Chapter 13: Europe

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Executive Summary

Where are we now?

Our current 1.1°C warmer world is already affecting natural and human systems in Europe (*very high confidence*[1]). Since AR5, there has been a substantial increase in detected or attributed impacts of climate change in Europe, including extreme events (*high confidence*). Compound hazards of warming and precipitation have become more frequent (*medium confidence*). Climate change has resulted in losses of and damages to people, ecosystems, food systems, infrastructure, energy and water availability, public health, and the economy (*very high confidence*) {13.1.4;13.2.1;13.3.1;13.4.1;13.5.1;13.6.1;13.7.1;13.8.1;13.10.1}.

As impacts vary both across and within European regions, sectors, and societal groups (*high confidence*), inequalities have deepened (*medium confidence*). Southern regions tend to be more negatively affected, while some benefits have been observed, alongside negative impacts in northern and central regions. Traditional lifestyles, for example in the European Arctic, are threatened already (*high confidence*). Poor households have lower capacity to adapt to, and recover from, impacts (*medium confidence*) {13.5.1;13.6.1;13.7.1;13.8.1.;13.8.2;13.10.1;Box 13.2}.

The range of options available to deal with climate-change impacts has increased in most of Europe since AR5 (*high confidence*). Growing public perception and adaptation knowledge in public and private sectors, increasing number of policy and legal frameworks, and dedicated spending on adaptation are all clear indications that the availability of options has expanded (*high confidence*). Information provision, technical measures, and government policies are the most common adaptation actions implemented. Nature-based solutions (NbS) that restore or recreate ecosystems, build resilience and produce synergies with adaptation and mitigation are increasingly used. Many cities are taking adaptation action, but with large differences in level of ambition and implementation (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.10.2;13.11.1;13.11.2;13.11.3}.

Observed adaptation actions are largely incremental with only a few examples of local transformative action; adaptation actions have demonstrated different degrees of effectiveness in reducing impacts and feasibility of implementation *(high confidence*). For example, adaptation actions such as flood defences and early warning systems have reduced flood damages and heat-related mortality in parts of Europe. Despite progress on adaptation, impacts are observed. Adaptation actions in the private sector are limited, with many businesses and regions remaining under-prepared. A gap remains between planning and implementation of adaptation action (*high confidence*) {13.2.2;13.5.2;13.6.2;13.7.2;13.11}.

What are the future risks?

Warming in Europe will continue to rise faster than the global mean, widening risk disparities across Europe in the 21st century (*high confidence*). Largely negative impacts are projected for southern regions (e.g., increased cooling needs and water demand, losses in agricultural production, and water scarcity) and some short-term benefits anticipated in the north (e.g. increased crop yields and forest growth) {13.1.4;13.2.1;13.3.1;13.4.1;13.5.1;13.6;13.7.1;13.10.2}.

Four key risks (KR) have been identified for Europe, with most becoming more severe at 2°C GWL compared to 1.5°C GWL in scenarios with low to medium adaptation (*high confidence*). From 3°C GWL and even with high adaptation, severe risks remain for many sectors in Europe (*high confidence*). Key risks are: mortality and morbidity of people and ecosystems disruptions due to heat (KR1: heat); loss in agricultural production due to combined heat and droughts (KR2: agriculture); water scarcity across sectors (KR3: water scarcity); impacts of floods on people, economies and infrastructure (KR4: flooding) {13.10.2}.

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

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KR1: The number of deaths and people at risk of heat stress will increase two- to threefold at 3°C compared to 1.5°C GWL (*high confiden*ce). Risk consequences will become severe more rapidly in Southern and Western Central Europe and urban areas (*high confidence*). Thermal comfort hours during summer will decrease significantly (*high confidence*), by as much as 74% in Southern Europe at 3°C GWL. Above 3°C GWL, there are limits to the adaptation potential of people and existing health systems, particularly in Southern Europe and Eastern Europe and areas where health systems are under pressure (*high confidence*) {13.6.1;13.6.2;13.7.1;13.7.2;13.8.1;13.10.2.1}.

KR1: Warming will decrease suitable habitat space for current terrestrial and marine ecosystems and irreversibly change their composition, increasing in severity above 2°C GWL (*very high confidence*). Fire-prone areas are projected to expand across Europe, threatening biodiversity and carbon sinks (*medium confidence*). Adaptation actions, e.g. habitat restoration and protection, fire and forest management, and agroecology, can increase the resilience of ecosystems and their services. Trade-offs between adaptation and mitigation options (e.g., coastal infrastructure and Nature based Solutions) will result in risks for the integrity and function of ecosystems (*medium confidence*) {13.3.1;13.3.2;13.4.1;13.4.2;13.10.2.1; Cross-Chapter Box SLR in Chapter 3; Cross-Chapter Box NATURAL in Chapter 2}.

KR2: Due to a combination of heat and drought, substantive agricultural production losses are projected for most European areas over the 21st century, which will not be offset by gains in Northern Europe (*high confidence*). Yield losses for maize will reach 50% in response to 3°C GWL, especially in Southern Europe. Yields of some crops, e.g. wheat, may increase in Northern Europe when warming does not exceed 2°C (*medium confidence*). While irrigation is an effective adaptation option for agriculture, the ability to adapt using irrigation will be increasingly limited by water availability, especially in response to GWL above 3°C (*high confidence*) {13.5.1;13.5.2;13.10.2.2}.

KR3: Risk of water scarcity will become high at 1.5°C and very high at 3°C GWL in Southern Europe (*high confidence*) and increase from moderate to high in Western Central Europe (*medium confidence*). In Southern Europe, more than a third of the population will be exposed to water scarcity at 2°C GWL; under 3°C GWL, this risk will double, and significant economic losses in water and energy dependent sectors may arise (*medium confidence*). The risk of water scarcity is strongly increasing for Western Central and Southern Europe, and many cities under 3°C GWL. Adaptation becomes increasingly difficult at 3°C GWL and above, due to geophysical and technological limits; hard limits are *likely*[2] first reached in parts of Southern Europe {13.2.1;13.2.2;13.6.1;13.10.2.3}.

KR4: Due to warming, changes in precipitation and sea level rise, risks to people and infrastructures from coastal, riverine, and pluvial flooding will increase in Europe (*high confidence*). Risks of inundation and extreme flooding will increase with accelerating pace of sea level rise along Europe's coasts (*high confidence*). Above 3°C GWL, damage costs and people affected by precipitation and river flooding may double. Coastal flood damage is projected to increase at least 10-fold by the end of the 21st century, and even more or earlier with current adaptation and mitigation (*high confidence*). Sea level rise represents an existential threat for coastal communities and their cultural heritage, particularly beyond 2100 {13.2.1;13.2.2;13.6.2;13.10.2.4;Box 13.1; Cross-Chapter Box SLR in Chapter 3).

European cities are hotspots for multiple risks of increasing temperatures and extreme heat, floods, and droughts (*high confidence*). Warming beyond 2°C GWL is projected to result in widespread impacts on infrastructure and businesses (*high confidence*). These include increased risks for energy supply (*high confidence*) and transport infrastructure (*medium confidence*), increases in air conditioning needs (*very high confidence*), and high water demand (*high confidence*) {13.2.2;13.6.1;13.7.1;13.10.2}.

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[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

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European regions are affected by multiple key risks, with more severe consequences in the south than in the north (*high confidence*). These risks may co-occur and amplify each other, but there is uncertainty about their interactions and their quantifications. There is *high confidence* that consequences for socio-economic and natural systems will be substantial; the number of people exposed to KRs and economic losses are projected to at least double at 3°C GWL compared to 1.5°C GWL (*medium confidence*); and increased risks are also projected for biodiversity and ecosystem services, such as carbon regulation. The risks resulting from changes in climatic and non-climatic drivers in many sectors is a key gap in knowledge (high confidence). This gap prevents the precise assessment of systemic risks, socio-ecological tipping points and limits to adaptation {13.10.2;13.10.3;13.10.4}.

Climate risks from outside Europe are emerging due to a combination of the position of European countries in the global supply chain and shared resources (*high confidence*). There is emerging evidence that climate risks in Europe may also impact financial markets, food production and marine resources beyond Europe. Exposure of European countries to interregional risks can be reduced by international governance and collaboration on adaptation in other regions (*medium confidence*){13.5.2;13.9.1; 13.9.2;13.11; Cross-Chapter Box INTEREG in Chapter16}.

What are the solutions, limits and opportunities of adaptation?

There is a growing range of adaptation options available today to deal with future climate risks (*high confidence*). Examples for adaptation to the key risks include: behavioural change combined with building interventions, space cooling and urban planning to manage heat risks (KR1); restoration, expansion and connection of protected areas for ecosystems, while generating adaptation and mitigation benefits for people (KR1: heat); irrigation, vegetation cover, changes in farming practices, crop and animal species, and shifting planting (KR2: agriculture); efficiency improvements, water storage, water reuse, early warning systems, and land use change (KR3: water scarcity); early warning systems, reserving space for water and ecosystem based adaptation, sediment or engineering based options, land use change and managed retreat (KR4: flooding). Nature-based solutions for flood protection and heat alleviation are themselves under threat from warming, extreme heat, drought and sea level rise (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

In many parts of Europe, existing and planned adaptation measures are not sufficient to avoid the residual risk, especially beyond 1.5°C GWL (*high confidence*). Residual risk can result in losses of habitat and ecosystem services, heat related deaths (KR1), crop failures (KR2), water rationing during droughts in SEU (KR3), and loss of land (KR4) (*medium confidence)*. At 3°C GWL and beyond, a combination of many, maybe even all, adaptation options are needed, including transformational changes, to reduce residual risk (*medium confidence*). {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

Although adaptation is happening across Europe, it is not implemented at the scale, depth and speed needed to avoid the risks (*high confidence*). Many sectors and systems, such as flood risk management, critical infrastructure and reforestation, are on self-reinforcing development paths that can result in lock-ins and prevent changes needed to reduce risks in the long term and achieve adaptation targets. Forward-looking and adaptive planning can avoid path-dependencies, maladaptation, and ensure timely action (*high confidence*). Monitoring climate change, socio-economic developments and progress on implementation is critical to assess if and when further actions are needed, and evaluating whether adaptation is successful {13.2.2;13.10.2;13.11.1;13.11.2;13.11.3;Cross-Chapter Box DEEP in Chapter 17}.

Systemic barriers constrain the implementation of adaptation options in vulnerable sectors, regions and societal groups (*high confidence*). Key barriers are limited resources, lack of private sector and citizens engagement, insufficient mobilisation of finance, lack of political leadership, and low sense of urgency. Most of the adaptation options to the key risks depend on limited water and land resources, creating competition and trade-offs, also with mitigation options and socio-economic developments (*high confidence*). Europe will face difficult decisions balancing these trade-offs. Novel adaptation options are pilot tested across Europe, but upscaling remains challenging. Prioritisation of options and transitions from incremental to

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transformational adaptation are limited due to vested interests, economic lock-ins, institutional path-dependencies, and prevalent practices, cultures, norms, and belief systems {13.11.1;13.11.2;13.11.3}.

Several windows of opportunity emerge to accelerate climate resilient development (CRD) (*medium confidence*). Such windows are either institutionalised (e.g. budget cycles, policy reforms and evaluations, infrastructure investment cycles), or open unexpectedly (e.g. extreme events, COVID-19 recovery programs). These windows can be used to accelerate action through mainstreaming and transformational actions (*medium confidence*). CRD is visible in European cities, particularly in green infrastructure, energy-efficient buildings and construction, and where co-benefits (e.g. to health, biodiversity) have been identified. Private sector adaptation takes place mostly in response to extreme events or regulatory, shareholder, or consumer pressures and incentives (*medium confidence*) {13.11.3; Box13.3;Cross-Chapter Box COVID in Chapter 7}.

Closing the adaptation gap requires moving beyond short-term planning and ensuring timely and adequate implementation (*high confidence*). Inclusive, equitable and just adaptation pathways are critical for climate resilient development. Such pathways require consideration of SDGs, gender, and Indigenous knowledge and local knowledge and practices. The success of adaptation will depend on our understanding of which adaptation options are feasible and effective in their local context (*high confidence*). Long lead times for nature-based and infrastructure solutions or planned relocation require implementation in the coming decade to reduce risks in time. To close the adaptation gap, political commitment, persistence and consistent action across scales of government, and upfront mobilization of human and financial capital is key (*high confidence*), even when the benefits are not immediately visible {13.2.2;13.8;13.11;Cross-Chapter Box GENDER in Chapter 18}.

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13.1 Point of Departure

13.1.1 Introduction and Geographical Scope

This regional chapter on climate-change impacts, vulnerabilities and adaptations in Europe examines the impacts 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 emphasis on the planned and implemented solutions, assessed their feasibility and effectiveness, considered the Sustainable Development Goals (SDG) and shared socioeconomic pathways (SSPs). Global warming level (GWL) refers to global climate change emissions relative to preindustrial levels, expressed as global surface air temperature (Chen et al., 2021, 1.6.2).

The chapter generally follows the overall structure of AR6 WGII. We first present our point of departure (13.1) followed by the key sectors, 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, solution space and adaptation options, and knowledge gaps. The solution space is defined as the space within which opportunities and constraints determine why, how, when, and who adapts to climate risks (Haasnoot et al., 2020a). Section 13.9 discusses impacts and adaptation beyond Europe, followed by the key risks for Europe (13.10). The chapter ends with an assessment of adaptation solution space, climate resilient development pathways, and SDGs (13.11), although recognizing that scientific literature on these aspects is only slowly beginning to emerge.

With the rapidly growing body of scientific literature since WGII AR5 (Callaghan et al., 2020) our assessment prioritized systematic reviews, meta-analyses, and synthesis papers and reports. Feasibility and effectiveness assessments used revised methods developed for the Special Report of Global warming of 1.5° (de Coninck et al., 2018; Singh et al., 2020). Protocols, as well as supporting material for figures and tables, can be found in the Supplementary Material.

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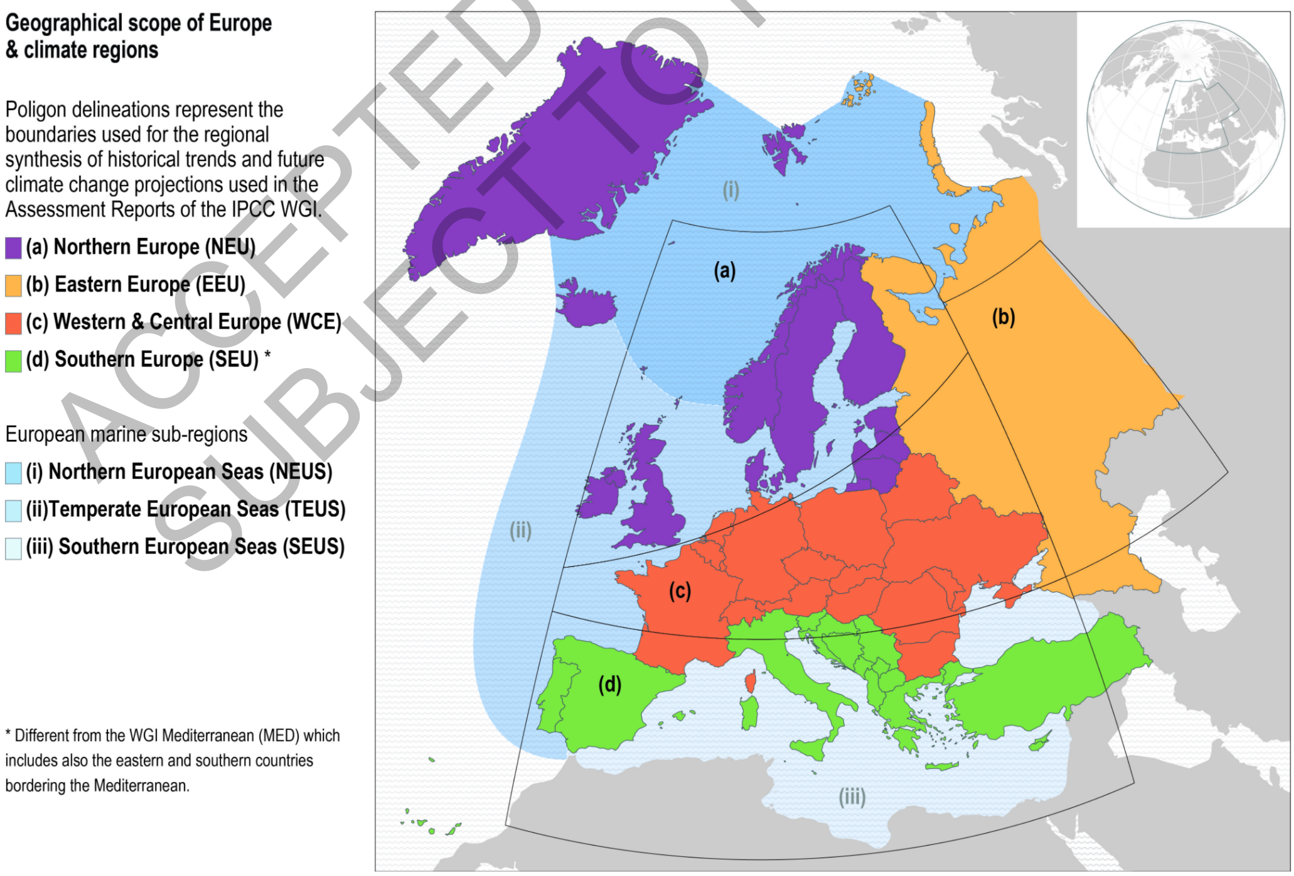

Figure 13.1: Geographical subdivision of land (a, b, c, d) and ocean (i, ii, iii) regions of Europe. The overlay represents the WGI AR6 subdivisions for climate-change projections of land, while the colour coding indicates the European

countries (or, in case of the Russian Federation, the European part of the country (EEU) used for this chapter. Note that for WGI AR6 region MED includes both southern Europe and northern Africa while this chapter only includes the northern (European) part of the MED region.

The geographical scope and subdivision of European land, coastal and ocean regions is largely the same as in WGII AR5 Chapter 23 (Kovats et al., 2014): Southern Europe (SEU), Western Central Europe (WCE), Eastern Europe (EEU) and Northern Europe (NEU). Note that WGI assesses a larger region for the Mediterranean (MED) which includes north Africa and the Middle East compared to the assessment in this chapter (SEU). The European part of the Arctic region is not systematically assessed here as it is extensively captured in Cross-Chapter Paper (CCP) 6. Information relevant to Europe is also synthesised in the CCPs, including European biodiversity hotspots (CCP 1), coastal cities and settlements (CCP 2), Mediterranean region (CCP 4) and mountains (CCP 5). European seas are broadly divided by latitude into (i) European Arctic waters (NEUS), (ii) European Temperate Seas (TEUS) and (iii) Southern Seas with the Mediterranean and Black Sea (SEUS) (Figure 13.1).

13.1.2 Socio-Economic Boundary Conditions

The adaptive capacity, as measured by GDP per capita, tends to be higher in northern and western parts of Europe (Figure 13.2a). In the last decades, climate change has led to substantial losses and damages to people and assets across Europe, mostly from riverine flooding, heatwaves, and storms (Figure 13.2b). Public concern about climate change, which is an indicator of the intention to mitigate and adapt, is particularly high in parts of Southern and Western Central Europe (Figure 13.2c). Current vulnerability to extreme weather and climatic events in European countries is low to moderate compared to the rest of the world (Figure 13.2d).

