protection walls and enlarged drainage) are necessary to support proactive maintenance strategies (Doll et al., 2014). Improving drainage or elevate critical road links can be cost effective but requires analysis at city level (Pregnolato et al., 2017). Adaptations in vessel design may reduce the vulnerability to low depth, but with a trade-off with performance in times of sufficient discharge (van Slobbe et al., 2016).
		b) Improved maintenance (e.g., vegetation management, visual road inspection)	Network maintenance can be a more cost-efficient way to reduce short- and medium-term damage risks (Doll et al., 2014).
		c) ICT and users (e.g., early warning on adverse weather, weather forecasting)	Lack of coherence between the climate adaptation plans of companies operating major transport infrastructure and their neighbouring municipalities may reduce the effectiveness of adaptation actions undertaken by the transport sector (EEA, 2014a).
		d) Modal shifts	
		e) Technological innovations (e.g., heat-resistant pavement materials, materials designed for a greater number of cycles of freezing and thawing, logistic chains).	Some of the new pavement materials may increase noise levels in urban areas (Enríquez-de-Salamanca, 2019).
		f) Revising operational guidelines and standards	The location-specific nature of weather impacts requires analysis and response also at route level to ensure investments in flood protection are cost effective (EEA, 2020). Dynamic heat management can reduce the heat-related disruption from unnecessary emergency speed restrictions (ESRs) on railway networks (Ferranti et al., 2016).
	Reduction of thermal comfort of passengers in railways and metro lines due to higher temperatures	Saloon cooling, cooling of platforms and tunnels (Jenkins et al., 2014b)	Saloon cooling alone may not be sufficient to maintain comfortable thermal conditions for some lines under high emission scenarios (Jenkins et al., 2014b).
Winter tourism	Reduction/Interruption of operation due to lack of snow	Snowmaking (including application of automated snowmaking systems)	High investment cost (i.e. for development of water supply systems, purchase and installation of snow cannons) and increased operational costs (Campos Rodrigues et al., 2018; Scott et al., 2019). Increased snowmaking can maintain snow reliability under low warming, but is not sufficient under high-end warming (Steiger and Scott, 2020).
		Protection and conservation of snowpack (e.g., water drainage, modification of the ski runs slopes, protection from avalanches, protection or storage of snow during the non-ski seasons)	Several techniques are available.
		Expansion of skiable area	Need of substantial investments and free areas, has adverse impacts (e.g., land-use conflicts, impacts of construction on natural areas, impacts on the landscape quality, increased water and energy use) (Campos Rodrigues et al., 2018).
		Nocturnal skiing (Campos Rodrigues et al., 2018)	Nocturnal skiing already offered at some ski resorts, but it can compensate for a small part of potential losses due to

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
			adverse weather and safety limitations (Campos Rodrigues et al., 2018).
		Shift to other ski destinations (spatial substitution)	The attachment ('loyalty') of glacier skiers to their favourite leisure destination, gender, demographics (i.e. age) and perceptions towards environmental sustainability were found to be important in guiding adaptation preferences (Demiroglu et al., 2018).
		Diversification of snow-based activities	Diversification may be too costly for some resorts. Skiing in indoor slopes may be the least preferred option for skiers, while other winter activities (e.g., snowboard, downhill skiing) may not be effective adaptation options as skiing is perceived as a necessity in some countries (Falk, 2015; Falk and Hagsten, 2016).
		Transformation to multi-recreational mountain resorts, compensating non-snow activities	Transformation may be too costly for some resorts (Campos Rodrigues et al., 2018). Non-snow activities not appealing to people for whom skiing is the main activity in their winter holiday (Steiger et al., 2020). Cultural differences affect the effectiveness of compensating activities (Landauer et al., 2013).
		Management options, e.g., grouping of resorts, pricing strategies (Campos Rodrigues et al., 2018)	Price discounts are effective under less severe warming scenarios (Steiger et al., 2020). Price discount in ski lift tickets may not be efficient for attracting foreign visitors (Falk and Scaglione, 2018).
Coastal and Summer tourism, Other forms of tourism	Loss of beaches/ coasts due to sea level rise and increased erosion	Hard defences (e.g., seawalls)	It is a measure that has been widely applied in Europe, but generally with no concern for future climate change impacts. It also requires high investments, proper maintenance (which is costly) and can affect sediment transport and coastal erosion (Pranzini et al., 2015).
		Soft measures(e.g., artificial beach nourishment, dune planting (Pranzini et al., 2015; Jiménez et al., 2017)	Selective sand nourishment is common in Europe (Pranzini et al., 2015), as in Spain where more than 22 mill m3 of sand were deposited on the Catalan coast during the last 30 years (Jiménez and Valdemoro, 2019). There is often a reduced availability and high costs of fill material. Potential governance difficulties (lack of well-defined roles in coordinating nearshore activities, division of costs between government, private owners and local communities).
		Inland shift of tourism activities	May not be possible due to land use and financial constraints, as well as environmental and administrative regulations.
	Disruption of tourism activities due to higher temperatures	Temporal shift/extension of recreational activities outside the summer period (e.g., transition time tourism, all year tourism)	Potential barriers include organizational issues, inability/reluctance of clientele (Mourey et al., 2020). Limiting factors to be considered include cost, school holidays or work (Brosy et al., 2014).
Business	Reduction/ Interruption of operation due to extreme events; Reduced sales due to lower demand.	Individual adaptation measures at enterprise level	
		Corporate adaptation. It is dominated by surveillance of climatic changes, climate proofing production facilities and assets, and supply chain management (Sakhel, 2017).	Corporate strategies to climate risks still predominantly focus on mitigation (Sakhel, 2017; Pinkse and Gasbarro, 2019).
Banking and finance	Risk of instability of the financial system due to damages caused by climate extremes	Extension of financial regulations and requirements for risk monitoring towards climate-related risks, such as climate-related stress tests (TCFD, 2017; D'Orazio and Popoyan, 2019)	Only in a few European countries, such regulations are in place but are voluntary (D'Orazio and Popoyan, 2019)