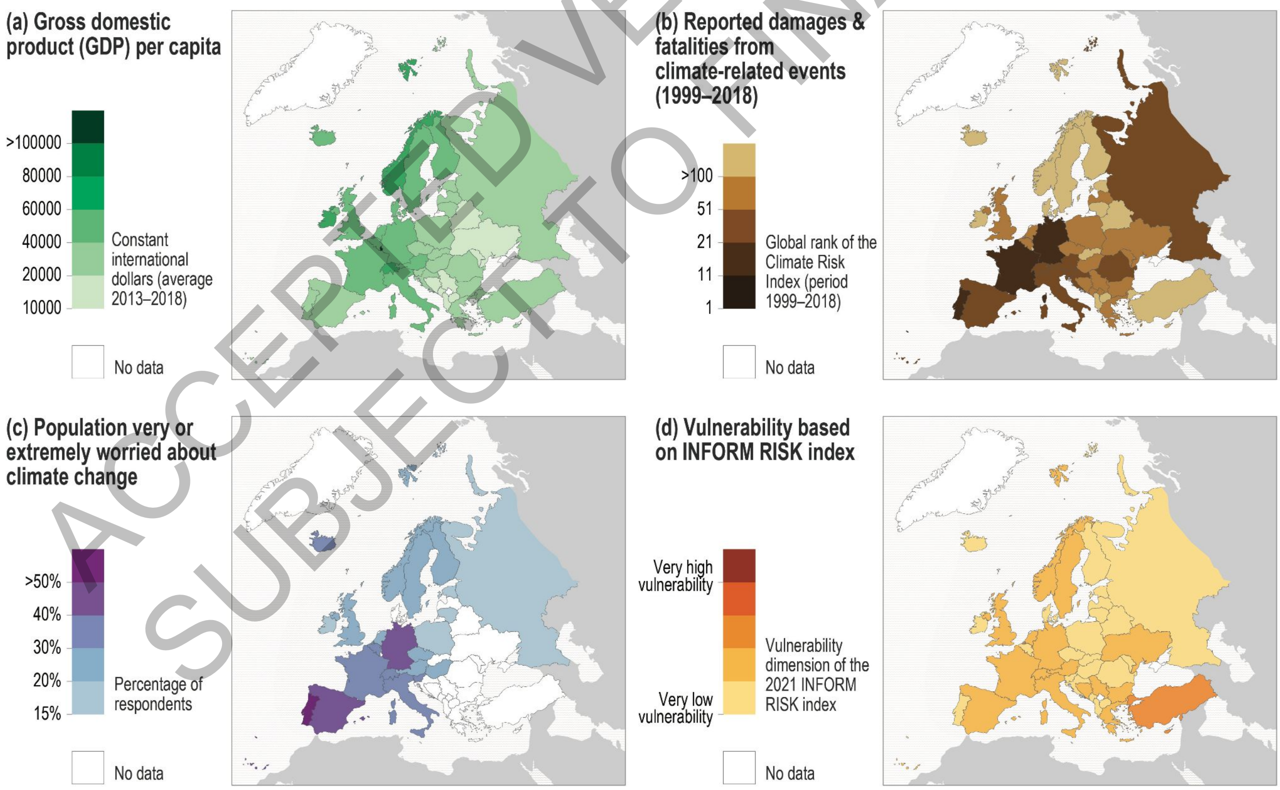

Figure 13.2: Indicators of reported damages to people and assets, vulnerability and adaptive capacity across European countries: (a) GDP per capita (average 2013-2018), in constant 2011 international dollars (WorldBank, 2020); (b) Exposure as measured by the global rank of the Climate Risk Index, which is based on economic damages and fatalities due to climate-related extreme weather events between 1999 and 2018 (Germanwatch, 2020); (c) Level of climate change concern among a representative weighted sample of residents 15 years and older in private households (European Social Survey, 2020) and (d) Vulnerability to disasters and humanitarian crisis in 2021; the index is based on socioeconomic factors (development, inequality, aid dependency) and vulnerable groups (DRMKC, 2020).

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13.1.3 Impact Assessment of Climate Change based on Previous Reports

The main findings of previous reports, particularly the WGII AR5 (Kovats et al., 2014) and the Special Report of Global warming of 1.5°C GWL (Hoegh-Guldberg et al., 2018), highlighted the impacts of warming and rainfall variations and their extremes on Europe, particularly southern Europe and mountainous areas. At 2°C GWL, 9% of Europe's population was projected to be exposed to aggravated water scarcity, and 8% of the territory of Europe were characterized to have a high or very high sensitivity to desertification (UNEP/UNECE, 2016). These impacts are driven by changes in temperature, precipitation, irrigation developments, population growth, agricultural policies, and markets (EEA, 2017a). Heat is a main hazard for high-latitude ecosystems (Kovats et al., 2014; Jacob et al., 2018; Hock et al., 2019). The majority of mountain glaciers lost mass during the last two decades, and permafrost in the European Alps and Scandinavia is reducing (Hock et al., 2019). In central Europe, Scandinavia and Caucasus, mountain glaciers were projected to lose 60% to 80% of their mass by the end of the 21st century (Hock et al., 2019). The combined impacts on tourism, agriculture, forestry, energy, health and infrastructure were suggested to make southern Europe highly vulnerable and increase the risks of failures and vulnerability for urban areas (Kovats et al., 2014). Previous reports stated that the adaptive capacity in Europe is high compared to other regions of the world, but that there are also limits to adaptation from physical, social, economic, and technological factors. Evidence suggested that staying within 1.5°C GWL would strongly increase Europe's ability to adapt to climate change (de Conick and Revi, 2018).

13.1.4 European Climate: Main Conclusions of WGI AR6

Changes of several climatic impact-drivers have already emerged in all regions of Europe: increases in mean temperature and extreme heat and decreases of cold spells (Ranasinghe et al., 2021; Seneviratne et al., 2021). Lake and river ice has decreased in NEU, WCE and MED and sea ice in NEUS (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). With increasing warming, confidence in projections is increasing for more drivers (Figure 13.3). Mean and maximum temperatures, frequencies of warm days and nights, and heat waves have increased since 1950, while the corresponding cold indices have decreased (*high confidence*) (Ranasinghe et al., 2021; Seneviratne et al., 2021). Average warming will be larger than the global mean in entire Europe, with largest winter warming in NEU and EEU and largest summer warming in the MED (*high confidence*) (Gutiérrez et al., 2021; Ranasinghe et al., 2021). An increase of hot days and a decrease of cold days are *very likely* (Figure 13.4.a,b). Projections suggest a substantial reduction of European ice glacier volumes and of snow cover below elevations of 1500-2000 m, as well as further permafrost thawing and degradation, during the 21st century even at a low GWL (*high confidence*) (Ranasinghe et al., 2021).

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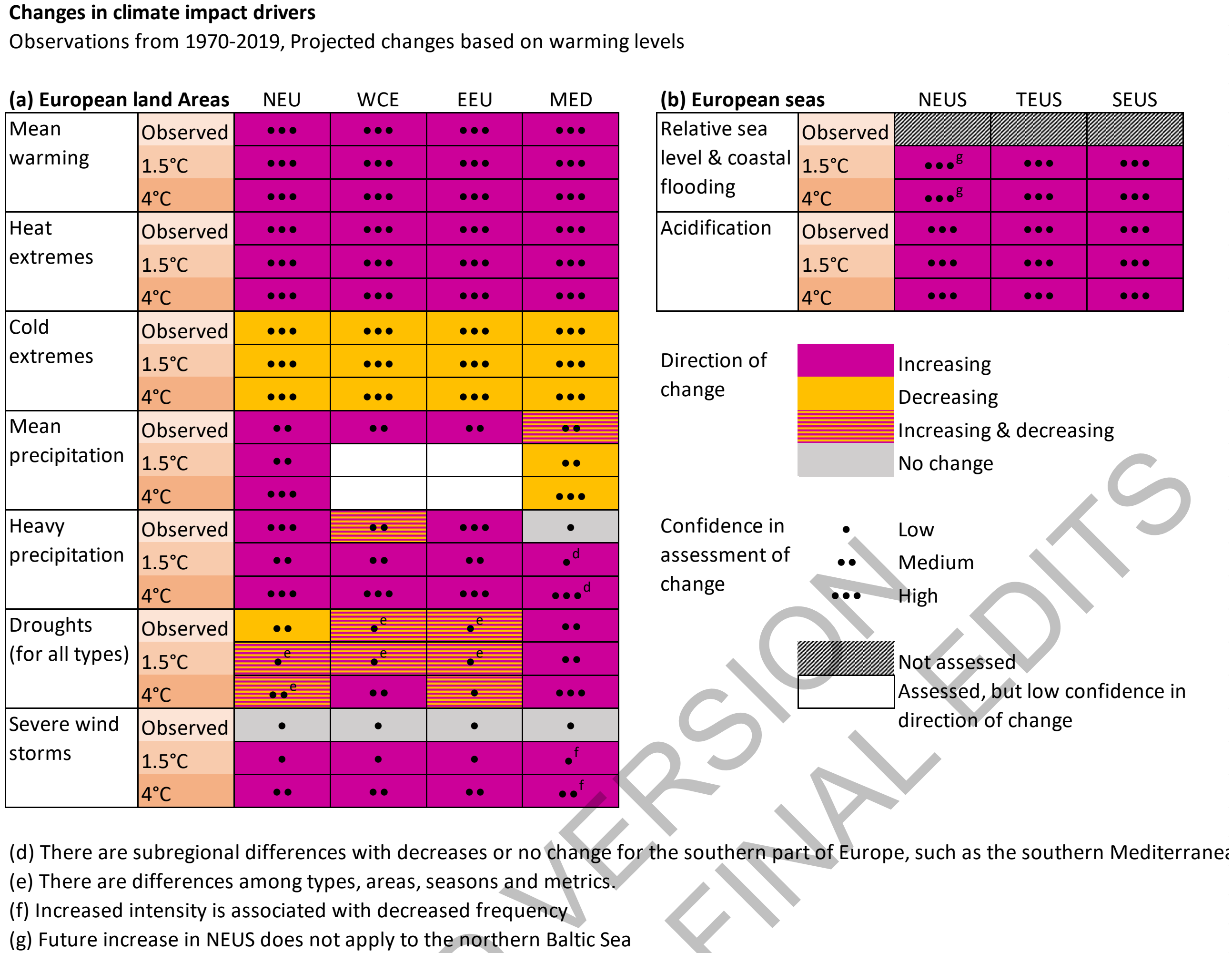

Figure 13.3: Observed and projected direction of change of climate impact drivers at 1.5°C and 4°C GWL for European sub-regions and European Seas (assessment from Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021)

The assessment of climate change in WGI AR 6 concludes that during recent decades mean precipitation has increased over NEU, WCE and EEU, while magnitude and sign of observed trends depend substantially on time period and study region in MED (*medium confidence*) (Douville et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021). Precipitation extremes have increased in NEU, and EEU (*high confidence*) (Seneviratne et al., 2021), vary spatially in WCE (*medium confidence*), and have not changed in MED *(low confidence*). For >2°C GWL, of mean precipitation in NEU in winter is increasing and decreasing in MED in summer (*high confidence*). A widespread increase of precipitation extremes is projected for > 2°C GWL for all subregions (*high confidence)*, except for MED where no change or decrease is projected in some areas (Figure 13.4c,d, Gutiérrez et al., 2021; Ranasinghe et al., 2021). WGI assessed projections for meteorological, agricultural/ecological, hydrological drought (Ranasinghe et al., 2021) with *low confidence* in the direction of change in NEU, WCE, EEU at 1.5°C GWL. MED is projected to be most affected within Europe with all types of droughts increasing for 1.5°C (*medium confidence*) and 4°C GWL (*high confidence*). At 4°C GWL, hydrological droughts in NEU, WCE and EEU will increase (*medium confidence*). Projections for the 21st century show increases of storms across all Europe (*medium confidence*) for >2°C GWL with a decrease of their frequency in the MED (Ranasinghe et al., 2021).

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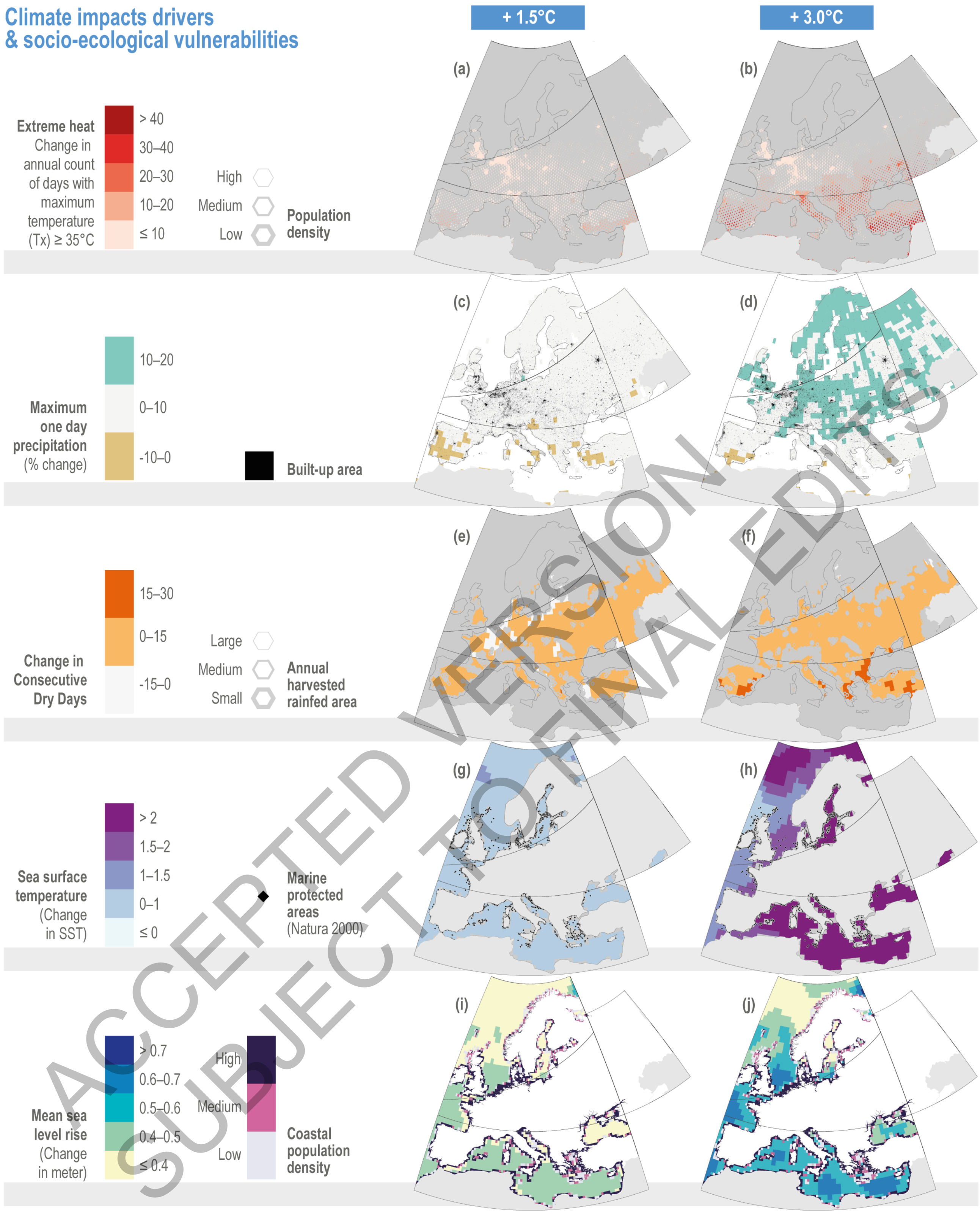

Figure 13.4: Changes of climate hazards with respect to the CMIP6 baseline (Gutiérrez et al., 2021) for global warming levels of 1.5°C and 3°C GWL and present exposure or vulnerability: (a,b) number of days with temperature maximum above 35°C (TX35) and population density (European Comission, 2019); (c,d) daily precipitation maximum (Rx1day) and built up area (JRCdatacatalogue, 2018); (e,f) consecutive dry days (CDD) and annual harvested rainfed area (Portmann et al., 2010); (g,h) sea surface temperature (TOS) and Marine Protected Areas (EEA, 2021b); and (k,l) sea level rise (SLR) and coastal population (Merkens et al., 2016). SLR data consider the long term period (2081-2100) and SSP1-2.6 for (i) and SSP3-7.0 for (j).

Sea surface warming between 0.25°C and 1°C has been observed in all regions over the last decades (*high confidence*) (Ranasinghe et al., 2021) and projected to continue increasing (*high confidence*), particularly in

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the SEUS and at the NEUS (Figure 13.4 g,h, Gutiérrez et al., 2021). Salinity has increased in the SEUS and decreased in northern European seas and projected to continue (*medium confidence*) (Fox-Kemper et al., 2021). European waters have been and will continue acidifying (*virtually certain*) (Eyring et al., 2021; Naik et al., 2021), resulting in a mean decrease of surface pH of about 0.1 and 0.3 pH units at 1.5°C and 3.0°C GWL with largest changes at high latitudes (Gutiérrez et al., 2021).

Relative sea level has risen along the European coastlines (Ranasinghe et al., 2021), regionally mitigated by post-glacial rise of land masses in Scandinavia (Fox-Kemper et al., 2021). SLR will *very likely* continue to increase during the 21st century (Figure 13.4 k,l) (*high confidence*), with regional deviations from global mean sea level rise (*low confidence*). Extreme water levels, coastal floods, and sandy coastline recession are projected to increase along many European coastlines (*high confidence*) (Ranasinghe et al., 2021).

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 within 10 m above mean sea level (Vousdoukas et al., 2020; McEvoy et al., 2021). Without further adaptation (section 13.2.2), flood risks along Europe's low-lying coasts and estuaries will increase due to sea level rise (SLR) compounded by storm surges, rainfall and river runoff (*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 population at risk of a 100-year flood event starts to rapidly increases beyond 2040 (Vousdoukas et al., 2018a) reaching 10 million people under RCP8.5 by 2100 but stays just below the 10 million under RCP2.6 by 2150 (Figure 13.5, Haasnoot et al., 2021b) assuming present population and protection. The number of people at risk is projected to increase and risk to materialise earlier particularly under SSP5 due to increasing population trends(Vousdoukas et al., 2018a; Haasnoot et al., 2021b). Under high rates of SLR resulting from rapid ice-sheet loss from Antarctica, risks may increase by a third by 2150 (Haasnoot et al., 2021b). Expected annual (direct) damages due to coastal flooding are projected to rise from €1.3 billion today to €13–39 billion by 2050 between 2°C and 2.5°C GWL and €93–960 billion by 2100 between 2.5° and 4.4°C GWL, largely depending on socio-economic developments (Cross-Chapter Box SLR in Chapter 3, Vousdoukas et al., 2018a) (*high confidence* in the sign; *low confidence* in the numbers). UNESCO World Heritage sites in the coastal zone are at risk due to SLR, coastal erosion and flooding (CCP4, Section 13.8.1.3, Marzeion and Levermann, 2014; Reimann et al., 2018b) as are coastal landfills and other key infrastructure in Europe (AR6/SROCC, Brand et al., 2018; Beaven et al., 2020).

Observations indicate that soft cliffs and beaches are most affected by erosion in Europe, with e.g. 27 to 40% of Europe's sandy coast eroding today, without climate change being identified as the main driver so far (Pranzini et al.; Luijendijk et al., 2018; Mentaschi et al., 2018; Oppenheimer et al., 2019). SLR will increase coastal erosion of sandy shorelines (*high confidence*) (Ranasinghe et al., 2021), but there is *low confidence* in quantitative values assessment of erosion rates and amounts (Athanasiou et al., 2019; Le Cozannet et al., 2019; Thieblemont et al., 2019). Without nourishment or other natural or artificial barriers to erosion, sandy shorelines can retreat by about 100m in Europe at 4°C GWL; limiting warming to 3°C GWL can reduce this value by one third (Vousdoukas et al., 2020).

[START BOX 13.1 HERE]

Box 13.1: Venice and its Lagoon

Venice and its lagoon are a UNESCO World Heritage Site. This socio-ecological system is the result of millennia of interactions between people and the natural environment. It is exposed to climatic and non-climatic hazards: more frequent floods, warming, pollution, invasive species, reduction of salt marshes, hydrodynamic and bathymetric changes, and waves generated by cruise ships and boat traffic.

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The elevation of the average city pedestrian level and of its inner historic area are respectively 105cm and 55cm above the present relative mean sea level (RMSL). Consequently, even small surges and compound events cause floods when they coincide with high tide (Lionello et al., 2021a). During the 20th century, RMSL has risen at about 2.5 mm/yr due to SLR and land subsidence (Zanchettin et al., 2021). The frequency of floods affecting the city has increased from once per decade in the first half of the 20th century to 40 times per decade in the period 2010-2019 (Figure Box 13.1.1a).

In 1973, the Italian government established a legal framework for safeguarding Venice and its lagoon. Construction of the flood protection system started in 2003 and were used for the first time in October 2020 to protect the city from floods (Lionello et al., 2021b). This system of mobile barriers (MoSE) closes the lagoon inlets to avoid floods when needed, while under normal conditions they lay on the seabed, thus allowing ship traffic and the exchange between the lagoon and the sea (Molinaroli et al., 2019). To prevent the flooding of the central monument area, additional measures are proposed including inlets, expansion of saltmarshes, and pumping seawater into deep brackish aquifers to raise the city's level (Umgiesser, 1999; Umgiesser, 2004; Teatini et al., 2011).

Without adaptation, potential economic damages between €7 and €17 billion have been estimated for the next 50 years (Caporin and Fontini, 2016). Additionally, the ecosystem is vulnerable to warming (Solidoro et al., 2010) and sea level rise (Day Jr et al., 1999; Marani et al., 2007). The duration of the closure of the lagoon inlets is expected to increase from 2 to 3 weeks per year for RMSL rises of 30 cm, to 2 months per year for 50 cm and 6 months per year for 75cm (Umgiesser, 2020; Lionello et al., 2021b) (Figure Box 13.1.1b), resulting in disconnection from the sea for most of the time for RMSL rise exceeding 75 cm. Frequent closures of the inlets would prevent ship traffic and in/outflow of water. For Venice, adaptation pathways considering the full range of plausible RMSL (Figure Box 13.1.1c) levels are not available, indicating a long-term adaptation gap. As planning and implementation of adaptation of this extent can take several decades (Haasnoot et al., 2020b, Cross-Chapter Box SLR in Chapter 3) this increases the risk that the city will not be prepared in case of rapid sea level rise.

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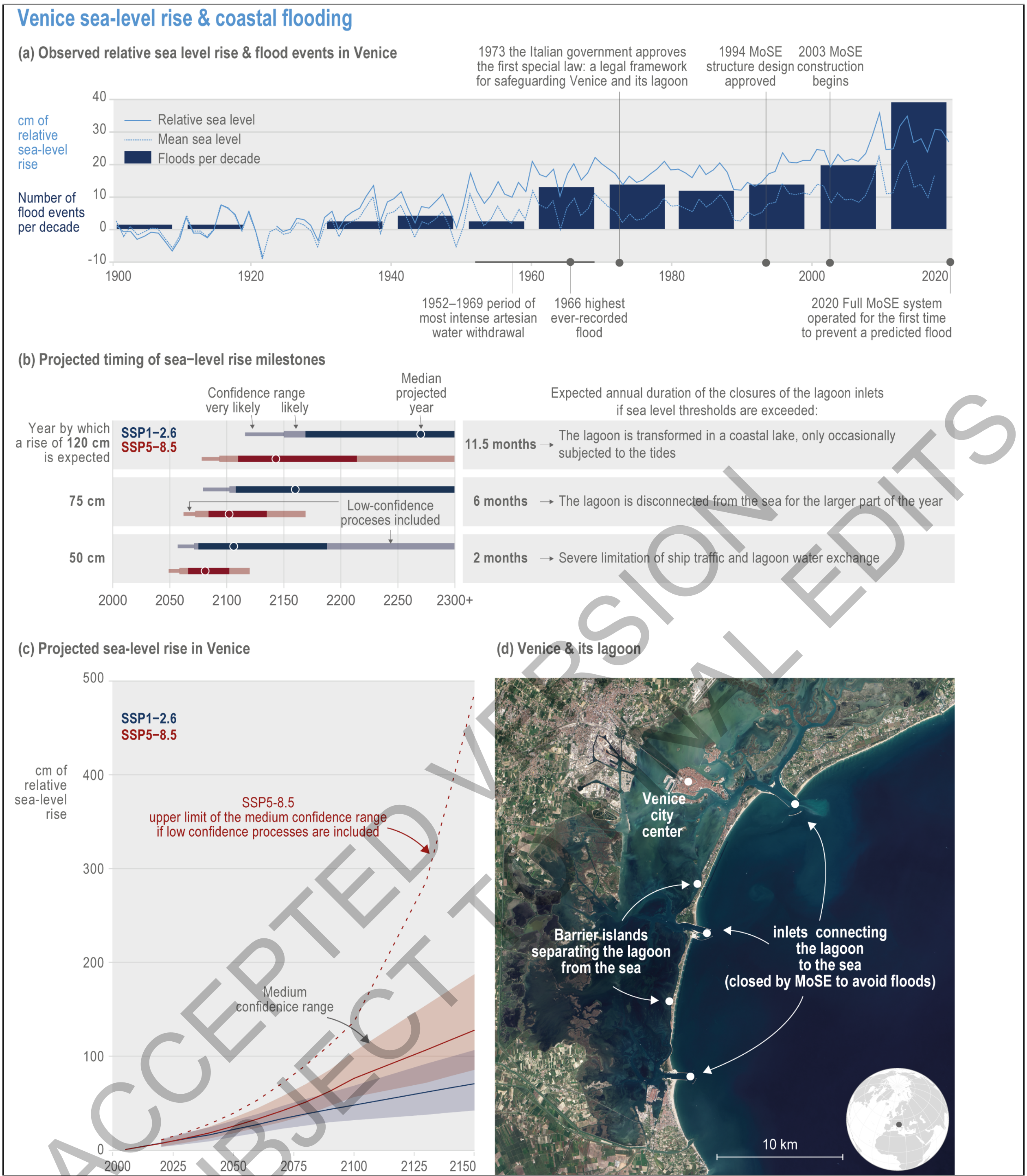

Figure Box 13.1.1: Venice sea level rise and coastal flooding. (a) Evolution of relative and mean sea level in Venice and decadal frequency of floods above the safeguard level in the city centre (Frederikse et al., 2020; Lionello et al., 2021a; Lionello et al., 2021b; Zanchettin et al., 2021). (b) Projected relative sea level rise at the Venetian coast (Fox-Kemper et al., 2021) and (c) timing when critical relative sea level thresholds will be reached depending on scenarios and confidence level (Lionello, 2012; Umgiesser, 2020; Lionello et al., 2021a). Panel d: landsat view of Venice, its lagoon with the three inlets connecting it to the Adriatic Sea.

[END BOX 13.1 HERE]

13.2.1.2 Risks Related to Inland Water

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13.2.1.2.1 Riverine and Pluvial Flooding

Precipitation has raised river flood hazards in WCE and UK by 11% per decade from 1960-2010 and decreased in EEU and SEU by 23% per decade (Douville et al., 2021; Ranasinghe et al., 2021). The most recent three decades had the highest number of floods in the past 500 years with increases in summer (Blöschl et al., 2020). Economic flood damages increased strongly, reflecting increasing exposure of people and assets (Visser et al., 2014; Hoegh-Guldberg et al., 2018; Merz et al., 2021).

Projections indicate a continuation of the observed trends of river floods hazards in WCE (*high confidence*) of 10% at 2°C GWL and 18% at 4.4°C GWL and a decrease in NEU and SEU (*medium confidence*) with respectively 5% and 11% in NEU and SEU for a 100-year peak flow, making Europe one of the regions with the largest projected increase in flood risk (Di Sante et al., 2021; Ranasinghe et al., 2021). While there is disagreement on the magnitude of economic losses and people affected, there is *high agreement* on direction of change, particularly in WCE (Alfieri et al., 2018). New research increases confidence in AR5 statements that without adaptation measures, increases in extreme rainfall will substantially increase direct flood damages (e.g., Madsen et al., 2014; Alfieri et al., 2015a; Alfieri et al., 2015b; Blöschl et al., 2017; Dottori et al., 2020; Mentaschi et al., 2020). With low adaptation, damages from river flooding are projected to be 3 times higher at 1.5°C GWL, 4 times at 2°C GWL, and 6 times at 3°C GWL (Alfieri et al., 2018; Dottori et al., 2020). At 2°C GWL, incidence of summer floods is expected to decrease across the whole alpine region, whereas winter and spring floods will increase due to extreme precipitation (Gobiet et al., 2014) and snow melt driven runoff (Coppola et al., 2018).

Pluvial flooding and flash floods due to intense rainfall constitute most flood events in SEU and a substantial risk in other European regions (CCP4, Llasat et al., 2016; Rudd et al., 2020). The majority (56 %) of flood events between 1860-2016 were flash floods (Paprotny et al., 2018a). These had considerable impacts including danger to human lives, e.g. causing total economic damage of USD 1 billion in Copenhagen (Denmark) 2011 (Wójcik et al., 2013), a damage to private households of more than €70 million in Münster (Germany) 2014 (Spekkers et al., 2017), and during the 2021 floods in Belgium, Germany and the Netherlands over 200 deaths, damage to thousands of homes and disrupted water and electricity supply (Kreienkamp et al., 2021). The intensity and frequency of heavy rainfall events is projected to increase (*high confidence*) (Figure 13.3, Ranasinghe et al., 2021). Combined with increasing urbanization, the risk of pluvial flooding is projected to increase (Westra et al., 2014; Rosenzweig et al., 2018; Papalexiou and Montanari, 2019). Small catchments, steep river channels and cities are particularly vulnerable due to large areas of impermeable surfaces where water cannot penetrate (Section 13.6).

13.2.1.2.2 Low Flows and Water Scarcity

The frequency and severity of low flows are projected to increase, making streamflow drought and water scarcity more severe and persistent in SEU and WCE (*medium confidence*) (Figure 13.3, Ranasinghe et al., 2021), but decreases are projected in most of NEU except southern UK (Forzieri et al., 2014; Prudhomme et al., 2014; Schewe et al., 2014; Roudier et al., 2016; Ranasinghe et al., 2021). In EEU, uncertainty about changes in water scarcity pose distinct challenges for adaptation (Greve et al., 2018). At 1.5°C GWL, the number of days with water scarcity (water availability vs water demand) and drought will increase slightly in SEU (Schleussner et al., 2016; Naumann et al., 2018), resulting in 18% of the population exposed to at least moderate water scarcity, increasing to 54% at 2°C GWL (Byers et al., 2018). Moderate water scarcity is emerging in some parts of WCE (Bisselink et al., 2018) increasing to16% of the population under 2°C GWL and SSP2 (Byers et al., 2018). Under 4°C GWL, areas in WCE experience water scarcity, especially in summer and autumn. Future intensive water use can aggravate the situation, in particular in southern Europe (13.5.1 and 13.10.3).

Groundwater abstraction rates reach up to 100 million m³/year across WCE and SEU, and exceed 100 million m³/year in parts of SEU (Wada, 2016). Low recharge rates lead to a depletion of groundwater resources in parts of SEU and WCE (Doll et al., 2014; Wada, 2016; de Graaf et al., 2017), increasing the impacts on water scarcity in SEU. Groundwater pumping and declines in groundwater discharge already threaten environmental flow limits in many European catchments, especially in SEU, 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 and lowers groundwater levels in SEU but also WCE (Goderniaux et al., 2015).

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Declines in groundwater recharge of up to 30% further increase groundwater depletion (Aeschbach-Hertig and Gleeson, 2012) especially in SEU and semi-arid to arid regions (Moutahir et al., 2017). Even in WCE and NEU projected increases in groundwater abstraction will impact groundwater discharge, threatening sustaining environmental flows under dry conditions (de Graaf et al., 2019).

The risks for soil moisture drought are projected to increase in WCE and SEU for all climate scenarios (Grillakis, 2019; Tramblay et al., 2020; Ranasinghe et al., 2021). At 3°C GWL compared to 1.5°C GWL, the drought area will increase by 40% and the population under drought by up to 42%, especially affecting SEU, and to a lesser extent in WCE (Samaniego et al., 2018).

13.2.1.2.3 Water Temperature and Quality

Water temperatures in rivers and lakes have increased over the past century by ~1 to 3°C in major European rivers (CBS, 2014; EEA, 2017b; Woolway et al., 2017). Warming is accelerating for all European river basins (Wanders et al., 2019) increasing by 0.8°C in response to 1.5°C GWL and 1.2°C for 3°C GWL relative to 1971-2000 (van Vliet et al., 2016a) aggravated by declines in summer river flow.

(Ground)water extractions or drainage have caused saltwater intrusions (Rasmussen et al., 2013; Ketabchi et al., 2016). During summer, seawater will also penetrate estuaries further upstream in response to reduced river flow and SLR and result 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) (*high agreement, low evidence*).

13.2.2 Solution Space and Adaptation Options

In recent decades water management in Europe has increasingly shifted towards integrated and adaptive strategies, with most noticeable shifts in WCE (*high confidence*) (e.g., Kreibich et al., 2015; Bubeck et al., 2017). While 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; Bloemen et al., 2019; Hall et al., 2019; Pot et al., 2019), more traditional water management approaches still dominate across Europe (OECD, 2013; OECD, 2015; Wiering et al., 2017). Current measures focus on structural flood protection and water resources supply and play an important role to preserve present land use and development patterns. The long-term effectiveness of such measures is increasingly challenged by their reinforcing path-dependency (e.g. flood defence and water supply attract developments which require further protection and supply); this path-dependency limits the solution space and may hamper implementation of transformative measures such as land use change to accommodate the water system *(medium confidence*) (CCP2, Di Baldassarre et al., 2015; Kreibich et al., 2015; Alfieri et al., 2016; Gralepois et al., 2016; Welch et al., 2017; Di Baldassarre et al., 2018; Haer et al., 2020).

Water laws, policies and guidance documents increasingly mainstream climate impacts and adaptation options (Runhaar et al., 2018; Mehryar and Surminski, 2021), though not everywhere. Differences are apparent for example in coastal adaptation where most but not all countries are planning for SLR (Figure 13.5) (McEvoy et al., 2021). Although the planning horizon of 2100 and 1m SLR are most common (adjusted for local conditions), there are significant differences between countries (e.g. the high-end SLR value in 2100 ranges from 0.3 to 3m), which may lead to unequal impacts, over time (McEvoy et al., 2021).

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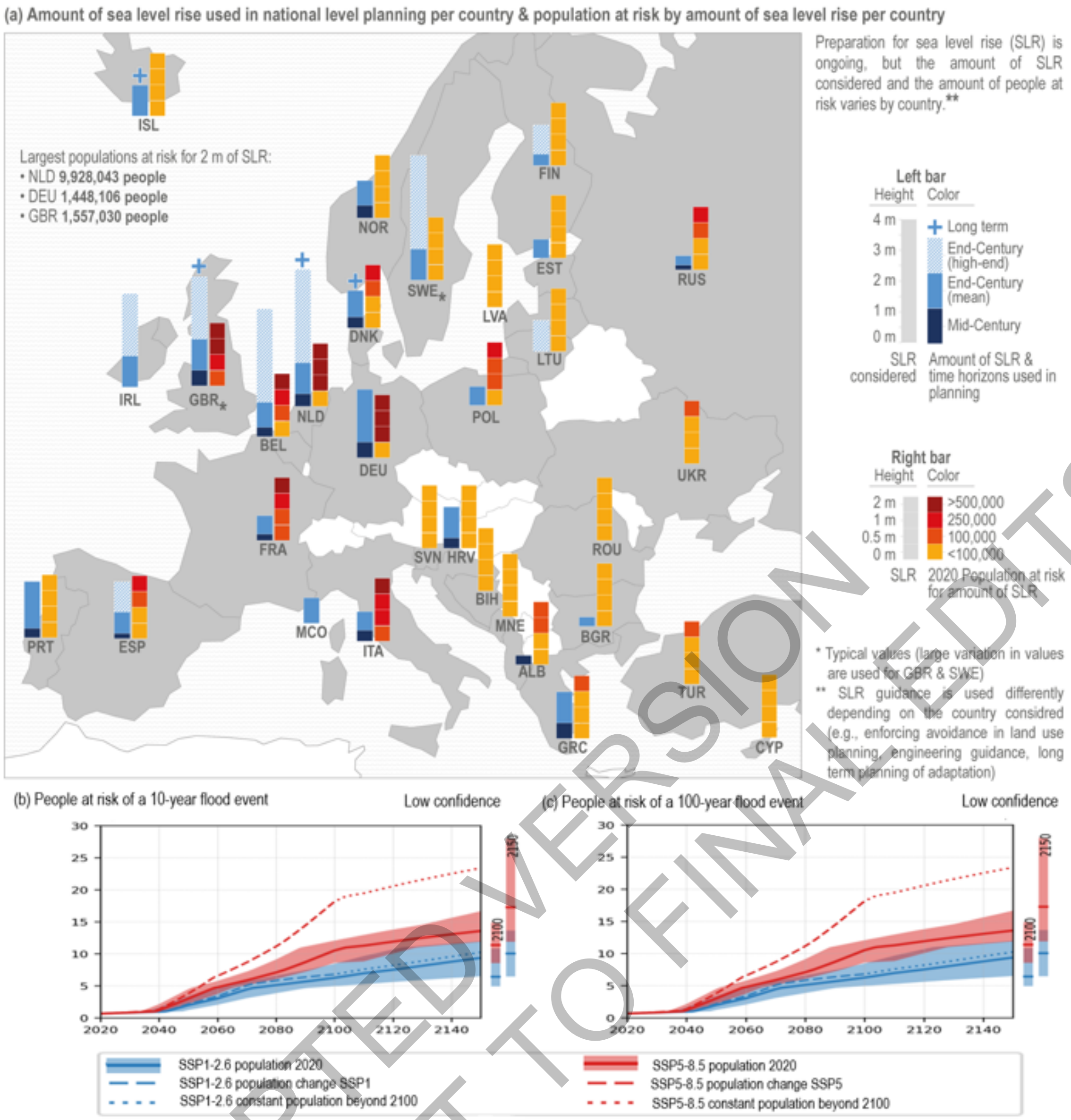

Figure 13.5: Sea level rise (SLR) vulnerability and national planning in Europe. (a) Map of countries in Europe summarizing the amount of SLR each country is planning for, at different time horizons (blue bars) and present population (2020) at risk of a 100-year coastal flood event (orange bars) (Haasnoot et al., 2021b). The amounts of SLR and time horizons reflect national guidance or planning; local or project-based levels may differ (McEvoy et al., 2021). (b) Projected population at risk to a 1 in 10-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5 assuming present protection and population, as well as population change according to respectively, SSP1 and SSP5, based on Merkens (2016); and (c) projected population at risk to 1 in 100-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5, assuming present protection and population, as well as population change according to respectively, SSP1 and SSP5, based on Merkens (2016) (Haasnoot et al., 2021b).

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13.2.2.1 Flood Risk Management

Across Europe a range of measures have been implemented to address flood risk (Figure 13.6), with protection as a most used strategy (*high confidence*). Early warning and flood protection have been successful in reducing vulnerability to coastal and riverine flooding (Jongman et al., 2015; Kreibich et al., 2015; Bouwer and Jonkman, 2018). Consequently, fatalities due to river flooding have decreased in Europe, despite similar numbers of people exposed (1990-2010 compared to 1980-1989) (Jongman et al., 2015; Paprotny et al., 2018a).

Coastal flood risk management

Further protection against coastal flooding is considered economically beneficial for densely populated areas (Lincke and Hinkel, 2018; Tiggeloven et al., 2020). At least 83% of flood damages due to coastal flooding could be avoided by elevating dykes along ~23-32% of Europe's coastline by 2100 (RCP4.5-SSP1, RCP8.5-SSP5) (Vousdoukas et al., 2020). Limitations of building flood defences include cost-benefit considerations in rural areas, available land, and social acceptability in densely populated areas (Haasnoot et al., 2018; Hinkel et al., 2018; Meyerhoff et al., 2021).