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Insurance	Risk of insurance default	Public reinsurance Extension of risk monitoring towards climate-related risks	
Cities	Reduced indoor and outdoor thermal comfort and power outages due to heatwaves [1]	Passive and active cooling measures in buildings (e.g., air-conditioning, ventilation, shading)	Coping appraisal is a strong predictor for citizens' motivation to adapt, while elderly are less motivated (Murtagh et al., 2019). Though necessary, natural ventilation alone cannot fully mitigate overheating (Dodoo and Gustavsson, 2016; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019; Shen et al., 2020), and its effectiveness is strongly affected by occupants' behaviour (Tillson et al., 2013; van Hooff et al., 2014), while a combination of shading and ventilation (including night-time) is needed (Ibrahim and Pelsmakers, 2018). Installation of air-conditioning may be too costly for many households (Thomson et al., 2019). Large increase of air-conditioning in densely populated areas may exacerbate the urban heat island and thus overheating (Kingsborough et al., 2017), and increases pressures on electricity systems.
		Interventions at the buildings' shell, e.g., improving insulation, increasing thermal mass, use of phase-change materials (PCM)	Addition of insulation in poorly ventilated and shaded buildings may increase overheating. Altering the thermal mass is much harder in older buildings (Tillson et al., 2013). PCM could reduce significantly the cooling load, but are a relatively new technology to the construction industry, with many uncertainties (e.g., future prices, long-term durability, energy cost) (Sajjadian et al., 2015). Material changes to buildings are often prohibited by restrictive tenancy relations (Thomson et al., 2019).
		Green, blue, and grey infrastructure (e.g., green areas, green roofs/walls, cool roofs/facades, cool pavements)	Climatic conditions may affect performance of options (Ward et al., 2016). On-site water reuse systems can provide supplementary water to green roofs and walls, gardens, and other smaller-scale urban nature-based solutions on an as-needed basis. The cooling potential of plants in green roofs or walls is influenced by the choice of plant species (Cameron et al., 2014). Cool roofs are less expensive and easier to apply than green roofs (Carvalho et al., 2017a).People's willingness to pay for green infrastructure (GI) was found to be mostly related to income and ethnicity, while citizens are willing to support climate adaptation through GI as long as the GI is multifunctional, i.e., comes with recreational and aesthetic benefits. (Derkzen et al., 2017). Urban governance mechanisms and institutional barriers to GI planning need additional research (Emmanuel and Loconsole, 2015). Cool roofs are an established technology, but this is not yet the case for cool pavement materials which may cause glare problems or excessive illuminance levels (Carnielo and Zinzi, 2013). Options are not easily transferable between countries or even cities (Hintz et al., 2018).
		Update building standards to consider the expected increase of extreme summer temperatures and the consequent increase of energy demand for cooling	Standards considering climate change and outdoor climate conditions, and realistic assumptions in terms of occupant adaptations are needed (Mulville and Stravoravdis, 2016; Sánchez-García et al., 2020; Shen et al., 2020). Standards should consider regional differences (Frolov et al., 2014).
		Watering of roads and pavements	Emergency option during heat waves, but not a long-term adaptation option (Hendel et al., 2016; Enríquez-de-Salamanca, 2019).

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
			Optimization of possible watering methods has only rarely been conducted, while water consumption is an issue (Hendel et al., 2015).
		Escape to nearby mountainous regions (Juschten et al., 2019a)	Mostly motivated by social and subjective norms, past experience with heat stress, outdoor sports as a travel motive, previous visits to the destination, positive media coverage, and perceived behaviour control (Juschten et al., 2019b).
	Reduced water supply due to drought	Water demand management	High degree of uncertainty regarding effectiveness. Coupled with new water reuse infrastructure, it could keep the probability of exceeding the target frequency of an emergency drought order below 0.01 in London under severe drought combined and high population growth (Kingsborough et al., 2016).
		Expand water supply	Water reuse, new water reservoirs, inter-basin transfers. Less flexible as it requires commitment to supply infrastructure which can be maladaptive under increasing water demand (Kingsborough et al., 2016).
	Corrosion of buildings due to permafrost and thaw melting	Use of materials with proper resistance to freezing and thawing cycles (Frolov et al., 2014) Increase corrosion resistance of structural elements (Frolov et al., 2014)	Development of an assessment methodology and database on the durability of materials under various climatic conditions is needed to support the selection of optimal materials under the future climate. Regular updating of regulatory parameters based on observational data (Frolov et al., 2014).
		Design solutions that prohibit an increase of moisture content in building structures (Frolov et al., 2014)	
	Damage to settlements and infrastructure due to flooding	Building new flood defenses (e.g., dikes)	Costs for maintaining the baseline flood protection level under climate change (and introducing a minimum of 100 years protection) through defenses would not outweigh benefits for many countries before 2030 under different RCP/SSPs, while in 2080 adaptation benefits would exceed costs in almost all countries (Bouwer et al., 2018). Update and increased maintenance of storm barriers comes along with concerns on their environmental impacts as in St Petersburg (Rodionov, 2016).
		Heightening and/or strengthening of existing dikes, dams, and levees. Widening of river floodplains and reduction of obstructions in floodplains (Bouwer et al., 2018). Updating the urban drainage system (Bodoque et al., 2019).	
		Flood protection measures at building/household level, such as dry-proofing (e.g., sealing walls with waterproof coatings, impermeable layering of masonry, sealants for openings), wet-proofing (e.g., building elevation, use of water-resistant materials), emergency measures (e.g., mobile flood barriers, sandbags), securement of sources of contamination	There is high confidence that past experience of damage strongly affects risk perception and hence motivation for adaptation (Baron and Petersen, 2015; Lujala et al., 2015; Osberghaus, 2015; Madsen et al., 2019). Though, protection may be motivated mostly by coping and threat appraisal and trust in public institutions (Bamberg et al., 2017). Dry-proofing is costly and thus usually applied to new buildings (Bouwer et al., 2018). The level of wet-proofing differs significantly between locations (Koerth et al., 2013; Stojanov et al., 2015). Perceptions of flood risks, expected climate impacts, risk attitudes and geographical characteristics were found to be the most important determinants in the decision to invest in elevating houses (Botzen et al., 2013).
		Nature-based solutions to manage water runoff, e.g., multifunctional green spaces, wetlands, retention/detention and infiltration basins, rain gardens and green roofs	Natural ecosystems remain under threat from changing climatic conditions. Potential barriers for development of green infrastructure for flood risk management include coordination and convincing stakeholders, limitations of the existing legislations, and difficulty in accounting non-monetary benefits (Liu and Jensen, 2018).
		Facilitate recovery after climate extremes	The location and composition of urban green spaces is key for effective adaptation (García Sánchez et al., 2018)

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
		Increase flood risk standards, land use planning, risk zoning, dedicated flood management legislation	Measures that work well in one region may not be effective in another region facing different flood hazards, and thus building codes and rest flood risk management policies have to be region-specific (Poussin et al., 2015). Legislation to delimit non-suitable land for urbanization often shows a slow implementation (Pérez-Morales et al., 2018), although it can be very effective in reducing risks under climate change (Thieken et al., 2016). Under high sea level rise, risk zoning can be more effective than hard defences (Andersson-Sköld et al., 2015).
		Emergency plans, training for evacuations, early warning systems	Require that the role and responsibilities of different administrative departments and organizations involved are well-defined, and that there is a clear plan on how to manage the different stages in the recovery process (Adedeji et al., 2019).
		Planned relocation	Higher resistance was found among seafront residents, second-home occupants, homeowners, elderly, retired, and multi-generation households (Dachary-Bernard et al., 2019; Rey-Valette et al., 2019; Seebauer and Winkler, 2020).
	Clay-related subsidence due to increased/ extreme drought	Deeper foundations, trees or terraces around light buildings to keep humidity in soils and prevent ground motions	Clay-related subsidence risks can be managed by appropriate adaptation measures at building scales (*medium confidence*) (Pritchard et al., 2015)

[1] Heatwave warnings and Heat Action Plans as means for adaptation are discussed in Section 13.7 on Health.

Table 13.A.4: Literature sources utilized in the assessment of feasibility and effectiveness of adaptation options for cities, settlements and key infrastructure in Europe

Risk & Adaptation measures	EC	TE	IN	SO	ENV	GE	EFF
Reduction of thermal comfort due to increasing temperatures and extreme heat							
Interventions in the building shell	(Tillson et al., 2013; Sajjadian et al., 2015; Murtagh et al., 2019)	(Sajjadian et al., 2015)	(Ibrahim and Pelsmakers, 2018; Murtagh et al., 2019)	(Ibrahim and Pelsmakers, 2018; Murtagh et al., 2019)	NE	(Tillson et al., 2013; Ibrahim and Pelsmakers, 2018; Domínguez-Amarillo et al., 2019)	(Tillson et al., 2013; Sajjadian et al., 2015; Ibrahim and Pelsmakers, 2018; Domínguez-Amarillo et al., 2019)
Ventilation	(van Hooff et al., 2014; Murtagh et al., 2019)	(van Hooff et al., 2014)	(Tillson et al., 2013; Mulville and Stravoravdis, 2016; Murtagh et al., 2019)	(Tillson et al., 2013; van Hooff et al., 2014; Mulville and Stravoravdis, 2016; Ibrahim and Pelsmakers, 2018; Murtagh et al., 2019; Thomson et al., 2019)	NE	(Tillson et al., 2013; van Hooff et al., 2014; Ibrahim and Pelsmakers, 2018)	(Tillson et al., 2013; van Hooff et al., 2014; Dodoo and Gustavsson, 2016; Mulville and Stravoravdis, 2016; Hamdy et al., 2017; Zinzi et al., 2017; Heracleous and Michael, 2018; Ibrahim and Pelsmakers, 2018; Dino and Meral Akgül, 2019; Thomson et al., 2019)
Air conditioning	(Ferrara and Fabrizio, 2017; Thomson et al., 2019)	NE	NE	(Thomson et al., 2019)	NE	(Jenkins et al., 2014a)	(Jenkins et al., 2014b; Dodoo and Gustavsson, 2016; Dino and Meral Akgül, 2019)
Shading	(Tillson et al., 2013; van Hooff et al., 2014; Murtagh et al., 2019)	(van Hooff et al., 2014)	(Murtagh et al., 2019; Thomson et al., 2019)	(Tillson et al., 2013; Ibrahim and Pelsmakers, 2018; Murtagh et al., 2019)	NE	(van Hooff et al., 2014; Thomson et al., 2019)	(Tillson et al., 2013; van Hooff et al., 2014; Dodoo and Gustavsson, 2016; Zinzi et al., 2017; Ibrahim and Pelsmakers, 2018)