Nature-based (NbS, e.g. wetlands) and sediment-based (e.g. sand nourishment) solutions are increasingly considered for environmental, economic and/or societal reasons (Cross-Chapter Box NATURAL in Chapter 2, Stive et al., 2013; Pranzini et al., 2015; Pinto et al., 2020; de Schipper et al., 2021). Coastal wetlands can be effective to reduce wave height and form habitats, but their feasibility and effectiveness is limited for densely populated areas with competing land use, runoff of pollution, 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). While losses of wetlands could be minor if warming stays below 1.7°C GWL, at high warming or SLR above 0.5m large scale losses of these habitats impact their ecological importance, ecosystem function (Section 13.4, Key Risk 1, 13.10) and their ability to protect coastlines (Roebeling et al., 2013; van der Spek, 2018; Wang et al., 2018; Xi et al., 2021). A combination with structural defences could reduce risk in urbanized coastal regions (*high confidence*). Accommodation through elevated or floating houses have been implemented and proposed locally within cities as part of a hybrid strategy together with protection and as a way of innovative urban development (13.6.2, CCP2, Penning-Rowsell, 2020; Storbjörk and Hjerpe, 2021).

Avoidance through restricting new developments in flood prone areas is applied along the coast of WCE and SEU (Harman et al., 2015; Lincke et al., 2020) and is considered a low-cost alternative to coastal defence at lower SLR. In SEU, an Integrated Coastal Zone Management (ICZM) protocol has been developed which requires a setback zone of 100m from the coast in unprotected areas. Setback zones are projected to reduce impacts considerably in urbanized regions (Lincke et al., 2020). Planned relocation is increasingly considered as a realistic adaptation option in case of extreme SLR (Haasnoot et al., 2021a; Lincke and Hinkel, 2021; Mach and Siders, 2021), e.g UK Shoreline Management Plans (Nicholls et al., 2013; Buser, 2020). Retreat is rarely applied in Europe (*medium confidence*), though it can have larger benefit-cost outcomes than protection, particularly in less populated parts of Europe (Lincke and Hinkel, 2021). 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; Kiesel et al., 2020). (Lincke and Hinkel, 2021)

Riverine and pluvial flood risk management

Structural flood protection (e.g. levees) is considered economically beneficial in densely populated areas (Alfieri et al., 2016; Dottori et al., 2020) and could reduce flood damage of ~45% is estimated under 1.5°C GWL and ~70% under 3°C GWL (Dottori et al., 2020).

Providing more room for water through NbS is increasingly considered (Kreibich et al., 2015) as they can reduce risk effectively at lower costs, except in places with limited space or in areas with large protection. Such measures include (forest) restoration for upstream retention, restoration of river channels, and widening riverbeds for natural flood retention (Kreibich et al., 2015; Barth and Döll, 2016; Wyżga et al., 2018). Natural retention areas are estimated to be the most effective option to reduce riverine flood risk across Europe in the 21st century, followed by protection (*low evidence*) (Dottori et al., 2020).

Wet and dry proofing of buildings can be applied at household level. While measures taken at household levels can reduce the risk of flooding, there is often insufficient investment (Bamberg et al., 2017; Aerts et al., 2018) (*medium confidence*). Reasons include low awareness or under-estimation of the risk (Kellens et al., 2013), low perceived efficacy of adaptation measures (van Valkengoed and Steg, 2019), and lack of financial support (Kreibich, 2011). In the long-term, risk reduction measures by governments are projected to outweigh floodproofing at household level, in particular in WCE, while for near-term household adaptation or regionally in SEU this could reduce risk more effectively (Haer et al., 2019). Relocation of households has occurred in response to river flood events, e.g. the 2013 flood events along the Danube river

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in Austria, with financial compensation playing a crucial role (Mayr et al., 2020; Thaler and Fuchs, 2020; Thaler, 2021).

Urban drainage infrastructure is designed based on historical rainfall intensities, and thus may not have sufficient capacity for increased future intensities (Dale et al., 2018). Adaptation options to pluvial flooding include large retention ponds , local green spaces and green roofs within cities (Zölch et al., 2017; Maragno et al., 2018; Babovic and Mijic, 2019; Ribas et al., 2020).

Effectiveness & feasibility of adaptation options for water-related climate impacts & risk in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility: Economic	Technological	Institutional	Socio-cultural	Ecological	Geophysical	Confidence: Evidence	Agreement
Flooding - Coast/River	Flood defenses (Protect)	H	M	H	H	NL	L	H 1	H	H
	Flood preparedness & early warning plans (Protect/Accommodate)	L 2	H	H	H	NL	H	NL	H	M
	Planned relocation (Retreat)	H	H	H	H	L	H	H	M	H
	No-build zone, restrict new developments (Avoidance)	M	H	H	M	NL	NL	NL	M	H
	Flood insurance (Supporting)	L	M	H	H	H	M	NL	M	H
Flooding - Coast	Ecosystem based (e.g. wetlands, oyster	M	H	H	NL	NL	H	M 1	M	H
	Sediment based (e.g. nourishment) (Protect)	M	M	M	H	NL	M	M 4	H	H
	Wet & dry proofing (Accommodate)	L	M	NL	H	H	NL	NL	L	H
Flooding - River	Ecosystem based (e.g. floodplain restoration, widening riverbed) (Protect)	H	M	M	NL	NL	H	M	M	H
	Retention & diversion (Accommodate)	M	H	H	NL	NL	NL	NL	L	H
	Wet & dry proofing (Accommodate)	M	M	M	H	H	NL	NL	H	M
Flooding - Pluvial	Retention: green roofs (Accommodate)	L	NL	NL	NL	NL	H	M	M	H
	Retention: parks (Accommodate)	H	NL	M	NL	NL	H	M	M	H
	Update drainage systems & pumps (Accommodate)	NL	L	NL	NL	NL	NL	M	M	H
Water Scarcity	Supply: Storage (reservoirs)	M	L	M	M 5	M	L	M	H	M
	Supply: Water diversion & transfer	L 6	L	M	H	M	M	NL	M	H
	Supply: Desalinization	H 7	L	H	H	H	L	H	M	H
	Supply: Water reuse	M 7	M	M	M	L	M	NL	H	H
	Demand: Water saving & efficiency	L	M	M	H	M	M	M	H	M
	Demand: Regulate distribution	M	H	M	M	NL	NL	NL	M	H
	Demand: Economic instruments	M	H	M	H	M	NL	NL	H	M
	Demand: Land management & cover change	M	H	M	H	NL	M	M	M	L
	Monitoring & operational management,	L	H	M	H	NL	H	NL	M	M

Legend
High = H
Medium = M
Low = L
No/Limited Evidence

1 Physically hampered in highly urbanized regions
2 Low on preventing damage, medium on preventing fatalities
3 Availability of sand can hamper feasibility in SEU
4 Low in SEU, high in NLU, WCE
5 In SEU, no evidence for other parts of Europe
6 Medium in SEU & high in WCE/NLU

Figure 13.6: Effectiveness and feasibility of water-related adaptation options to achieve objectives under increasing climate hazards (SM13.1, SM13.9).

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Early warning systems, insurance and behaviour change can complement protect and accommodate measures to limit residual risk (*high confidence*). Early warning systems have high monetary benefits (Pappenberger et al., 2015). Behavioural adaptation to flooding relies on recognition of the threat and capacity to respond, both of which are often lacking (Section 13.11.2.2, Bamberg et al., 2017; Haer et al., 2019). Flood risk insurance and compensation systems vary across European countries, ranging from post-disaster payments by governments, compulsory flood insurance, to public-private partnerships where the state acts as reinsurer (Keskitalo et al., 2014; Surminski et al., 2015; Hanger et al., 2018). Risk-based insurance premiums can induce risk averting behaviour but may become unaffordable to poor households and some households in high risk zones (Hudson, 2018; Surminski, 2018). Increasing future flood risks due to both climatic and socioeconomic change could overburden government budgets (*medium confidence*) (Section 13.11.2, Paudel et al., 2015; Mysiak and Perez-Blanco, 2016; Schinko et al., 2017; Mochizuki et al., 2018), result in unavailable or unaffordable insurance for private customers (13.8.3, Hudson et al., 2016; Surminski, 2018), and underfunding and insufficient solvency of insurance companies (Section 13.6.2.5, Lamond and Penning-Rowsell, 2014). Local knowledge about disastrous flood events in the past can be lost across generations, reverting behaviours to avoid settlement in risky areas (Fanta et al., 2019).

Limits to adaptation to extremely high sea level rise scenarios have been identified for coastal defences, such as the Venice MoSE barrier (box 13.1), Thames Barrier in the UK (Ranger et al., 2013) and the Maeslant Barrier in the Netherlands (Kwadijk et al., 2010; Haasnoot et al., 2020b). However, the scale and pace of adaptation required to face high-end SLR scenarios along all coasts of Europe is poorly studied. Given the lead and long lifetime of large critical infrastructure, there is a growing need to look beyond 2100 to support the design of new infrastructure (Cross-Chapter Box SLR in Chapter 3).

13.2.2.2 Water Resources Management

Planning adaptation to water scarcity has centred on increasing availability and supply of fresh water through water storage, diversification of sources and water diversion and transfer (*high confidence*). Reservoirs are costly, have negative environmental impacts, and will not be sufficient under higher warming levels in every place (Papadaskalopoulou et al., 2015a; Di Baldassarre et al., 2018; Garnier and Holman, 2019). Waste water reuse is considered a low-cost and effective measure where wastewater is available (Lavrnic et al., 2017; De Roo et al., 2020), but public acceptance for domestic reuse is presently limited (*high confidence*) (Papadaskalopoulou et al., 2015b; Morote et al., 2019). Increasing desalination capacity is used particularly in SEU but has high energy demands and produces brine waste (Garnier and Holman, 2019; Jones et al., 2019; Morote et al., 2019).

Adaptation measures on the demand side include monitoring (e.g., water meters, early warning systems of drought) and regulating demand, e.g. water restrictions, water pricing, water saving and efficiency measures and land management and cover change (Papadaskalopoulou et al., 2015b; Varela-Ortega et al., 2016; Manouseli et al., 2018; Garnier and Holman, 2019). Prolonged water restrictions and prioritising sectoral supply could result in economic losses e.g. for irrigated agriculture (Section 13.5.2, Wimmer et al., 2014; Salmoral et al., 2019). Economic instruments, such as water pricing, can be effective when combined with incentives for water saving and efficiency (Kayaga and Smout, 2014; Esteve et al., 2018; Crespo et al., 2019). Water saving and efficiency measures, such as leakage repair, education and improved irrigation, could limit conflicts across sectors, but necessitate technological advances and changes of practice together with a willingness to cooperate (Garnier and Holman, 2019; Papadimitriou et al., 2019; Teotónio et al., 2020). Increased irrigation efficiency has reduced water scarcity, particularly in SEU (13.5, De Roo et al., 2020), and occur at farm level in WCE and NEU (Papadaskalopoulou et al., 2015b; van Duinen et al., 2015; Rey et al., 2017), but come with increasing path-dependency on supply and trade-offs which may not be sustainable on the long-term (*high confidence*) (Di Baldassarre et al., 2018).

The assessment of the effectiveness and feasibility of adaptation options shows that a portfolio of supply and demand measures is needed to reduce water scarcity (Key Risk 3, Section 13.10.3), although locally demand-side measures could be sufficient (Kingsborough et al., 2016). Under high warming levels, adaptation to drought and low flows by water saving and efficiency measures may not be sufficient to counteract reduced availability (*medium agreement, low evidence*) (Collet et al., 2015; De Roo et al., 2020). Successful adaptation in the water sector depends on integrating water considerations into sectoral policies (Collet et al., 2015; Papadaskalopoulou et al., 2016). Inclusive and participatory approaches where (local) stakeholders are actively involved in the initiation and execution of water management can enhance problem ownership, quality and democratic legitimacy of processes and decisions, enhance support and accelerate decisions (Edelenbos et al., 2017; Begg, 2018).

13.2.3 Knowledge Gaps

An assessment of the full solution space of adaptation options and pathways under low to high GWLs including the long-term is lacking. A quantification of the effectiveness of measures in reducing risk is limited in the scientific literature. Available assessments consider adaptation by incremental measures. Transformative options, such as land use changes, planned relocation from exposed areas or restricting future development, are rarely considered. While high-end scenarios, describing *low confidence* processes and scenarios beyond 2100 are considered to be useful for risk-averse decision making, in particular coastal adaptation (Hinkel et al., 2019; Haasnoot et al., 2020b), they are rarely considered in practice.

13.3 Terrestrial and Freshwater Ecosystems and their Services

13.3.1 Observed Impacts and Projected Risks

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13.3.1.1 Observed Impacts on Terrestrial and Freshwater Ecosystems

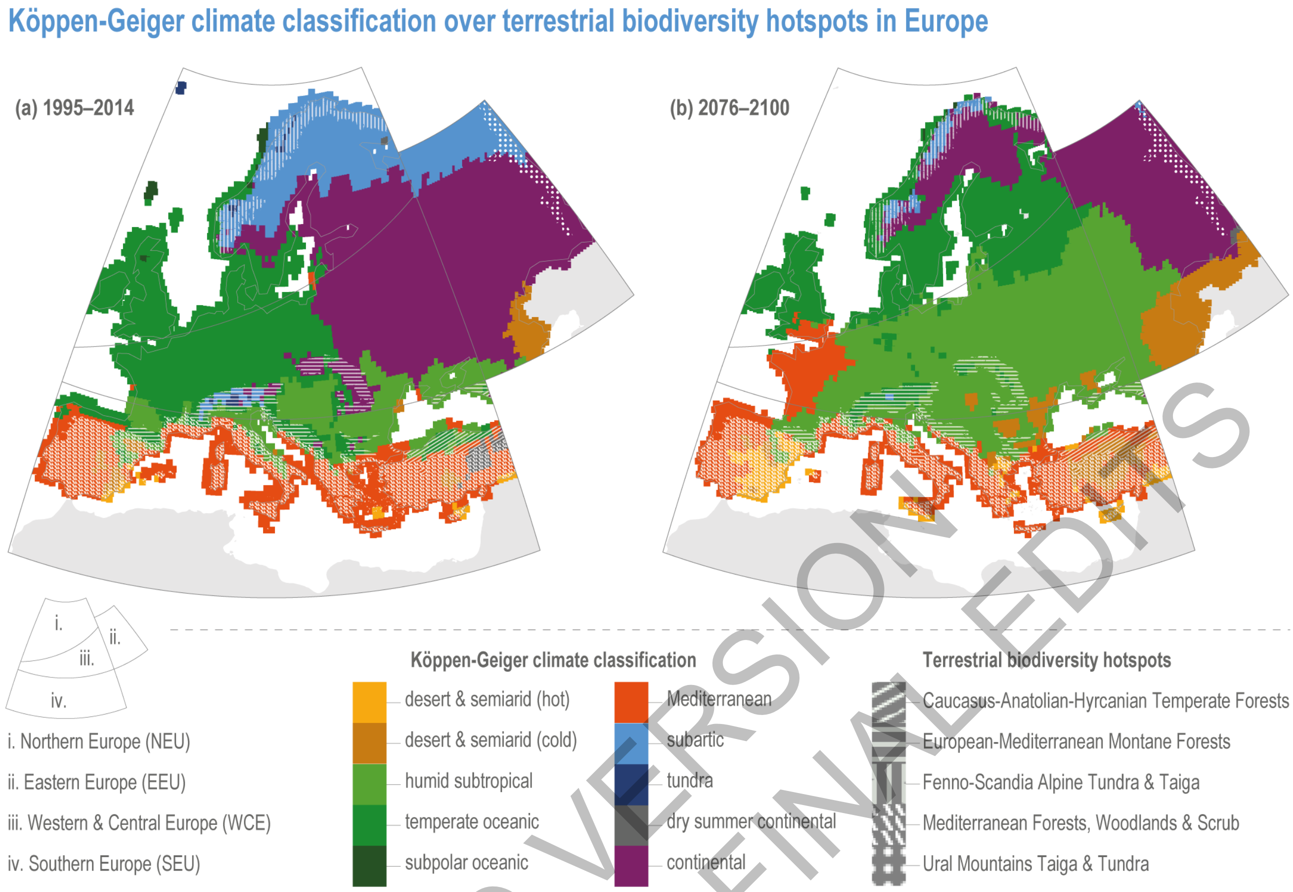

Figure 13.7: Köppen-Geiger climate classification and biodiversity hotspots in Europe. Boundaries of the (a) Northern (NEU), (b) Western-Central (WCE), (c) Southern (SEU), and (d) Eastern (EEU) European regions for 1985-2014 (left) and 2076-2100 (right, A1FI scenario, ~4°C GWL), based on Rubel and Kottek (2010).

European land and freshwater ecosystems (Figure 13.7) are already strongly impacted by a range of anthropogenic drivers (*very high confidence*), particularly habitats at the southern and northern margins, along the coasts, up mountains and in freshwater systems (CCP1). Interacting with climate change are non-climatic hazards, such as habitat loss and fragmentation, over-exploitation, water abstraction, nutrient enrichment, and pollution, all of which reduce resilience of biotas and ecosystems (*very high confidence*). Peatlands in NEU and EEU and other historically important cultural landscapes in Europe are overexploited for forestry, agriculture, and peat mining (Page and Baird, 2016; Tanneberger et al., 2017; Ojanen and Minkkinen, 2020). Inland wetland RAMSAR convention sites in Europe, which constitute 47% of the global sites, have lost area in WCE and gained in SEU from 1980 to 2014 (Xi et al., 2021). Forests in WCE were impacted by the extreme heat and drought event of 2018, with effects lasting into 2019 (Schuldt et al., 2020) and losses in conifer timber sales in Europe (Hlásny et al., 2021).

Extirpation, e.g. local losses of species, have been observed in response to climate change in Europe (*medium confidence*) (Wiens, 2016; EEA, 2017a; Soroye et al., 2020). Strong climate-induced declines have been detected in thermosensitive taxa (Hellmann et al., 2016), including many freshwater groups, insects (Habel et al., 2019; Harris et al., 2019; Seibold et al., 2019; Soroye et al., 2020), amphibians, reptiles (Falaschi et al., 2019), birds (Lehikoinen et al., 2019) and fishes (Myers et al., 2017a; Jarić et al., 2019). The loss of native species, especially specialised taxa, is changing biodiversity; however overall biodiversity could remain stable because losses may be compensated by range shifts of native and the establishment of non-native species (Dornelas et al., 2014; McGill et al., 2015; Hillebrand et al., 2018; Outhwaite et al., 2020).

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Major terrestrial ecosystem impacts and risks:	**LEGEND:**	Direction of change	Confidence
Observed and projected for two different warming levels (1.5 ºC/ 3.0 ºC)	Increase		• Low
	Decrease		•• Medium
	Both increase and decrease	••	••• High
	No Evidence		
	Not Assessed		

IMPACT / RISK						Direction of Change by Regions			
OF	FROM (Hazards)		ON / TO						
Effect	Climatic hazards	Interacting Non-climatic hazards	Affected Systems and Processes		Europe	SEU	WCE	EEU	NEU
Reduction in habitat availability of cold-adapted groups	Warming, heatwaves drought	Land-use change; habitat fragmentation	Rare, cold-adapted, endemic species, low dispersal capacity groups.	Observed	••	••	••	••	••
				Projected: +1.5 °C	••	••	••	••	••
				Projected: +3.0 °C	•••	•••	•••	••	••
Reduction in biodiversity of cold-adapted groups	Warming, heatwaves, drought	Land-use change; habitat fragmentation	Rare, cold-adapted, thermosensitive and drought-sensitive species, endemic species, low dispersal capacity groups	Observed	••	••	••	••	••
				Projected: +1.5 °C	••	••	••	••	••
				Projected: +3.0 °C	•••	•••	•••	••	••
Range shifts	Warming, change in precipitation	Land-use change; habitat fragmentation	Northward shifts and altitudinal movements of species and populations.	Observed	••	••	••	••	••
				Projected: +1.5 °C	••	••	••	••	••
				Projected: +3.0 °C	•••	•••	•••	••	••
Changes in phenology	Warming		Species and populations	Observed	•••	•••	•••	•••	•••
				Projected: +1.5 °C	•••	•••	•••	•••	•••
				Projected: +3.0 °C	•••	•••	•••	•••	•••
Decrease in ecosystem production	Warming, heatwaves drought	Land-use change	Ecosystem productivity, and nutrient and carbon cycling	Observed	•••	•••	•••	•••	•••
				Projected: +1.5 °C	••	•••	••	••	••
				Projected: +3.0 °C	••	•••	••	••	••
Rising incidence of fire	Warming, heatwaves drought	Land-use change; management	Ecosystems	Observed	•••	•••	•••	•	••
				Projected: +1.5 °C	••	••	••	••	••
				Projected: +3.0 °C	•••	•••	•••	•••	•••
Reduced pollination services	Warming, heatwaves drought	Land-use change; management	Pollination and crop yields	Observed	•••	•••	•••	•	•••
				Projected: +1.5 °C	••	••	••	•	••
				Projected: +3.0 °C	••	••	••	•	••
Increased soil erosion	Warming, heatwaves, drought, precipitation	Land-use change, management	Soil erosion	Observed	•••	•••	•••	••	•••
				Projected: +1.5 °C	••	••	••	No Evidence	••
				Projected: +3.0 °C	••	••	••	No Evidence	••

Figure 13.8: Summary of major impacts on and risks for terrestrial and freshwater ecosystems in Europe for 1.5ºC and 3ºC GWL (Table SM13.2).

Range shifts are leading to northward and upward expansions of warm-adapted taxa (*very high confidence*) (Figure 13.8 and Chapter 2). These shifts altered species living in the boreal and alpine tundra (Elmhagen et al., 2015; Post et al., 2019; Mekonnen et al., 2021) and are greening the high Arctic tundra with shrubs and trees (Myers-Smith et al., 2020). Plants display more stable distributions at low than at higher mountain altitudes (Rumpf et al., 2018). Microclimatic variability in some locations can buffer warming impacts (*medium confidence*) (Suggitt et al., 2018; Zellweger et al., 2020; Carnicer et al., 2021). Northward shifts of tree species distributions is documented in North Western Europe (Bryn and Potthoff, 2018; Mamet et al., 2019) but not consistently detected (Cudlín et al., 2017; Vilà-Cabrera et al., 2019).

The timing of many processes, including spring leaf unfolding and autumn senescence and flight dates changed in response to changes in seasonal temperatures, water and light availability (*very high confidence*) (Chapter 2, Szabó et al., 2016; Asse et al., 2018; Peaucelle et al., 2019; Menzel et al., 2020; Rosbakh et al., 2021), resulting e.g. in earlier arrival dates for many birds and butterflies (Karlsson, 2014; Bobretsov et al., 2019; Lehikoinen et al., 2019). Greatest growing season lengthening in plants has been detected in WCE, NEU and EEU, but shortening in parts of SEU driven by later senescence (Garonna et al., 2014), increasing population growth for butterflies and moths (Macgregor et al., 2019) and birds (Halupka and Halupka, 2017), and residence time for migrant birds (Newson et al., 2016).

13.3.1.2 Projected Risks for Terrestrial and Freshwater Ecosystems

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Risks for terrestrial ecosystems will increase with warming (*very high confidence*) with high impacts at > 2.4ºC GWL and very high impacts > 3.5ºC GWL (*medium confidence*) (13.10.3.1). Land use changes will increase extirpation and extinction risk (Vermaat et al., 2017) (*very high confidence*). In NEU, biodiversity vulnerability is projected to be lower as new climate and habitat space is becoming available (Warren et al., 2018; Harrison et al., 2019). Warming < 1.5ºC GWL would limit risks to biodiversity, while 4ºC GWL and intensive land use may lead to a loss of suitable climate and habitat space for most species (*low confidence*) (Warren et al., 2018; Harrison et al., 2019).

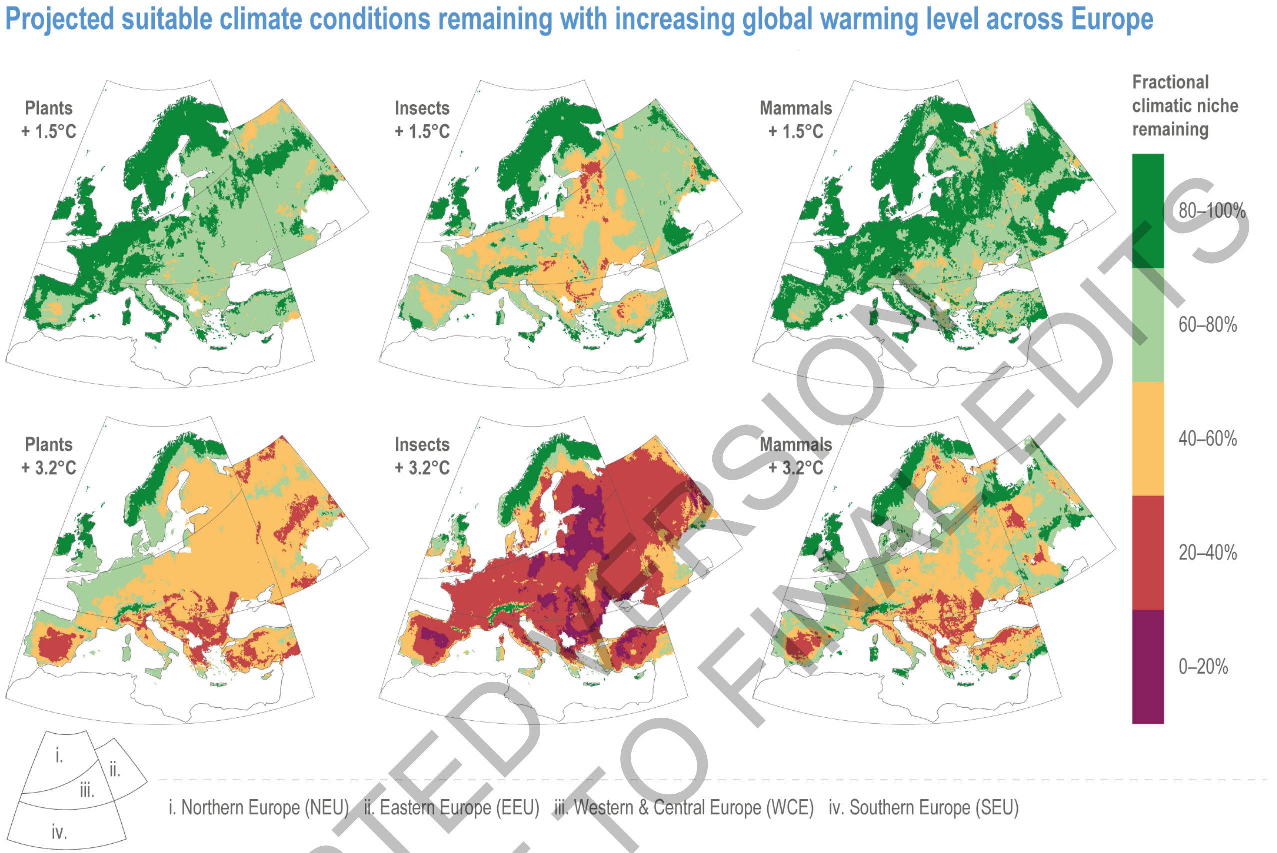

Figure 13.9: Species projected to remain within their suitable climate conditions at increasing levels of climate change. Colour shading represent proportion of species projected to remain within their suitable climates averaged over 21 CMIP5 climate models (Warren et al., 2018). Areas shaded in green retain a large number of species with suitable climate conditions, while those in purple represent areas where climates become unsuitable for more than 80% of the without dispersal (Table SM13.3).

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Disruption of habitat connectivity reduces resilience and is projected to impact 30% of lake and river catchments in Europe by 2030, through drought and reduced river flows (Markovic et al., 2017) (*medium evidence*). Average wetland area is not projected to change at 1.7°C GWL across Europe, while for > 4°C GWL expanding sites in NEU are not sufficient to balance losses in SEU and WCE (*high confidence*) (Xi et al., 2021). At 3°C GWL the alpine tundra habitat and its associated species are projected to be lost in the Pyrenees and shrink dramatically in NEU, WCE and EEU (Anisimov et al., 2017; Barredo et al., 2020).

Population range shifts (Figure 13.7, 13.10) are projected to continue (Figure 13.8) (*medium confidence* at 1.5° GWL, *high confidence* at 3.0°C GWL). The largest losses of suitable climatic conditions are projected for plants and insects, with different taxon-specific regions of highest risk, while proportions of species projected to loose suitable climates are lower for other groups (*medium confidence*) (Figure Box 13.1.1, Table SM13.3, Warren et al., 2018). > 1.5°C GWL will lead to a progressive subtropicalisation in SEU, expanding into WCE at > 3°C GWL, a northward shifting of the temperate domain into NEU (Feyen et al., 2020) (*medium confidence*), and an expansion of desert biomes in EEU (Sergienko and Konstantinov, 2016). Changes in distribution are projected for major tree species in all European regions at 1.7°C GWL (Dyderski et al., 2018; Leskinen et al., 2020), with economic implications for managed forests (13.5.1.4). The longer growth season in NEU and WCE will support the establishment of invasive species (CCP1). < 1.5ºC GWL would limit expansion and novel appearances of pests while > 3.4ºC GWL will make large parts of SEU and WCE suitable for pest, e.g. wood beetles (Urvois et al., 2021), and increase economic losses due to lower harvest quality of timber (Toth et al., 2020).

Risks emerging from climate change for phenology are uncertain, given asynchrony between species, taxa and trophic responses (Thackeray et al., 2016; Posledovich et al., 2018; Keogan et al., 2021) and the complexity of phenological events and their cues (Delgado et al., 2020; Ettinger et al., 2020) (*medium confidence*). Spring events may continue to occur earlier (Gaüzère et al., 2016), but reduced chilling may decrease this temporal shift (Wang et al., 2020). Projections for autumn are mixed, with continuing delays (Prislan et al., 2019) or earlier onset of leaf senescence (Wu et al., 2018), but reduced chilling may also decrease these developments (Wang et al., 2020). Advancement, combined with longer autumn growth, may extend the growing season of trees by two days per decade in SEU (Prislan et al., 2019). Warming to > 3°C GWL will impact forest planning in NEU (Caffarra et al., 2014).

13.3.1.3 Observed Impacts and Projected Risks of Wildfires

Fires affect over 400,000 ha every year in the European Union (San-Miguel-Ayanz et al., 2019), with 85% of the area located in SEU (Khabarov et al., 2016; de Rigo et al., 2017; Costa et al., 2020), where 'fire weather' conditions (determined by temperature, precipitation, wind speed and relative humidity) are most pronounced (Figure 13.10). Fire hazard conditions, including heat waves (Boer et al., 2017), have increased throughout Europe from 1980 to 2019 (Figure 13.10), with substantive increases in SEU and WCE (*high confidence*) (Urbieta et al., 2019; Di Giuseppe et al., 2020; Fargeon et al., 2020). Extreme wildfires have been observed in recent years, including 2017 in Portugal, 2018 in Sweden (Krikken et al., 2021) and 2021 in south-eastern Europe. In SEU, WCE and NEU human activities caused more than 90-95% of the fires, while natural ignition accounts for a substantial portion of burnt area in EEU (Wu et al., 2015; Filipchuk et al., 2018).

Except for Portugal, burnt area in SEU has shown a slightly decreasing trend since 1980, with high inter-annual variability (CCP 4, Turco et al., 2016; de Rigo et al., 2017). In SEU, burned terrestrial biomass declined from 2003 to 2019 (Turco et al., 2016), despite increasing fire risks. This trend is parallel to increasing fire management measures implemented (Fernandez-Anez et al., 2021). The slight increase in burned biomass in WCE and NEU is associated with more hazardous landscape configurations and warming in recent decades (Turco et al., 2016; Urbieta et al., 2019).

Projections of wildfire risks are uncertain due to multiple factors, including compound events, fire-vegetation interaction and social factors (Thompson and Calkin, 2011; San-Miguel-Ayanz et al., 2019). Wildfire risks can increase across all regions of Europe at 1.5°C and 3°C GWL (*medium* to *high confidence*) (Figure 13.8). In SEU, the frequency of heat-induced fire-weather is projected to increase by 14% at 2.5°C GWL and rising to 30% at 4.4°C GWL (Turco et al., 2018; Costa et al., 2020; Ruffault et al., 2020). In the European Arctic, the extent and duration of extreme fire seasons will increase because of increasing extreme fire weather, increased lightning activity, and drier vegetation and ground fuel conditions due to prolonged droughts (McCarty et al., 2021). Projections suggest that new fire-prone regions in Europe could emerge, particularly in WCE and NEU where wildfires have been uncommon and fire management capacity is slowly increasing (Wu et al., 2015; Forzieri et al., 2021).

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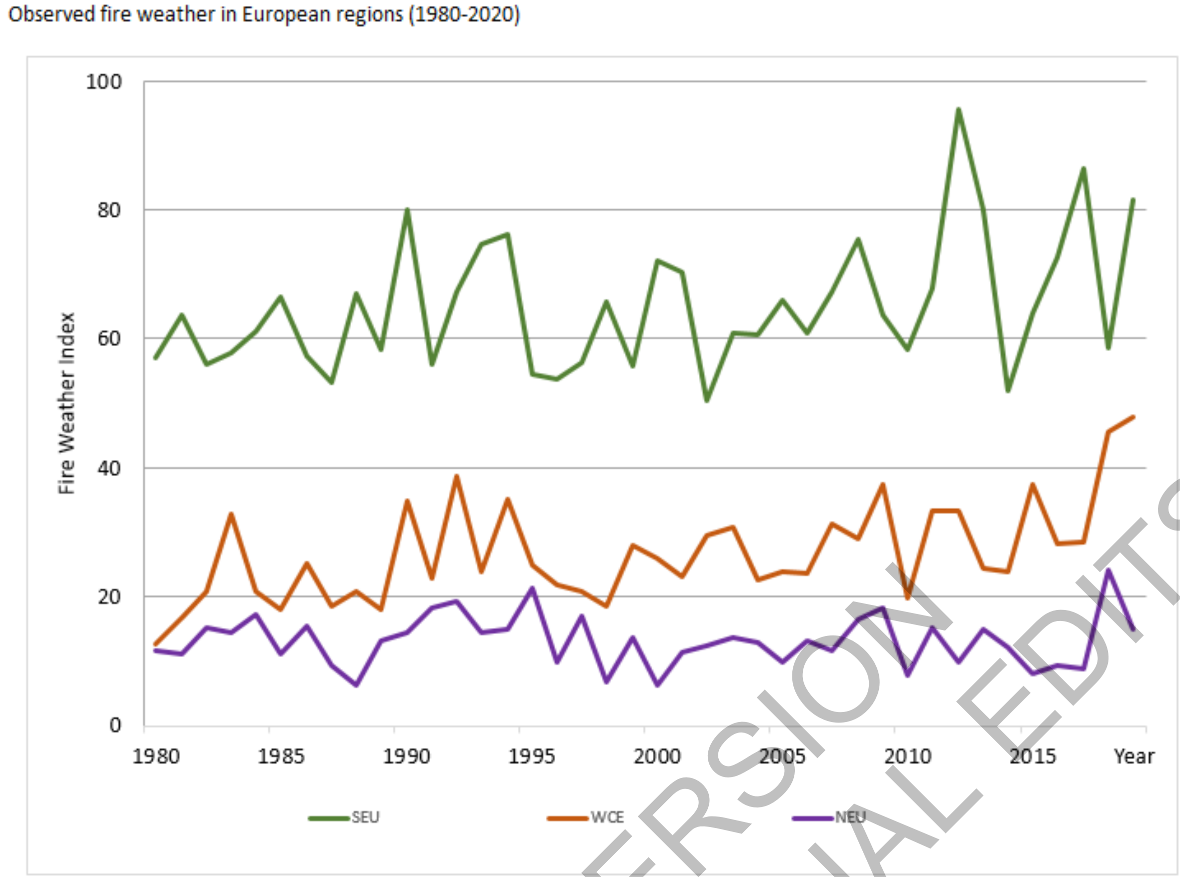

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Figure 13.10: Geographical variability and dynamic changes in fire danger in Europe over the last decades. Significant increases in fire hazard at the multidecadal scale and unprecedented years of elevated fire hazard have occurred over the last decade in Southern and Western and Central Europe (SEU, WCE). The environmental conditions required for fires to spread and intensify were evaluated using fire hazard estimates ('Fire Weather Index' (FWI) based on meteorological variables such as temperature, precipitation, wind speed and relative humidity). FWI trends were calculated with the ECMWF ERA-5 FWI reanalysis dataset (Copernicus, 2019; Copernicus, 2020a; Copernicus, 2020b).

13.3.1.4 Observed Impacts and Projected Risks on Ecosystem Functions and Regulating Services

European temperate and boreal forests, wetlands and peatlands hold important carbon stocks (Bukvareva and Zamolodchikov, 2016; Yousefpour et al., 2018). Effects of warming and increasing droughts on soil moisture, respiration and carbon sequestration have been detected across European regions (*high confidence*) (Tab. 13.3, Sanginés de Cárcer et al., 2018; Carnicer et al., 2019; Green et al., 2019; Schuldt et al., 2020). Forest expansion in boreal regions results in net warming (Bright et al., 2017), possibly influencing cloud formation and rainfall patterns (*medium confidence*) (Teuling et al., 2017). These changes are affecting climate, pollination and soil protection services (Table 3.3, Verhagen et al., 2018). If not managed through increased reforestation/revegetation or peatland restoration, future climate change impacts will progressively limit the climate regulation capacity of European terrestrial ecosystems (*medium confidence*) (Figure 13.8), especially in SEU (Peñuelas et al., 2018; Xu et al., 2019). Predominantly positive CO_2 fertilization effects at current warming will change into increasingly negative effects of warming and drought on forests at higher temperatures (*medium confidence*) (Peñuelas et al., 2017; Green et al., 2019; Ito et al., 2020; Wang 2020; Yu et al., 2021). In NEU and EEU, peatlands are projected to shrink with 1.7°C GWL, and become carbon sources at 3°C GWL (Qiu et al., 2020), peat bogs to lose 50% carbon at 2°C GWL, and blanket peatland to shrink or regionally disappear (Gallego-Sala et al., 2010; Ferretto et al., 2019)

Declines in pollinator ranges in response to climate are occurring for many groups in Europe (h*igh confidence*) (Figure Box 13.1.1, Table 13.3, Kerr et al., 2015; Soroye et al., 2020; Zattara and Aizen, 2020), with observed shifts to higher elevations of southern and lower elevation in northern species (Kerr et al., 2015) resulting in higher pollinator richness in NEU (Franzén and Öckinger, 2012). Lags in responses to climate change suggest current impacts on pollination have not been fully realized (IPBES, 2018).

Pollinators are also declining due to lack of suitable habitat, pollution, pesticides, pathogens and competing invasive alien species (Settele et al., 2016; Steele et al., 2019).

Projected climate impacts on pollinators show mixed responses across Europe, but are greater under 3°C GWL (*medium confidence*) (Rasmont et al., 2015). Increasing homogenisation of populations may increase vulnerability to extreme events (Vasiliev and Greenwood, 2021). Geographic changes to the climatic niche of pollinators are similar to insects, with mixed trends, depending on group and location (Figure 13.9, Kaloveloni et al., 2015; Rasmont et al., 2015; Radenković et al., 2017). In NEU, species richness may increase for some groups (Rasmont et al., 2015), with unclear trends for bumblebees (Fourcade et al., 2019; Soroye et al., 2020). Future land use will have important effects on pollinator distribution (Marshall, 2018) as habitat fragmentation in densely populated Europe decreases opportunities for range shifts and micro-climatic buffering (Vasiliev and Greenwood, 2021).