Risk & Adaptation measures	EC		TE		IN		SO		ENV		GE		EFF	
Green roofs, green walls		(Cameron et al., 2014; Virk et al., 2015; Carvalho et al., 2017a; de Munck et al., 2018)		(Cameron et al., 2014; Carvalho et al., 2017a; de Munck et al., 2018)		(Cameron et al., 2014; Virk et al., 2014)		(Cameron et al., 2014; van Hooff et al., 2014; Virk et al., 2015; Carvalho et al., 2017a; Derkzen et al., 2017)		(Virk et al., 2015)		(van Hooff et al., 2014)		(Cameron et al., 2014; van Hooff et al., 2014; Virk et al., 2014; Virk et al., 2015; Carvalho et al., 2017a; de Munck et al., 2018)
Urban green spaces		(Carvalho et al., 2017a; de Munck et al., 2018)		(Carvalho et al., 2017a; de Munck et al., 2018)		(Emmanuel and Loconsole, 2015)		(Carvalho et al., 2017a; Derkzen et al., 2017; Thomson et al., 2019)		(de Munck et al., 2018)		(Emmanuel and Loconsole, 2015; Carvalho et al., 2017a; de Munck et al., 2018; Thomson et al., 2019)		(Emmanuel and Loconsole, 2015; Ward et al., 2016; Carvalho et al., 2017a; de Munck et al., 2018)
Use of 'cool' paints and coatings		(van Hooff et al., 2014; Virk et al., 2015; Carvalho et al., 2017a; Murtagh et al., 2019)		(Carnielo and Zinzi, 2013; Carvalho et al., 2017a)		(Virk et al., 2014)		(Carnielo and Zinzi, 2013; Virk et al., 2015; Murtagh et al., 2019)	NE			(Zinzi, 2016)		(Carnielo and Zinzi, 2013; van Hooff et al., 2014; Virk et al., 2014; Virk et al., 2015; Zinzi, 2016; Carvalho et al., 2017a)
Escape to nearby non-urban destinations	NE		NE		NE			(Juschten et al., 2019a; Juschten et al., 2019b)	NE		NE		NE	
Loss of critical services due to heatwaves and drought														
Improvements in cooling systems		(Koch et al., 2014; van Vliet et al., 2016d; Behrens et al., 2017; Bogmans et al., 2017; EEA, 2019a)		(Sieber, 2013; Ferranti et al., 2016)		(Jenkins et al., 2014a; Koch et al., 2014; Byers et al., 2015; Hendel et al., 2016; Kingsborough et al., 2016;	NE		NE			(Sieber, 2013; Koch et al., 2014; van Vliet et al., 2016d; Behrens et al., 2017)		(Jenkins et al., 2014a; Koch et al., 2014; Byers et al., 2015; Ferranti et al., 2016; Kingsborough et al., 2016; van Vliet et al., 2016d; Behrens et al., 2017; Bogmans et al., 2017)

Risk & Adaptation measures	EC	TE	IN	SO	ENV	GE	EFF
			Behrens et al., 2017)				
Shifting production to less water-intensive plants	(Khan et al., 2016; Behrens et al., 2017)	(Khan et al., 2016)	(Behrens et al., 2017)	NE	NE	NE	(Khan et al., 2016)
Regulatory measures	(Eisenack, 2016)	NE	(Eisenack, 2016)	NE	NE	NE	(Eisenack, 2016)
Management measures	(Ferranti et al., 2016; Ranzani et al., 2018; Wang et al., 2019)	(Hendel et al., 2015; Kingsborough et al., 2016)	(Ferranti et al., 2016; EEA, 2019a; Palkowski et al., 2019)	NE	(Hendel et al., 2015)	(Gaudard et al., 2013; Hendel et al., 2015)	(Gaudard et al., 2013; Hendel et al., 2015; Ferranti et al., 2016; Kingsborough et al., 2016; Ranzani et al., 2018; Wang et al., 2019)
Use of heat-resilient materials	(Carnielo and Zinzi, 2013; EEA, 2019a; Wang et al., 2019)	(Carnielo and Zinzi, 2013; EEA, 2019a; Wang et al., 2019)	(Carnielo and Zinzi, 2013; EEA, 2019a; Wang et al., 2019)	(Carnielo and Zinzi, 2013; EEA, 2019a; Wang et al., 2019)	NE	NE	(Carnielo and Zinzi, 2013; EEA, 2019a; Wang et al., 2019)
Replace vulnerable infrastructure with resilient one	(van Slobbe et al., 2016; Wang et al., 2019)	NE	NE	NE	NE	NE	(van Slobbe et al., 2016; Wang et al., 2019)
Damages to infrastructures from flooding due to intense rain and sea level rise							
Flood defenses	(Bollinger and Dijkema, 2016; Pregnolato et al., 2017; Thacker et al., 2018; EEA, 2019a; EEA, 2020)	(Thacker et al., 2018)	(Bollinger and Dijkema, 2016; Thacker et al., 2018; EEA, 2019a; EEA, 2020)	(Pregnolato et al., 2017)	(Andersson-Sköld et al., 2015; Pérez-Morales et al., 2018)	(EEA, 2019a)	(Andersson-Sköld et al., 2015; Bollinger and Dijkema, 2016; Pregnolato et al., 2017; Bouwer et al., 2018; Pérez-Morales et al., 2018; Thacker et al., 2018; EEA, 2019a;