Soil erosion varies across Europe, with higher rates in parts of SEU and WCE, but lower in NEU (*high confidence*) (Table 13.3, Petz et al., 2016; Polce et al., 2016; Borrelli et al., 2020), related to vegetation type and amount of cover, slope and soil type (Panagos et al., 2015a). Short-term, land use change and management may impact soil erosion more than climate (Verhagen et al., 2018). Where conservation agriculture is practised or vegetation cover increasing, erosion is slightly decreasing (Panagos et al., 2015b; Guerra et al., 2016). Reduced soil loss due to reduced spring snow melt has been observed in EEU (Golosov et al., 2018) , while fire exacerbates soil loss, especially in SEU (Borrelli et al., 2016; Borrelli et al., 2017).

Projected increase in rainfall could increase soil erosion, while warming enhances vegetation cover, leading to overall mixed responses (*medium confidence*) (Berberoglu et al., 2020; Ciampalini et al., 2020). In Europe, rainfall erosivity could increase by >81% (Panagos et al., 2017) at 2°C GWL, especially in NEU (Borrelli et al., 2020) where risks can be limited by soil erosion control (Polce et al., 2016). Decreased rainfall projected for parts of SEU could reduce erosion, although increases in rainfall intensity could offset this (Serpa et al., 2015). Soil losses from fire will increase in SEU in response to 2°C GWL (Pastor et al., 2019), especially if combined with extreme rainfall (Morán-Ordóñez et al., 2020). In northern regions, reduced soil losses are projected during spring snowmelt (Svetlitchnyi, 2020).

13.3.2 Solution Space and Adaptation Options

Autonomous species adaptation, via range shifts towards higher latitudes and altitudes and changes in phenology, but extirpation have been documented in all European regions (Figure 13.8) (*very high confidence*). Lowering vulnerability by reducing other anthropogenic impacts (Gillingham et al., 2015), such as land use change, habitat fragmentation (Eigenbrod et al., 2015; Oliver et al., 2017; Wessely et al., 2017), pollution, and deforestation (Chapter 2), enhances adaptation capacity and biodiversity conservation (*high confidence*) (Ockendon et al., 2018). Protected areas, such as the EU Natura 2000 network, have contributed to biodiversity protection (*medium confidence*) (Gaüzère et al., 2016; Sanderson et al., 2016; Santini et al., 2016; Hermoso et al., 2018) but 60% of terrestrial species in these sites could lose suitable climate niches at 4°C GWL (Figure Box 13.1.1, EEA, 2017a).

Most protected areas are static and thus do not take species migration into consideration (*high confidence*) (Gillingham et al., 2015; Heikkinen et al., 2020b). More dynamic areas of protection, such as networks of protected areas with corridors, buffer zones and zoning, can facilitate population shifts (Barredo et al., 2016; Nila et al., 2019; Crick et al., 2020; Keeley et al., 2021) and thereby reduce but not eliminate vulnerability (Wessely et al., 2017; Pavón-Jordán et al., 2020).

Rehabilitation and restoration of land (Prober et al., 2019), particularly abandoned agricultural areas in SEU and NEU (Terres et al., 2015), are long-term strategies to improve regulating services and enhance biodiversity conservation (Morecroft et al., 2019; Campos et al., 2021). Their success will depend on consideration of the future climate niche when restoring peatlands (Bellis et al., 2021) or long-lived species with limited mobility (Hazarika et al., 2021) (*high confidence*). Combination of supporting the resilience of species, increasing functional diversity of habitats, and assisted migration of species at the limit of their adaptive capacity (Park and Talbot, 2018) are needed to protect and restore ecosystems, e.g. forests (Boiffin et al., 2017; Messier et al., 2019). Successful interventions consider habitat and the ecological and evolution

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interactions of species (Šeho et al., 2019; Diallo et al., 2021) combined with monitoring to assess their effectiveness (Casazza et al., 2021).

Fire management plans and programs are in place in most of SEU, and increasingly developed in the parts of Europe where wildfires are less common (Fernandez-Anez et al., 2021). Capacity to implement and maintain these options remains limited, however (*medium confidence*). The dominant fire management paradigm of fire suppression in some regions of SEU has been questioned, as it contributes to fuel accumulation. Approaches are advocated which combining fire-risk mitigation, prevention, and preparation (Moreira et al., 2020), recovery through post-fire management (Lucas-Borja et al., 2021), diverse fuels treatment (Mirra et al., 2017), including prescribed burning (Fernandes et al., 2013).

Ecosystem-based adaptations (EbA) and nature-based solutions (NbS) that restore or recreate ecosystems, build resilience and produce synergies with adaptation and mitigation in other sectors are increasingly used in Europe (*high confidence*)(Cross-Chapter Box NATURAL in Chapter 2, Berry et al., 2015; Chausson et al., 2020). Planting trees or recreating wetlands can function as part of natural flood management (Dadson et al., 2017; Cooper et al., 2021), whilst urban green infrastructure can reduce flooding (13.2.2) and heat stress and provide recreation opportunities and health benefits (13.6.2.3; Box 13.3) (Kabisch et al., 2016; Choi et al., 2021).
Appropriately implemented ecosystem-based mitigation, such as reforestation with climate-resilient native species (13.3.1.4), peatland and wetland restoration and agroecology (13.5.2), can enhance carbon sequestration or storage (*medium confidence*) (Seddon et al., 2020). Saltmarsh protection or recreation can increase carbon storage capacity, enhance coastal flood protection and provide cultural services (Beaumont et al., 2014; Bindoff et al., 2019). Trade-offs between ecosystem protection, their services and human adaptation and mitigation needs can generate challenges, such as loss of habitats, increased emissions from restored wetlands (Günther et al., 2020) and conflicts between carbon capture services, and provisioning of bioenergy, food, timber and water (Lee et al., 2019; Krause et al., 2020) (*medium confidence*).

The solution space for responding to climate-change risks for terrestrial ecosystem has increased in parts of Europe (*medium confidence*). For example, EbA and NbS figure prominently in the EU Adaptation Strategy (2021a) and climate change adaptation is mainstreamed in the EU Biodiversity Strategy for 2030 (European Comission, 2020), the EU Forest Strategy for 2030 (European Comission, 2021b), the EU Green Infrastructure Strategy (European Comission, 2013a), as well as several national and regional policies. Yet, in the northern parts of EEU and NEU (e.g. Greenland, Iceland, NW Russian Arctic), areas which are often sites of pronounced biodiversity shifts and changes, solutions are lacking or slow in emergence, due to remoteness, lack of resources and sparse populations (Canosa et al., 2020). In the EU, innovative financing schemes such as the Natural Capital Financing Facility are being explored by the European Investment Bank and the European Commission which supports projects delivering on biodiversity and climate adaptation through tailored loans and investments. Multiple EU-level service platforms have been promoted to track climate change impacts on land ecosystems and adaptation (e.g. Climate-Adapt, Copernicus Land and Fire Monitoring Service, Forest Information System of Europe) (13.11.1).

Despite an expanding solution space, widespread implementation and monitoring of natural and planned adaptation across Europe is currently limited, due to high management costs, undervaluation of nature, and conservation laws and regulations that do not consider species shifts under future socioeconomic and climatic changes (*high confidence*) (Kabisch et al., 2016; Prober et al., 2019; Fernandez-Anez et al., 2021). Climate risks are not perceived as urgent due to a continuing perception of high adaptive capacity of ecosystems (Uggla and Lidskog, 2016; Esteve et al., 2018; Vulturius et al., 2018). Limited financial resources prevent widespread implementation of large-scale and connected conservation areas (*high confidence*) (Hermoso et al., 2017; Lee et al., 2019; Krause et al., 2020). Particularly in WCE, competition for land use with other functions, including mitigation options, is a critical barrier to implementation of adaptation. Risks to terrestrial and freshwater ecosystems are rarely integrated into regional and local land use planning, land development plans, and agro-system management (*medium confidence*) (Nila et al., 2019; Heikkinen et al., 2020a) .

13.3.3 Knowledge gaps

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Despite growing evidence of climate change impacts and risk, including attributed changes to terrestrial ecosystems (13.10.1), this information is geographically not equally distributed, leaving clear gaps for some processes or regions *(high confidence*). For processes such as wildfire, the Fire Weather Index (13.3.1.3) suggests increasing risks for fires in Europe but robust projections on incidents and magnitudes of wildfire and their impacts on ecosystems and other sectors is currently limited, particularly for NEU, EEU and WCE (*high confidence*).

Many studies consider only individual climate drivers, though new research shows strong interactions between hazards such as warming and drought (13.3.1), as well as non-climatic drivers (Chapter 2). This creates uncertainty about the emergence of extinctions and the magnitudes of impacts for European ecosystems and the services they provide (*high confidence*), such as pollination on food production. RCP-SSP combinations to assess risks are only just emerging (Harrison et al., 2019).

Assessments of the long-term effectiveness of adaptation actions is missing, due to the time lag in determining effectiveness of an action and attributing risk reduction (Morecroft et al., 2019). For example, many landscape restoration actions are discussed but it is unclear which would bring highest benefits and which species should be used for the restoration (Ockendon et al., 2018). Further, adaptation actions will depend on local implementation and benefit from being assessed using cultural and Indigenous knowledge where applicable, but this is hardly studied (*medium confidence*).

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 for European seas (Figure 13.1). Interacting with other climatic and non-climatic drivers, it has detectable and attributable impacts at a wide range of biological and ecological organisational levels (Figure 13.11).

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Major marine ecosystem impacts and risks:

Observed and projected for two different warming levels (1.5 ºC/ 3.0 ºC)

LEGEND:	Direction of change	Confidence
Increase		• Low
Decrease		•• Medium
Increase and decrease	I/D	••• High
No evidence	No evidence	
Not assessed	Not assessed	

IMPACT / RISK	Hazards: Climatic hazards	Hazards: Interacting non-climatic hazards	ON / TO (Affected systems & processes)		EUROPE	SEUS	TEUS	NEUS
A. Loss of habitat availability	Warming Heatwaves Sea-level rise Sea-ice decline	Fishing, eutrophication, coastline modification, pollution	Ecosystems	Observed Impacts	•••	•••	No evidence	••
				Projected Risks at +1.5 °C	•••	•••	••	••
				Projected Risks at +3.0 °C	•••	•••	•••	•••
B. Shifts in ranges (incl. invasions), compositions (taxonomic, functional), phenologies	Warming, acidification	Shipping	Populations, Species, communities, biomes	Observed Impacts	•••	•••	•••	•••
				Projected Risks at +1.5 °C	•••	•••	•••	•••
				Projected Risks at +3.0 °C	•••	•••	•••	•••
C. Reduction in growth and reproductive success	Warming, acidification		Species	Observed Impacts	I/D ••	I/D ••	I/D ••	I/D ••
				Projected Risks at +1.5 °C	I/D ••	No evidence	I/D ••	No evidence
				Projected Risks at +3.0 °C	•	•	•	No evidence
D. Loss in biodiversity	Warming Heatwaves Sea-ice decline	Fishing, eutrophication, coastline modification, pollution	Populations, Species, Communities	Observed Impacts	I/D •••	I/D •••	I/D •••	I/D •••
				Projected Risks at +1.5 °C	I/D ••	••	I/D ••	I/D ••
				Projected Risks at +3.0 °C	•••	•••	••	••
E. Decline in production	Warming	Eutrophication	Ecosystems: - Production	Observed Impacts	I/D •••	No evidence	•••	•••
				Projected Risks at +1.5 °C	I/D ••	I/D ••	•••	••
				Projected Risks at +3.0 °C	I/D ••	I/D ••	•••	••
F. Emergence of harmful algal blooms and pathogens	Warming, acidification, deoxygenation	Eutrophication	Species, communities, ecosystems	Observed Impacts	•*	•*	•*	No evidence
				Projected Risks at +1.5 °C	•	•	•	•
				Projected Risks at +3.0 °C	•	•	•	•
G. Reduction in ecosystem services	Warming, acidification, deoxygenation, sea-level rise	Fishing, eutrophication, coastline modification, pollution	Ecosystems: - Regulating - Provisioning - Coastal protection	Observed Impacts	I/D •	•	•	No evidence
				Projected Risks at +1.5 °C	I/D •••	•	•	•
				Projected Risks at +3.0 °C	I/D •••	•	I/D ••	I/D ••

Figure 13.11: Major impacts and risks for marine and coastal ecosystems in Europe for observed and projected 1.5 °C and 3.0 °C GWL (Table SM13.4).

Particularly habitat loss in shallow coastal waters and at the coasts themselves, and northward distribution shifts of populations and communities are evident across all European marine subregions (Figure 13.11: *high confidence*; Chapter 3). Marine heatwaves have had severe ecological impacts in SEUS (*high confidence*) (CCP 4), threatening sessile benthic biotas and coastal habitats (Munari, 2011; Kersting et al., 2013; Rivetti et al., 2014; Garrabou et al., 2019). Range contractions, extirpations (*medium confidence*) (Smale, 2020) and species redistributions have been observed (*high confidence*) in TEUS (Cottier-Cook et al., 2017) and SEUS (Castellanos-Galindo et al., 2020). Habitat losses, range shifts, species invasions and species thermal preferences altered community compositions (Vasilakopoulos et al., 2017), resulting in the 'subtropicalisation' of TEUS and 'tropicalisation' of SEUS (Chapter 3; CCP 4) and temperature-dependent timing of abundance and reproduction cycles (Hjerne et al., 2019; Polte et al., 2021; Uriarte et al., 2021).

Reductions in growth and reproductive success of calcifying species are not yet unambiguously detected and attributed in European seas (Figure 13.11) (*medium confidence*), as many show resilience (Kroeker et al., 2010; Wall et al., 2015). However, fish population sizes are shrinking (Queirós et al., 2018; Ikpewe et al., 2021), and growth, reproduction and recruitment are negatively impacted (Lindegren et al., 2018; Goldberg et al., 2019; Hidalgo et al., 2019; Vieira et al., 2019; Denechaud et al., 2020; Maynou et al., 2020; Polte et al., 2021), though positive effects also occur (Sguotti et al., 2019; Tanner et al., 2019). Biodiversity changes depend on region, habitat, and taxon (Figure 13.11) (*medium confidence*) overall resulting in the redistribution of biodiversity in Europe (García Molinos et al., 2016), and biodiversity declines in some subregions (*high confidence*) (IPBES, 2018).

Biological and ecological impacts have cascading effects for marine ecosystem functioning (Chivers et al., 2017; Baird et al., 2019) and biogeochemical cycling (Huete-Stauffer et al., 2011; Munari, 2011; Kersting et

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al., 2013; Rivetti et al., 2014; Garrabou et al., 2019). In TEUS, increased water-column stratification (Section 13.1) and decreasing eutrophication, result in reduced primary production (*high confidence*) (Figure 13.11, Capuzzo et al., 2018) and productivity at higher trophic levels (Free et al., 2019) (*high confidence*), while in NEUS sea-ice decline resulted in primary production increase by 40-60% (Figure 13.11) (*high confidence*) (Arrigo and van Dijken, 2015; Borsheim, 2017; Lewis et al., 2020). Climate-related deoxygenation impacts are small in most European waters (Figure 13.11) (*medium confidence*), expect for semi-enclosed seas such as the Baltic and Black Seas (Frolov et al., 2014; Jacob et al., 2014; Reusch et al., 2018). Here warming and eutrophication altered ecosystem functioning (*high confidence*), reduced potential fish yield, increased harmful algal blooms (Alekseev et al., 2014; Carstensen et al., 2014; Berdalet et al., 2017; Daskalov et al., 2017; Riebesell et al., 2018; Stanev et al., 2018), and the risks of *Vibrio* pathogens and vibriosis (Section 13.7.1, Baker-Austin et al., 2017; Semenza et al., 2017). Across all European seas there is only *low confidence* of a consistent change in provisioning ecosystem services (e.g., fishing yields, Section 13.5), because of interregional variability, but *high confidence* in the decrease in regulating services and coastal protection because of cascading effects of ecosystem impacts (Figure 13.11).

13.4.1.2 Projected Risks

Risks to marine and coastal European ecosystems are *very likely* to intensify (Figure 13.11) in response to projected further warming. Since the capacity of natural systems for autonomous adaptation is limited (Thomsen et al., 2017; Miller et al., 2018; Bindoff et al., 2019) (*medium confidence*), pronounced changes in community composition and biodiversity patterns are projected by 2100 for TEUS and the eastern Mediterranean Sea (SEUS) for> 3°C GWL (García Molinos et al., 2016), challenging conservation efforts (Corrales et al., 2018; Cramer et al., 2018; Kim et al., 2019). At 1.5°C GWL, particularly in winter, Mediterranean coastal fish communities are projected to lose ~10% of species, increasing to ~60% at 4°C GWL (Dahlke et al., 2020), exacerbating regime shifts linked to overexploitation (Clark et al., 2020) (*medium confidence*). Warming at this level will threaten many species currently living in Marine Protected Areas (MPA) in TEUS and NEUS (Bruno et al., 2018). Increasing marine heatwaves (MWH), particularly in SEUS at 4°C GWL (Darmaraki et al., 2019a), elevate risks for species (Galli et al., 2017), coastal biodiversity, and ecosystem functions, goods and services (Smale et al., 2019). However, MWH-related risk levels differ among biotas (Pansch et al., 2018) and across European seas (Smale et al., 2015).

Marine primary production is projected to further decrease by 2100 in most European seas between 0.3% at 1.5°C GWL to 2.7% at 4°C GWL (Figure 13.11) (*high confidence*), mainly caused by stratification-driven reductions in nutrient availability, impacting food webs (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). In the Barents Sea, however, largely stable primary production is projected under all scenarios in response to sea-ice decline (Slagstad et al., 2011) and in the eastern Mediterranean due to reduced stratification (Macias et al., 2015; Moullec et al., 2019). These changes in productivity are projected to increase of fish and macroinvertebrate biomass between 5 and 22% (Moullec et al., 2019). Decreasing net primary production will impact higher trophic levels (Section 13.5.1), e.g., in TEUS (Holt et al., 2016; Holt et al., 2018). Marine animal biomass is projected to *likely* decline in most European waters, with decreases < 10% under all scenarios until the 2030s but losses growing to 25% at 2°C GWL and 50% at 4°C GWL in coastal waters of the NE Atlantic (Lotze et al., 2019; Bryndum-Buchholz et al., 2020).

Ocean acidification and its biological and ecological risks are projected to rise in European waters by impeding growth and reproductive success of vulnerable calcifying organisms (Figure 13.11) (*medium confidence*). Coralline algae are projected to reduce skeletal performance at 3°C GWL, with negative consequences for habitat formation (Ragazzola et al., 2016) (*medium confidence*). Regionally (Brodie et al., 2014), differences in species-specific vulnerability will result in community shifts from calcifying macroalgae (Ragazzola et al., 2013) (*medium confidence*) to non-calcifying macroalgae (Gordillo et al., 2016) *(high confidence*). Experimental studies demonstrated high resilience of some important habitat formers, such as the deep-water coral Lophelia pertusa (Wall et al., 2015; Morato et al., 2020), and habitat engineers, such as Mediterranean limpets (Langer et al., 2014), . facilitated by energy reallocation. However, if not supported by sufficient food availability (Thomsen et al., 2013; Clements and Darrow, 2018), such energy reallocation will negatively impact growth or reproduction (*medium confidence*) (Büscher et al., 2017). (Thomsen et al., 2013)This suggests that acidification risks will be amplified by increased

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stratification and reduced primary production (*medium confidence*). The emergence of harmful algal blooms and pathogens at higher GWLs is unclear across all European seas (Figure 13.11) (*low confidence*).