Risk & Adaptation measures	EC	TE	IN	SO	ENV	GE	EFF
							EEA, 2020; Umgiesser, 2020)
Planned relocation	(Thacker et al., 2018; Seebauer and Winkler, 2020)	(Thacker et al., 2018)	(Thacker et al., 2018)	(Koerth et al., 2013; Dachary-Bernard et al., 2019; Rey-Valette et al., 2019; Seebauer and Winkler, 2020)	(Dachary-Bernard et al., 2019)	NE	(Thacker et al., 2018; Dachary-Bernard et al., 2019)
Update drainage systems	(Liu and Jensen, 2018; EEA, 2020)	NE	(Liu and Jensen, 2018)	(EEA, 2016a)	(EEA, 2020)	(Liu and Jensen, 2018; EEA, 2020)	(Skougaard Kaspersen et al., 2017)
Elevate infrastructure/equipment					NE	NE	
Flood prevention plans & early warning	NE				NE	NE	
Emergency plans	NE	NE		NE	NE	NE	
Flood insurance	NE	NE			NE	NE	
Dry proofing		NE		NE	NE	NE	
Land management	NE	NE		NE		NE	

Table 13.A.5: Reported adaptation limits in Europe

Technical limits • Seawater cooling feasible only for coastal plants (Behrens et al., 2017) • Water temperature caps can reduce thermal power availability and cause blackouts (Eisenack, 2016) • Management optimization not applicable to run-of-river hydropower plants (Gaudard et al., 2013) • Automation for flood discharge not suitable for certain hydropower dams (EEA, 2020) • Minimum Energy Performance standards covering only residential air-conditioners (Palkowski et al., 2019) • Wet-bulb temperature for snowmaking (Spandre et al., 2016; Hartl et al., 2018) • Too large sediment volumes needed for beach nourishment (Galofré et al., 2016; Jiménez and Valdemoro, 2019) • Physical characteristics of the existing housing stock preventing high ventilation (Tillson et al., 2013) • Limited efficacy of hard defences for high sea level rise (i.e. >1m)/ rapid rates of sea-level rise (e.g., above 1cm/year) (Umgiesser, 2020) [see also section 13.2 - Venice Box]
Environmental limits • Lack of nearby alternative non-fresh water sources for plant cooling (Sieber, 2013) • Limited/no availability of free areas in higher altitudes and orographic constraints for expanding skiable corridors (Campos Rodrigues et al., 2018) • Limited water resources for increasing snowmaking (Spandre et al., 2016; Scott et al., 2019; Steiger and Scott, 2020) • Impossible inland shift of tourism and settlements due to coastal urbanization or geomorphology (Toimil et al., 2018) • Space constraints on green infrastructure for flood management (Liu and Jensen, 2018)
Economic and social limits • No adaptation benefits from turning aerial transmission cables into underground ones in flood-prone areas (Sieber, 2013) • High investments needed for upgrading current drainage to new standards (EEA, 2020) • High installation costs for applying flood-proofing measures beyond critical substations (EEA, 2020) • Energy poverty limits the households' capacity to adapt to overheating (Sanchez-Guevara et al., 2019; Thomson et al., 2019) • Low flood probability prohibits the pay-off of costly investments in home flood proofing (Poussin et al., 2015)

13.A.4 Supplementary Material "Health, Wellbeing and the Changing Structure of Communities" (13.7)

Table 13.A.6: References used for assessing observed impact, and projected risks (1.5 and 3 degrees) of climate sensitive infectious diseases in Europe. [PLACEHOLDER FOR FINAL DRAFT: to be updated]

Climate sensitive infectious diseases		**Supportive references**
Vector borne diseases		
	Tick-borne encephalitis	(Daniel et al., 2003; Semenza and Menne, 2009; Jaenson and Lindgren, 2011; Estrada-Pena et al., 2012; Jaenson et al., 2012; Medlock et al., 2013; Porretta et al., 2013; Boeckmann and Joyner, 2014; Jore et al., 2014; Heinz et al., 2015; Alfredsson et al., 2017; Semenza and Suk, 2018).
	Lyme borreliosis	(Semenza and Menne, 2009; Jaenson and Lindgren, 2011; Jaenson et al., 2012; Semenza et al., 2016a; Alfredsson et al., 2017).
	West Nile fever	(Semenza et al., 2016b; Vogels et al., 2017; Haussig et al., 2018; Semenza and Suk, 2018).
	Dengue fever	(Fischer et al., 2011; Rogers et al., 2014; Schaffner and Mathis, 2014; Kraemer et al., 2015; Liu-Helmersson et al., 2016).
	Chikungua fever	(Nsoesie et al., 2016; Semenza and Suk, 2018)
	Malaria	(Semenza and Menne, 2009; Danis et al., 2013; Piperaki and Daikos, 2016; Hertig, 2019).
	Zika	(Caminade et al., 2017)

Water borne diseases		
	Vibriosis	(Semenza et al., 2016a)
	Legionella	(Walker, 2018)
Food borne diseases		
	Salmonella	(Yun et al., 2016; Lake, 2017).
	Campylobacter	(Yun et al., 2016; Lake, 2017; Kuhn et al., 2020).

Table 13.A.7: references used for feasibility and effectiveness of health adaptation options for Europe (only including heat related options).

Adaptation option	Supportive reference
Heat protection behaviour - Modify sleeping habits	(Hendel et al., 2017)
Heat protection behaviour (general)	(Khare et al., 2015)
Home protection behaviour (general)	(Khare et al., 2015)
Cool roofs	(Macintyre and Heaviside, 2019)
Building improvements	(Åström et al., 2017)
Enhancing reflective properties of buildings	(Fallmann et al., 2013)
Installation of external shutters/shading	(Taylor et al., 2018)
Energy efficiency upgrades (of entire housing stock)	(Taylor et al., 2018)
Urban planning - Green areas	(Taylor et al., 2018)
Urban planning (GENERAL)	(Åström et al., 2017)
Urban planning - Green areas	(Fallmann et al., 2013)
Urban planning - Decrease building density	(Fallmann et al., 2013)
Urban planning (siting of constructions)	(Donner et al., 2015)
Urban planning - Land cover management	(Donner et al., 2015)

Adaptation option	Supportive reference
Urban planning - Green infrastructures (e.g., tree canopy cover)	(Venter et al., 2020)
Urban planning - reurbanisation + green roofs in all buildings	(Richter, 2016)
Prevention plans for extreme temperatures	(Carmona et al., 2016b)
Public health intervention programmes	(Gasparrini et al., 2015)
Heath Health Action Plans and Heat Warning System	(Heudorf and Schade, 2014)
Heat protection plans	(Reischl et al., 2018)
Bundle of options (e.g., health plans, culture of heat, etc…) and associated heat "habituation"	(Díaz et al., 2019)

13.A.5 Supplementary Material "Poverty, Livelihoods and Cultural Heritage" (13.8)

Table 13.A.8: Climate change-related impacts affecting nomadic reindeer herding in Northern Europe. [PLACEHOLDER FOR FINAL DRAFT: confidence will be added to trends; list of reference will be expanded]

Indicator	Observed	Projected	References
(b) Changing weather conditions			
Amount of snow	Negative	Negative	WGI, Ch.12
Unstable ice conditions	Negative	Negative	(Forbes et al., 2016; Mallory and Boyce, 2018)
Frequent freeze thaw cycles	Negative	Negative	(Johansson et al., 2011; Hansen et al., 2014; Bokhorst et al., 2016; Rasmus et al., 2018)
Late snow melting during spring	Negative		[PLACEHOLDER FOR FINAL DRAFT: references will be added]
Higher summer temperatures		Both	[PLACEHOLDER FOR FINAL DRAFT: references will be added]
(c) Effects on animals and people			
Diseases and insect harassment	Negative	Negative	(Mallory and Boyce, 2018; Tryland et al., 2019)
Mortality and weight loss of animals	Negative	Negative	(Tyler et al., 2007; Helle and Kojola, 2008)
Psychological stress	Negative	Negative	(Kaiser et al., 2010; Furberg et al., 2011; Stoor, 2016)
Increased workload and costs	Negative	Negative	(Furberg et al., 2011; Löf, 2013; Rosqvist et al., 2020)
Conflicts	Negative	Negative	(Lawrence, 2014; Sehlin MacNeil, 2015; Lawrence and Kløcker Larsen, 2017; Persson et al., 2017; Beland Lindahl et al., 2018)
Self-determination and adaptive capacity	Negative	Negative	(Brännlund and Axelsson, 2011) (Löf, 2013) (Andersson et al., 2015) (Brännström, 2017) (Allard, 2018) (Kløcker Larsen and Raitio, 2019)
(d) Combined effects from land pressure			

Mining	Negative	Negative	(Herrmann et al., 2014; Eftestøl et al., 2019; Lawrence and Kløcker Larsen, 2019; Österlin and Raitio, 2020)
Hydropower	Negative	No change	(Össbo and Lantto, 2011; Össbo, 2018)
Forestry	Both	Both	(Kivinen et al., 2012; Sandström et al., 2016; Fischer et al., 2020)
Wind power	Negative	Negative	(Skarin et al., 2015; Skarin and Alam, 2017; Österlin and Raitio, 2020)

13.A.6 Supplementary Material "Detection and Attribution and Key Risks Across Sectors and Regions" (13.10)