Risks to marine biotas and ecosystems in European seas are projected to impact important ecosystem services (Figure 13.11). Elevated CO_2 levels predicted at 4°C GWL will affect the C/N ratio of organic-matter export and, hence, the efficiency of the biological pump (*low confidence*), depending on the shifts in plankton composition and, hence, food-web structure (Taucher et al., 2020). Atlantic herring (*Clupea harengus*) will benefit with enhanced larval growth and survival from indirect food-web effects (Sswat et al., 2018a), whereas Atlantic cod (*Gadus morhua*) will face overall negative impacts (*medium confidence*) (Section 13.5, Stiasny et al., 2018; Stiasny et al., 2019). Anoxic dead zones in the Black (Altieri and Gedan, 2015) and the Baltic (Jokinen et al., 2018; Reusch et al., 2018) Seas are projected to increase, e.g., by 5% in the Baltic Sea at 4°C GWL (Saraiva et al., 2019). Europe's coastal vegetated 'blue-carbon' ecosystems (subtidal seagrass meadows and intertidal salt marshes) are highly vulnerable (Spencer et al., 2016; Schuerch et al., 2018; Spivak et al., 2019), particularly in microtidal areas such as the Baltic and Mediterranean coast. Losses are projected for *Posidonia oceanica* seagrass habitats in the Mediterranean by of up to 75% at 2.5°C GWL (*low confidence*) (Chapter 3). The Wadden Sea, the world's largest system of intertidal flats, is projected to 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', will be reached by 2030 at 1.5°C GWL (*medium confidence*), or even earlier through subsidence due to human activities (van der Spek, 2018). European coastal zones provided a total of €494 billion of ecosystem services in 2018, and 4.2 to 5.1% of this value will be lost due to coastal erosion by 2100 at 2.5°C and 4.6°C GWL, respectively (*medium confidence*) (Paprotny et al., 2021).

13.4.2 Solution Space and Adaptation Options

Human adaptation options for marine systems encompass socio-institutional adaptation, technology, and measures supporting autonomous adaptation (Chapter 3). Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP) are frameworks for addressing climate-change adaptation needs, as well as operationalizing and enforcing marine conservation. However, ICZM and MSP do commonly not explicitly take climate-change adaptation into consideration (Elliott et al., 2015), Transboundary ICZM and/or MSP (Gormley et al., 2015) will become even more important with the projected acceleration of range extensions and ecological regime shifts due to climate change (IPCC, 2019).

Many climate-change adaptation governance and implementation measures are embedded in international strategies, such as HELCOM (Baltic Marine Environment Protection Commission (HELCOM) (Backer et al., 2010), OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic) (OSPAR, 2009), and the Marine Strategy Framework Directive (MFSD) and European Water Framework Directive (EWFD) of the European Union. In the Russian Arctic, mainly the Barents Sea, conservation priority areas (CPA) have been identified as Ecologically and Biologically Significant Areas (EBSA) (Solovyev et al., 2017). However, plans are generally at a relatively early stage (Miller et al., 2018), and assessments of the effectiveness of these policy frameworks to accelerate climate-change adaptation are ongoing (Haasnoot et al., 2020a).

'Green' adaptations, either 'Ecosystem based Adaptations' or 'Nature based Solutions, are part of adaptive management strategies (European Comission, 2011) that facilitate coastal flood protection (Section 13.2.2; Chapter 3; CCC SLR) and generate benefits beyond habitat creation (*medium confidence*), e.g., from avoided expenditures for flood defence infrastructure and avoided loss of the built assets (Gedan et al., 2010). Marine Protected Areas (MPAs) have been identified as adaptation options for natural areas, including permitted and non-permitted uses (Chapter 3, Selig et al., 2014; Hopkins et al., 2016a; Roberts et al., 2017). The extent of MPAs has been increasing in Europe, albeit with strong regional variations (Figure 13.12). MPAs provide protection from local stressors, such as commercial exploitation, and enhance the resilience of marine and coastal ecosystems and thus lessen the impacts of climate change (*medium confidence*) (Narayan et al., 2016; Roberts et al., 2017). However, climate change risk reduction is only a limited MPA objective (Hopkins et al., 2016b; Rilov et al., 2019). The implementation of the legal frameworks, such as the EC Habitats Directive and EC Birds Directive, allows for enabling adaptation (Verschuuren, 2015) as does the incorporation of climate considerations in management of Natura 2000 sites (European Comission, 2013b).

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There is evidence that better international cooperation is required to increase effectiveness of the MSFD (Cavallo et al., 2019), and the Good Environmental Status is currently not effectively monitored (Machado et al., 2019).

The greatest benefits are obtained from large, long established, no-take MPAs (Edgar et al., 2014). Yet most MPAs in Europe are partially protected or multi-use areas, and existing no-take areas tend to be very small (< 50 km^2). No take areas are accounting in total for less than 0.4% of the area European waters (Figure 13.12) and are often nested within multi-use MPAs. In some partially protected MPAs, local stressors, such as fishing, are higher than adjacent unprotected areas (*medium confidence*) (Zupan et al., 2018a; Mazaris et al., 2019). Despite evidence for climate mitigation benefits of no-take zones (Roberts et al., 2017), the efficacy of partial protected MPAs is debated and dependent on local management (Zupan et al., 2018b). MPAs of all types require effective management to contribute to mitigating climate change impacts, including effective monitoring and enforcement (Watson et al., 2014), yet the management effectiveness of European MPAs has repeatedly been called into question (Batista and Cabral, 2016; Amengual and Alvarez-Berastegui, 2018; Fraschetti et al., 2018; Rilov et al., 2019). Many MPAs lack management plans, and insufficient resources are frequently an issue (Álvarez-Fernández et al., 2017; Schéré et al., 2020). Thus, whilst substantial in potential, the current capacity of the European MPA network to reduce climate change impacts is limited (Jones et al., 2016; Claudet et al., 2020).

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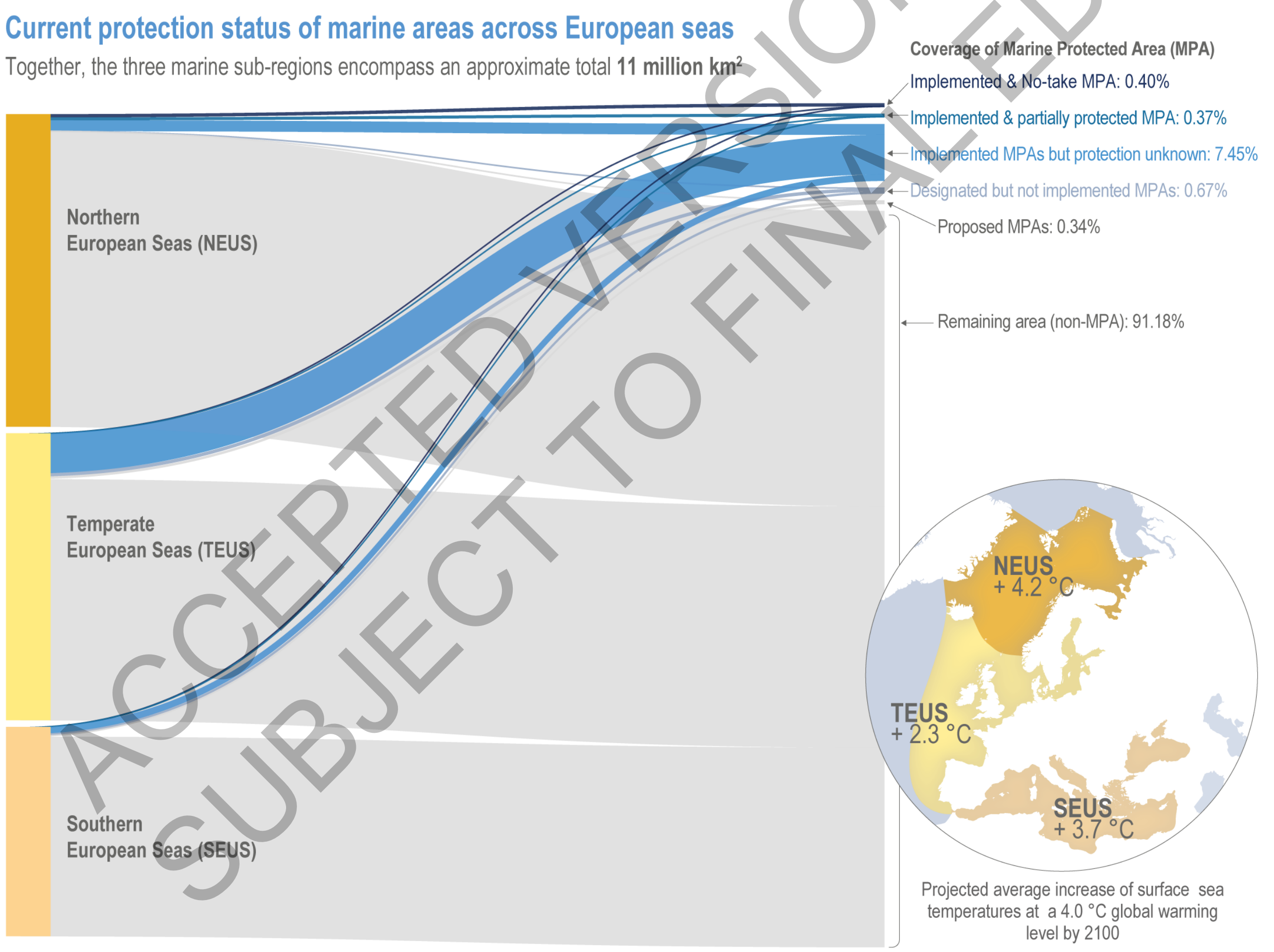

Figure 13.12: Marine Protected Areas (MPA) in European seas. Proportions of designated and proposed MPAs in the total areas of northern (NEUS), temperate (TEUS) and southern (SEUS) European seas, as well as the shares of no-take, partial, unimplemented and unknown protection levels of designated MPAs (Marine Conservation Institute, 2021). Moreover, the average increase of surface-sea temperatures (SST) at 4.0°C GWL by 2100 in NEUS, TEUS and SEUS is indicated.

Conservation approaches (MPAs, climate refugia), habitat restoration efforts (Bekkby et al., 2020), and further ecosystem-based management policies do support alleviation of or adaptation to climate-change impacts (*medium confidence*) but are themselves impacted by climate change (Chapter 3). Moreover, the interaction of adaptation and mitigation measures poses risks to marine systems. 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 protect human infrastructure against sea level rise (Section 13.2) will lead to loss of coastal habitats, with negative impacts on marine biodiversity (Cross-Chapter Box SLR in Chapter 3, Airoldi and Beck, 2007; Cooper et al., 2016). While rising sea levels will also directly threaten intertidal and beach ecosystems, coastal wetlands will benefit (*medium confidence*), in case lateral accommodation space and the opportunity for systems to migrate landwards and upwards is provided, enhancing their ability to capture and store carbon (Rogers et al., 2019) (WGIII AR6 Chapter 4). In general, European coastal blue-carbon ecosystems, e.g. seagrass meadows, kelp forests, tidal marshes (Bekkby et al., 2020) are potentially effective as carbon sinks in climate mitigation, akin to reforestration efforts on land (section 13.3). However, their expansion has the potential to interfere with other ecosystem services (Cadier et al., 2020) and biodiversity conservation (Howard et al., 2017; Chausson et al., 2020). The 'Blue Growth' strategy of the European Commission with the aim to increase offshore activities (European Comission, 2012) will increase the pressures on the marine environments (*medium confidence*). Large-scale offshore wind-park infrastructure is currently developed in European seas, mostly in the North Sea (WindEuropeBusinessIntelligence, 2019), as a major component of climate-change mitigation efforts (WGIII AR6 Chapter 6). The introduction of novel hard-substrate intertidal habitats has and will have profound ecological ramifications for marine systems, including hydrodynamic changes, stepping-stones for non-native species, noise and vibration, and changes of the food web (Lindeboom et al., 2011; De Mesel et al., 2015; Gill et al., 2018; Dannheim et al., 2019) (*high confidence*).

13.4.3 Knowledge Gaps

Major knowledge gaps are uncertainties and shortcomings in our understanding of combined, cascading and interacting impacts of climatic and non-climatic pressures on European marine and coastal socio-ecological systems (Korpinen et al., 2021). Further observational, experimental, and modelling work will enhance the insight into multiple drivers, processes and their interactions, strengthen the confidence of risk projections and provide a foundation for future adaptation actions.

There is limited knowledge about the connectivity among populations, species, and ecosystems which would provide new recruits, enable gene flow in Marine Protected Areas (MPA) networks (Dubois et al., 2016; Sahyoun et al., 2016), and facilitate assisted migration. MPAs cover a wide range of protection status with *limited evidence* which level of protection and connectivity is needed to achieve adaptations goals in response to future warming.

Although European seas and coasts are comparatively well-studied on a global scale, the spatial and temporal resolution and coverage of open-access data is still limited in many regions, particularly in eastern Europe. The detection and attribution of ongoing or emerging environmental and biological changes is therefore limited. Some efforts are in place, such as the six 'Sea-basin Checkpoints' (North Sea, Mediterranean Sea, Arctic, Atlantic, Baltic, Black Sea) that were established since 2013 under The European Marine Observation and Data Network, but high quality observations of key ocean characteristics at the level of regional sea-basins are still too scarce to support decision-making for marine adaptation (Míguez et al., 2019).

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 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 the commodities produced and consumed in Europe traded internationally (FAOSTAT, 2019).

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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*). Warming and precipitation changes since 1990 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). 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 (13.2.1, 13.3.1, 13.10.2) increased costs and cause economic losses in forest productivity (Schuldt et al., 2020) and annual and permanent crops and livestock farming (Stahl et al., 2016), including losses in wheat production in the EU (van der Velde et al., 2018) and EEU (Ivanov et al., 2016; Loboda et al., 2017) (*high confidence*), with the severity of impacts from extreme heat and drought tripling over last 50 years (Brás et al., 2021). Meteorological extremes due to compound effects of cold winters, excessive autumn and spring precipitation, and summer drought caused production losses (up to 30% relative to trend expectations) 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). Regionally, warming caused 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 both wet conditions and earlier harvests in central Europe in response to warming impacted wine quality (Cook and Wolkovich, 2016; van Leeuwen and Darriet, 2016; Di Lena et al., 2019).

Evidence for growing regional differences of projected climate risks 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). At 1.5°C GWL, compound events which led to recent large wheat losses are projected to become 12% more frequent (Ben-Ari et al., 2018). Growing regions will shift northward or expand for melons (Bisbis et al., 2019), tomatoes and grapevines reaching NEU and EEU in 2050 under 1.5°C GWL (Hannah et al., 2013; Litskas et al., 2019) (*high confidence*), while warming would increase yields of onions, Chinese cabbage and French beans (Bisbis et al., 2019) (*medium confidence*). In response to 2°C GWL, agro-climatic zones in Europe are expected to move northward 25-135 km/decade, fastest in EEU (Ceglar et al., 2019). 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).

Reductions in agricultural yields will be higher in the south at 4°C GWL, with lower losses or gains in the north (Figure 13.5, Trnka et al., 2014; Webber et al., 2016; Szewczyk et al., 2018) (*high confidence*). Largest impacts of warming are projected for maize in SEU (Deryng et al., 2014; Knox et al., 2016) (*high confidence*) with yield losses across Europe of 10-25% at 1.5-2°C GWL and 50-100% at 4°C GWL (Deryng et al., 2014; Webber et al., 2018; Feyen et al., 2020).

Use of longer season varieties can compensate for heat stress on maize in WCE and lead to yield increases for Northern Europe, but not SEU for 4°C GWL (Siebert et al., 2017; Ceglar et al., 2019) (*medium confidence*). Irrigation can reduces projected heat and drought stress, e.g., for wheat and maize (Ruiz-Ramos et al., 2018; Feyen et al., 2020), but use is limited by water availability (13.2.1; KR3). The advantages of a longer growing season in NEU and EEU are outbalanced by the increased risk of early spring and summer heat waves (Ceglar et al., 2019).

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). Regionally predicted reduction in rainfall (13.1) can lead to carryover of herbicides (Karkanis et al., 2018).

Net yield losses will reduce economic output in the EU from agriculture, reaching a reduction of 7% for the EU and UK combined, and 10% in SEU at 4°C GWL (Naumann et al., 2021). Farmland values are projected to decrease by 5-9% per degree of warming in SEU (Van Passel et al., 2017). Increased heat and drought stress and reduced irrigation water availability will decreased profitability and cause abandonment of farmland in SEU (Holman et al., 2017) (*limited evidence, low confidence*).

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13.5.1.2 Livestock Production

Heat and humidity affect livestock directly exposed in open barns and outdoors, such as dairy cows and goats (Gauly et al., 2013; Bernabucci et al., 2014; Silanikove and Koluman, 2015), and cold adapted husbandry (Box 13.2, Section 13.8.3) (*high confidence*). 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, particularly in SEU (Dumont et al., 2015) and EEU (Bezuglova et al., 2020), as well as altering the prevalence, distribution and load of pathogens and their vectors (2.4.2.7.3) (Morgan et al., 2013; Charlier et al., 2016) (*high confidence*). Projected impacts on poultry and pigs are low due to temperature control in large parts of Europe, but greater in SEU where open systems prevail (Chapter 5).

Warming increases the pasture growing season and farming period in NEU and at higher altitudes (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) (*high confidence*) (Section 13.8.3). At 2-4°C GWL grassland biomass production for forage-fed animals will increase in NEU and the northern Alps, while forage production will decrease in SEU and the southern Alps due to heat and water scarcity (Gauly et al., 2013; Jäger et al., 2020), causing regional reductions of cow milk production in WCE and SEU (Silanikove and Koluman, 2015) (*high confidence*).

13.5.1.3 Aquatic Food Production

Seafood production in Europe provides jobs for >250,000 people, predominantly in SEU (Carvalho et al., 2017). Marine fisheries contribute 80% to European aquatic food 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).

Climate change has impacted European marine food production (*high confidence*). However, extraction is still the major impact on commercially important fish stocks in Europe (Mullon et al., 2016), with 69% of 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 by warming with losses of 15-35% in maximum sustainable yields (MSY) during the last decades (Free et al., 2019). Warming caused ongoing northward movement and range expansion of Northeast Atlantic fish stocks (13.4, Baudron et al., 2020). In the North Sea, cuttlefish (van der Kooij et al., 2016; Oesterwind et al., 2020) and tuna (Bennema, 2018; Faillettaz et al., 2019) became new target species (*medium confidence*). In SEU, warm-water species increasingly dominate fisheries landings (Fortibuoni et al., 2015; Teixeira et al., 2016; Vasilakopoulos et al., 2017).

European countries are assessed to be globally among the least vulnerable to the impacts of climate change on fisheries-related food security risks (*high confidence*) due to low levels of exposure to climate hazards, low dependency of economies on fisheries and a high adaptive capacity (Barange et al., 2014; Ding et al., 2017). European freshwater production is suggested to be less vulnerable than marine sectors and marine production vulnerability increases with latitude (Blanchet et al., 2019). In the aquaculture sector Norway is highly vulnerable due to high sensitivity of salmon farming to warming and high per-capita production (Handisyde et al., 2017). In the fisheries sector, vulnerability for fishing communities is highest in SEU and UK (Figure 13.9A , Handisyde et al., 2017; Payne et al., 2021), while for aquaculture sectors it is highest in SEU and some NEU and WCE countries (Figure 13.9B, 2020).