Table 13.A.9: Detected changes and literature supporting attribution

Assessment statement	**Supporting References**
Forest growth and production has been influenced by temperature and moisture conditions combined over the last centuries. The consequences of climate change differed regionally, especially along the south to north axis	(Pretzsch et al., 2014; Reyer et al., 2014; Seidl et al., 2014; Gazol et al., 2015; Keenan et al., 2016; Reich et al., 2016; Tian et al., 2016; Alrahahleh et al., 2017; Ballantyne et al., 2017a; Zlatanov et al., 2017; Humphrey et al., 2018; Marqués et al., 2018; Stocker et al., 2018; Vitali et al., 2018; Carnicer et al., 2019a; Ciais et al., 2019; Green et al., 2019; Yuan et al., 2019; Brodribb et al., 2020).
Tundra vegetation growth rate and shrub height have been accelerated by climate change	(Belonovskaya et al., 2016; Martin et al., 2017).
Drought consequences in the Mediterranean region showed significant increase of adverse effects, and outside the southern region effects of drought varied considerably	(Fantappié et al., 2011; Giuntoli et al., 2013; Yigini and Panagos, 2016; Potopová et al., 2017; Stagge et al., 2017; Samaniego et al., 2018; García-Herrera et al., 2019; Spinoni et al., 2019; Zhou et al., 2019).
Crops decreased due to temperature related regional changes with variable regional impact in Europe, and optimal conditions of some crops moved northwards	(Garcia-Mozo et al., 2015; Long et al., 2016; Ceglar et al., 2017; Potopová et al., 2017; Zhao et al., 2017; Pérez-Domínguez and Fellmann, 2018; Webber et al., 2018; Di Lena et al., 2019).
River floods have had increasing damaging effects in central Europe, but decreased in other regions	(Alfieri et al., 2015a; Polemio and Lonigro, 2015; Ljungqvist et al., 2016; Blöschl et al., 2017; Kundzewicz et al., 2017; Paprotny et al., 2018; Berghuijs et al., 2019; Blöschl et al., 2019; Ganguli and Merz, 2019; Lenderink et al., 2019; Umgiesser, 2020).
Wildfire effects are jointly influenced by climate variables such as drought and temperature, but they are also highly influenced by management	(Moriondo et al., 2006; Moreno et al., 2014; Turco et al., 2014; Jolly et al., 2015; Tedim et al., 2015; Turco et al., 2016; de Rigo et al., 2017a; Turco et al., 2017; Turco et al., 2018b; Michetti and Pinar, 2019).
Marine heatwaves induced mass mortality of sessile life forms, and such episodes have increased in frequency	(Garrabou et al., 2009; Munari, 2011; Rivetti et al., 2014; Smale et al., 2015; Rubio-Portillo et al., 2016; Oliver et al., 2018; Darmaraki et al., 2019a; Holbrook et al., 2019; Smale et al., 2019).
Terrestrial species relocation rate towards higher latitude and altitude have increased	(Scherrer and Körner, 2011; Oliver et al., 2015; Melero et al., 2016; Stephens et al., 2016; Wiens, 2016; Bowler et al., 2017; Spooner et al., 2018b; Lehikoinen et al., 2019; van Klink et al., 2020).
Marine species relocation from warm waters to previously colder but warming waters increased	(Fossheim et al., 2015; Hiddink et al., 2015; Montero Serra et al., 2015; van der Kooij et al., 2016; Chivers et al., 2017; García-Molinos et al., 2017; Cozzi et al., 2019; Vilà-Cabrera et al., 2019).
Coastal flood damaging effects increased.	(Haigh et al., 2011; Wahl et al., 2015; Malagon Santos et al., 2017; Garnier et al., 2018; Fernández-Montblanc et al., 2020; Umgiesser, 2020)
Phenology changes were well documented in AR5, and later literature have confirmed the trends	(HASSALL et al., 2007; Visser et al., 2012; Karlsson, 2014; Thackeray et al., 2016; Mayor et al., 2017; Cohen et al., 2018b).
Vector borne diseases have expanded northwards	(Daniel et al., 2003; Jaenson et al., 2012; Medlock et al., 2013; Jore et al., 2014; Tokarevich et al., 2017; Semenza and Suk, 2018).

Assessment statement	Supporting References
Winter tourism has experienced decreased potential due to reduced snow cover and reliability of natural snow, with severity of loss highest at low altitudes	(Falk, 2015; Falk and Vanat, 2016; Klein et al., 2016; Beniston et al., 2018; Falk and Lin, 2018; Schöner et al., 2019). Rain on snow event frequency have increased (Beniston and Stoffel, 2016).
Damages from thaw of permafrost have been detected in a large range of societally important infrastructure, such as buildings and roads	(Stoffel et al., 2014; Porfiriev et al., 2017; Ravanel et al., 2017; Beniston et al., 2018; Duvillard et al., 2019).
Electricity consumption for cooling demand due to increasing temperatures have increased	(De Rosa et al., 2015; Spinoni et al., 2015), and heating demand have decreased (van Vliet et al., 2016c; Abi-Samra, 2017).
Macroeconomic damages for Europe has been detected	(Burke et al., 2015; Diffenbaugh and Burke, 2019a).
Shoreline erosion is detected but literature is limited	(Castelle et al., 2018; Mentaschi et al., 2018).
Aquatic species relocation includes expansion northwards, which in the southern region implies tropicalization	(Zhang et al., 2017; Monchamp et al., 2018; Kärcher et al., 2019; van Klink et al., 2020).
Heatwaves induced mortality at increasing frequency and severity	(Shaposhnikov et al., 2015; Morabito et al., 2017; Vogel et al., 2019).
Ocean acidification combined with warming affects several aspects of marine commercial gain	(Lacoue-Labarthe et al., 2016; Fernandes et al., 2017).
Fisheries specimen size distribution changed. Frequency of small specimen size in increased in southern regions of European waters	(Fortibuoni et al., 2015; Gamito et al., 2015; Teixeira et al., 2016; Ding et al., 2017; Ojea et al., 2017; Free et al., 2019; Stecf, 2019).
Miscellaneous effects with limited evidence were not been included in table 13.xx. Several lone standing examples of effects that can be attributed to climate change have been adequately reported	For example increase in groundwater heavy metal contamination from fractured aquifers (Bondu et al., 2016), effects in livestock (Handisyde et al., 2017; Rojas-Downing et al., 2017), pathogene sensitivity (McIntyre et al., 2017; Moretti et al., 2019), and heat damage to railway tracks (Ferranti et al., 2018).

Table 13.A.10: Macroeconomic losses of multiple climate risks, measured by GDP and welfare for 3°C relative to no additional warming; GDP loss: very high (VD), high (HD), moderate (MD); GDP gain/increase: very high (VI), high (HI), moderate (MI); both (B)I; no (N); limited evidence (LE); * Only Europe in total is covered, no subregions; ** single country or subset of countries

	MED	NEU	WCE	EEU	Europe	References
Agriculture	VD (•••)	B (••)	MD (••)	B (••)	MD (•••)	Roson and Sartori 2016; Aaheim et al. 2017; Dellink et al. 2019; Szewczyk et al. 2018; Szewczyk et al. 2020; Bosello et al. 2020
Coastal flooding	HD (•••)	HD (•••)	MD (•••)	MD (•••)	HD (•••)	Roson and Sartori 2016; Aaheim et al. 2017; Dellink et al. 2019; Szewczyk et al. 2018; Szewczyk et al. 2020; Parrado et al. 2020; Pycroft et al. 2016; Bosello et al. 2020
River flooding	HD (•••)	MD (•••)	HD (•••)	HD (•••)	MD (•••)	Dottori et al. 2018; Szewczyk et al. 2018; Szewczyk et al. 2020; Koks et al. 2019; Bosello et al. 2020
Health	VD (•••)	MD (•••)	MD (•••)	HD (•••)	HD (•••)	Roson and Sartori 2016; Aaheim et al. 2017; Dellink et al. 2019;

						Szewczyk et al. 2018; Szewczyk et al. 2020
Labor productivity	HD (••)	MD (••)	MD (••)	MD (••)	MD (••)	Roson and Sartori 2016; Szewczyk et al. 2018; Orlov et al 2020; Bosello et al. 2020; Knittel et al. 2020
Energy	B (••)	B (••)	B (••)	B (••)	B (••)	Aaheim et al. 2017; Dellink et al. 2019; Szewczyk et al. 2018; Szewczyk et al. 2020; Bosello et al. 2020
Forestry	LE	LE	LE	LE	LE	Aaheim et al. 2017; Bosello et al. 2020
Fisheries	LE	LE	LE	LE	LE	Bosello et al. 2020
Drought / water scarcity	HD (••)	B (•)	MD (•)	MD (•)	MD (••)	Faust 2015**; Koopman et al 2017**; Roson and Damania 2017, Szewczyk et al. 2020; Teotonio et al. 2020**
Tourism	MD (•)	MI (•)	MD (•)	B (•)	MD (•)	Roson and Sartori 2016; Dellink et al. 2019; Ciscar et al. 2014
Transport	LE	LE	LE	LE	LE	Bachner 2017**; Bosello et al. 2020
Trade	MD (•)	MD (•)	MD (•)	MD (•)	MD (•)	Dellink 2017; Kulmer et al. 2020; Knittel et al. 2020; Mandel et al. 2020
TOTAL	HD (•••)	MD (•••)	MD (•••)	MD (••)	HD (•••)	Aaheim et al. 2017; Dellink et al. 2019; Szewczyk et al. 2018; Szewczyk et al. 2020; Kompas et al. 2018; Kalkuhl and Wenz, 2020; De Cian et al. 2017*; Takakura et al. 2019*

References: (Ciscar et al., 2014; Faust et al., 2015; De Cian et al., 2016; Pycroft et al., 2016; Roson and Sartori, 2016; Aaheim et al., 2017; Bachner, 2017; Dellink et al., 2017; Koopman et al., 2017; Roson and Damania, 2017; Takakura et al., 2017; Dottori et al., 2018; Szewczyk et al., 2018; Dellink et al., 2019; Koks et al., 2019b; Orlov et al., 2019; Bosello et al., 2020; Kalkuhl and Wenz, 2020; Knittel et al., 2020; Kulmer et al., 2020; Mandel et al., 2020b; Parrado et al., 2020; Szewczyk et al., 2020; Teotónio et al., 2020)

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