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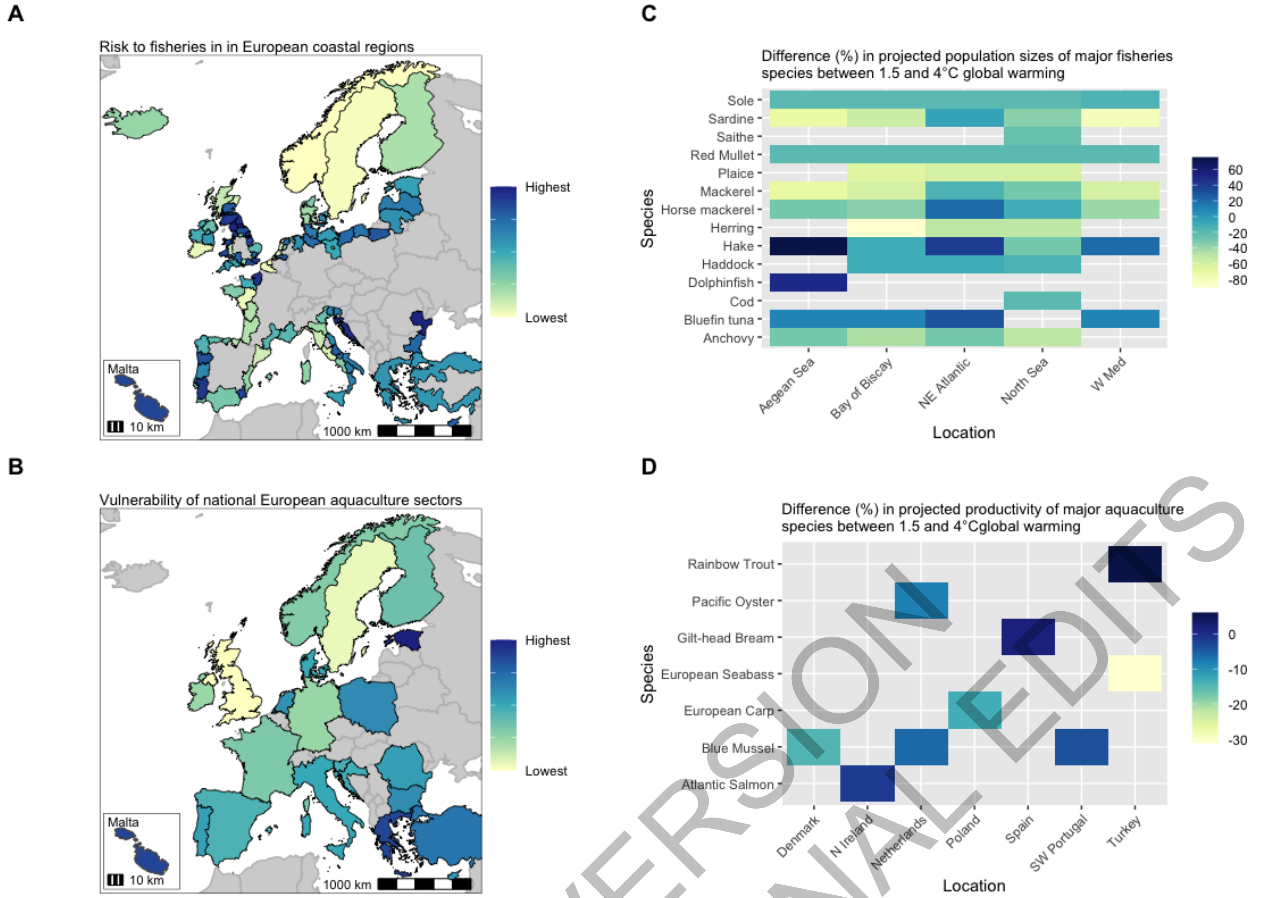

Figure 13.13: Future vulnerability and risks for aquatic food production. (a) Vulnerability for fisheries in 105 coastal regions across 26 countries based on biological traits and physiological metrics of 556 resource populations (Payne et al., 2021); (b) Vulnerability of major aquaculture species in European countries on physiological attributes, farming methods and economic output (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) changes in abundance of major fish species by region, and (d) changes in productivity of major aquaculture species by country.

Future vulnerabilities, risks and opportunities are projected to strongly vary regionally and between major fisheries and aquaculture species (Peck et al., 2020) (Figure 13.13 c,d). Assuming MSY-management, projections suggest reduced abundance of most commercial fish stocks in European waters of 35% (up to 90% for individual stocks) between 1.5°C and 4.0°C GWL (Peck et al., 2020; Payne et al., 2021) (*medium confidence*) (Figure 13.13). In response to 4°C GWL, higher trophic level biomass is projected to increase in the SEUS mainly due to increases of small pelagic and thermophilic, often exotic species (Moullec et al., 2019).

Ocean acidification (Section 13.4, Chapter 4) will develop into a major risk for marine food production in Europe under 4°C GWL (*high confidence*), affecting recruitment of important European fish stocks such as those of cod in the Western Baltic and Barents Sea by 8 and 24%, respectively (Sswat et al., 2018b; Stiasny et al., 2018; Voss et al., 2019). Acidification is also projected to negatively affect marine shellfish production and aquaculture in Europe with 4°C GWL (*medium confidence*) (Fernandes et al., 2017; Narita and Rehdanz, 2017; Mangi et al., 2018).

13.5.1.4 Forestry and Forest Products

Climate change is altering the structure and function of European forests via changes in temperature, precipitation and atmospheric CO_2 as well as through interaction with pests and fire (13.3.1) (Moreno et al., 2018; Morin et al., 2018; Senf et al., 2018; Orlova-Bienkowskaja et al., 2020) (*high confidence*). 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 (Reyer et al., 2014; Kellomäki et al., 2018). While warming and extended growing seasons have positive impacts on forest

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growth in cold areas in WCE and NEU (Pretzsch et al., 2014; Matskovsky et al., 2020), EEU (Tei et al., 2017) and higher altitude (Sedmáková et al., 2019), drought stress across Europe has been increasing (Primicia et al., 2015; Marqués et al., 2018; Ruiz-Pérez and Vico, 2020) (*high confidence*). Combined with land-use, climate change has increased large scale forest mortality since the 1980s (Senf et al., 2018). Extreme events such as the 2018 drought in WCE caused widespread leaf shedding and mortality of trees (Buras et al., 2020) with carryovers into 2019 (Schuldt et al., 2020) and bark beetle outbreaks (Netherer et al., 2019) resulting in felling and cuttings of more than 1 Million ha of spruce forest and disrupting timber markets (Mauser, 2021).

In response to 3°C GWL, forest productivity is projected to increase in NEU and altitudes, show mix trends in WCE and decreases in SEU (Reyer et al., 2014) (*medium confidence*). This trend is driven by increases in productivity of pine and spruce and decreases of beech and oak and excludes disturbances and management options (Reyer et al., 2014). Water stress exacerbates the incidence from and effects of fire and other natural disturbances (13.3.1), resulting in forest productivity declines or cancelling out productivity gains from CO_2 (Seidl et al., 2014; Reyer et al., 2017) (*high confidence*). In response to 1.7 °C GLW, managed forest and unmanaged woodland areas are projected to decrease only minimally, while at >2.5°C GLW declines increasing for managed forest and unmanaged woodland area increases (Harrison et al., 2019). Reducing warming from 4°C GLW to below 1.7 °C GLW would reduce the Europe wide impacts on managed forest by 34% (Harrison et al., 2019).

13.5.2 Solution Space and Adaptation Options

The solution space for climate change adaption for food and timber includes production related options (13.5.2.1 - 13.5.2.3) and market-based changes to consumer demand and trade (13.5.2.4). The assessment of effectiveness and feasibility of options in the food system is summarised in Figure 13.14.

Effectiveness & feasibility of adaptation options for food system to climate impacts & risk in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility: Economic	Technological	Institutional	Socio-cultural	Ecological	Geophysical	Confidence: Evidence	Agreement
Heat stress	Irrigation	M	M	H	M	L	L	L	M	M
	Change of sowing/harvest date	M	H	H	NL	M	M	H	H	M
	Change of cultivars	L	M	M	NL	M	M	H	M	M
Drought	Irrigation	H	H	M	M	H	L	L	H	H
	Change of sowing/harvest date	M	H	H	NL	M	M	H	M	M
	Change of cultivars	L	M	M	NL	M	M	H	H	M
	Soil management	M	M	M	H	M	H	M	L	M
Flooding	Change of sowing/harvest date	L	L	M	NL	H	M	L	L	M
Compound & extreme weather	Plant & livestock breeding, including GMO	M	M	L	L	M	M	M	M	M
	Mixed use - agroecology & agroforestry	H	M	M	L	L	H	M	M	M
	Agricultural policy changes	M	M	M	M	M	M	H	L	H
	Training & information	L	M	NL	M	M	M	H	L	M
	Crop selection changes	M	H	H	NL	L	L	L	L	L
	Land cover change, incl. agricultural land abandonment	L	M	M	L	L	L	L	L	L
Disease pathogen & vectors	Plant & livestock breeding, including GMO	NL	NL	L	L	L	NL	NL	L	NL
	Management, including high frequency rotations	NL	NL	NL	NL	NL	NL	NL	L	NL
Combined impacts on productivity	International trade changes	M	M	NL	L	M	L	M	L	M
	Consumer shifts in consumption	NL	M	NL	NL	L	NL	NL	L	M

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.14: Effectiveness and feasibility of the main adaptation options for food systems in Europe. (SM13.9 and Table SM13.5).

13.5.2.1 Crops and Livestock

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Farm management adaptations options to climate change include changing sowing and harvest dates, changes in cultivars, irrigation and selecting alternative crops (Figure 13.14, 13.15) (Donatelli et al., 2015). Irrigation is effective at reducing yield loss from heat stress and drought, e.g., for wheat and maize (Figure 13.14, 13.15), but increases demand for water withdrawals (Siebert et al., 2017; Ruiz-Ramos et al., 2018; Feyen et al., 2020). Where sufficient water and infrastructure is available, irrigation of wheat reverses yield losses across Europe at 2°C GWL to become gains, while yield losses in maize in SEU are reduced from up to 80% to 11% (Feyen et al., 2020). 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 (KR3, 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 have successfully been used in the 2018 drought for European wheat (van der Velde et al., 2018).

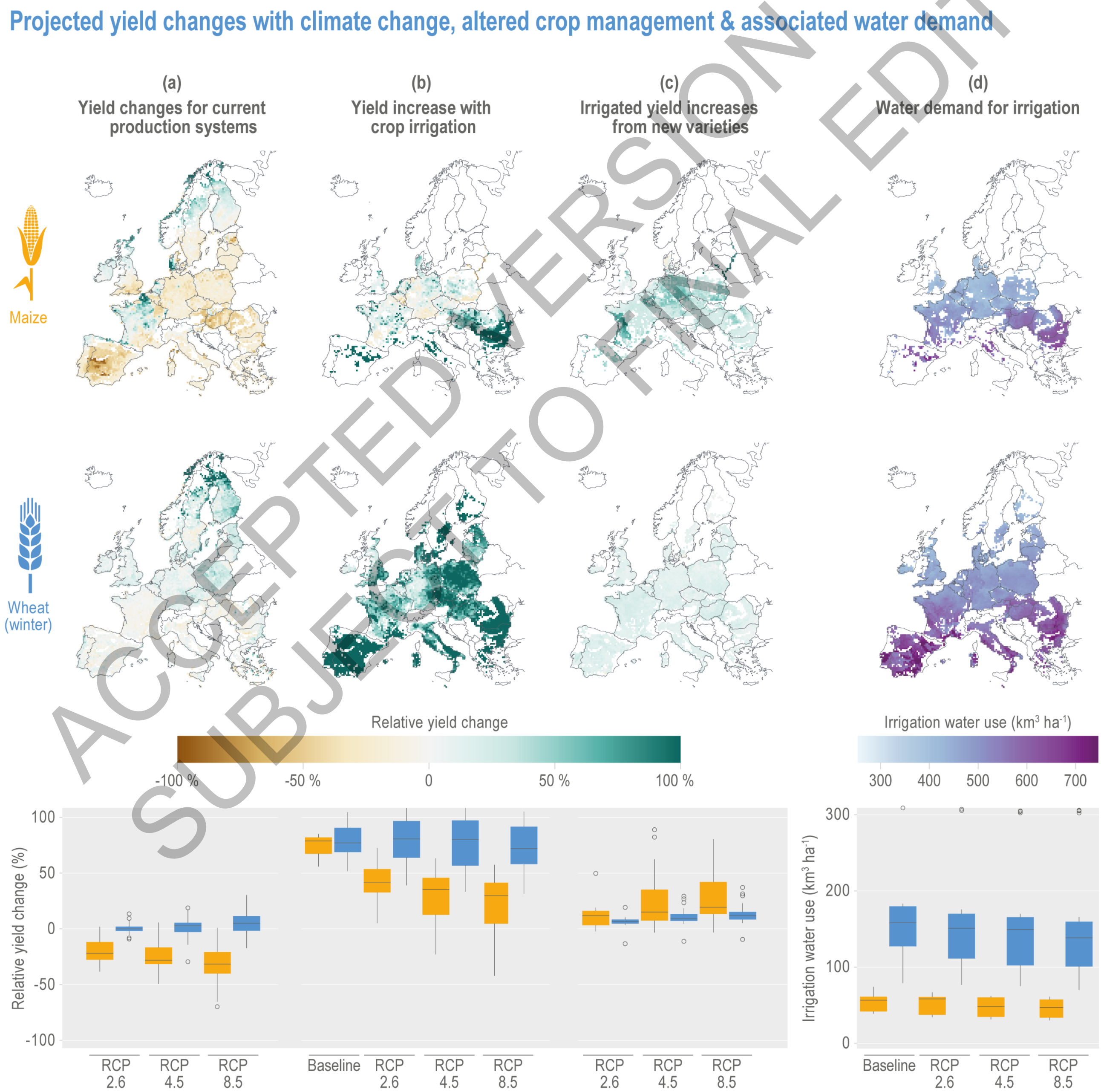

Figure 13.15: Projected yield changes with climate change for 1.5 °C GWL (RCP 2.6), 1.7 °C (RCP4.5) and 2°C GWL (RCP8.5) and altered crop management, and associated water demand, showing: (a) relative yield changes under climate change and elevated CO_2 for current production systems, i.e. rainfed and irrigated simulations weighted by

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current share of rainfed and irrigated areas; (b) yield increase if current predominantly rainfed areas are full irrigated; (c) additional yield increases for irrigated production systems if new varieties used to avoid losses associated with faster development and earlier maturity under climate change; and, (d) water demand for irrigated systems with current varieties in currently rainfed areas (Webber et al., 2018). Relative yield changes to a period centred on 2055 to a baseline period centred on 1995. Boxplots are Europe aggregate results considering current production areas (a) or current rainfed areas (b, c) with boxplots showing uncertainty across crop models and GCMs. The maps are for the crop model median for RCP 4.5 (1.7°C GWL) with GFDL-CM3.

Changes to cultivars and sowing dates can reduce yield losses (Figure 13.15), but are insufficient to fully ameliorate losses projected >3℃ GWL, with an increase of risk from north to south and for crops growing later in the season such as maize and wheat (*high confidence*) (Ruiz-Ramos et al., 2018; Feyen et al., 2020). Adaptations for early maturing reduce yield loss by moving the cycle towards a cooler part of year, and also constrains the increases in irrigation water demands, but reduce the period for photosynthesis and grain filling (*high confidence*) (Ruiz-Ramos et al., 2018; Holzkämper, 2020). Crop breeding for drought and heat tolerance can improve sustainability of agricultural production under future climate (Costa et al., 2019), particularly in SEU where drought tolerant varieties provide 30% higher yields than drought-sensitive varieties at 3°C GWL (Senapati et al., 2019). 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 adaptation in 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 (Gauly et al., 2013), but limited in mountain pastures (Deléglise et al., 2019) (*high confidence)*. 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; EEA, 2019c), 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) (*medium confidence*). Genetic adaptation of crops, pasture and animals could be a long-term adaptation strategy (Anzures-Olvera et al., 2019; Deléglise et al., 2019). 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), and regulations to ensure safe trade and reduce risks of introducing or spreading pests (European Comission, 2016).

Agro-ecological systems provide adaptation options that 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 , Aguilera et al., 2020). 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 (Chapter 5), but implementation in Europe needs improved training programs and policy support (Hernández-Morcillo et al., 2018) (*high confidence*).

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 include simplifying procedures for obtaining subsidies and insurance premiums and interest rates that incentivise adoption of climate friendly agricultural methods (Garrote et al., 2015; Iglesias and Garrote, 2015; Zakharov and Sharipova, 2017; Hamidov et al., 2018; Wiréhn, 2018). The EU's Common Agricultural Policy has increasingly focused on environmental outcomes (AllianceEnvironnement, 2018) but does not sufficiently provide for adaptation measures (Leventon et al., 2017; Pe'er et al., 2020). Limits to European farm-level adaptation include lack of resources for investment,

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political urgency to adapt, institutional capacity, access to adaptation knowledge and information from other countries (EEA, 2019c).

13.5.2.2 Aquatic Food

Climate-resilient fish production in Europe is the goal of the European Union's Common Fisheries Policy (CFP) rebuilding fish stocks to maximum sustainable yield (MSY) levels, but success has been variable (Froese et al., 2018; Stecf, 2019). Adaptation is largely ignored in related EU policy frameworks such as the CFP, the Marine Strategy Framework Directive, and the "Strategic guidelines for the sustainable development of EU aquaculture." (Pham et al., 2021). A major governance challenge for adaptation will be the redistribution of the fixed allocation scheme for total allowable catches (Harte et al., 2019; Baudron et al., 2020). Inflexible and non-adaptive allocation schemes can result in conflicts among European countries (*medium confidence*), as demonstrated by the case of the North East Atlantic mackerel (Spijkers and Boonstra, 2017).

The development of adaptation strategies for seafood production since the Paris Agreement is insufficient in Europe (*high confidence*) (Kalikoski et al., 2018; Pham et al., 2021). Concrete plans for adaptation planning towards climate-ready fisheries and aquaculture are lacking in all parts of Europe (European Comission, 2018), 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).

Recent scientific progress towards adaptation in European fisheries and aquaculture include conceptual guidance and demonstration cases on climate adaptation planning (Pham et al., 2021) and climate vulnerability assessments (Blanchet et al., 2019; Peck et al., 2020; Payne et al., 2021). Socio-political scenarios for European aquatic resources have been developed and have the potential to inform adaptation planning by European fisheries and aquaculture sectors (Kreiss et al., 2020; Hamon et al., 2021; Pinnegar et al., 2021).

13.5.2.3 Forests

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). Successful adaptation strategies include altering the tree species composition to enhance the resilience of European forests (Schelhaas et al., 2015; Zubizarreta-Gerendiain et al., 2017; Pukkala, 2018) (*high confidence*). 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 confidence*). 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 confidence*). Conservation areas can also help climate change adaptation by keeping the forest cover intact, creating favourable microclimates and protecting biodiversity (Jantke et al., 2016) (*low confidence*).

Reforestation reduces warming rates (Zellweger et al., 2020) and extremely warm days (Sonntag et al., 2016) inside forests reducing natural disturbances and fires (*high confidence*). Active management approaches can limit the impact of fires (13.3.1) on forest productivity, including fuel reduction management, prescribed burning, changing from conifers to deciduous, less flammable species, and recreating mixed forests (Feyen et al., 2020) and agroforestry (Damianidis et al., 2020).

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; Ercin et al., 2021). Consumer demand for food and timber products can adapt to productivity changes and be mediated by price (e.g., in response to production changes or policies on food related taxation), 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

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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 strong driver for change (Harrison et al., 2019, Kebede, 2021, Integrated assessment of the food-water-land-ecosystems nexus in Europe: Implications for sustainability) (*medium confidence*). 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).

13.5.3 Knowledge Gaps

Aggregated projections of impacts, especially of combined hazards, 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 developed (Mitter et al., 2019). Effectiveness of adaptation options is predominantly qualitatively mentioned but not assessed and effectiveness of combinations of measures is rarely assessed (Ewert et al., 2015; Holman et al., 2018; Müller et al., 2020) (*high confidence)*. Effective adaptation planning would be supported by 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 the eastern part of WCE and EEU, despite dramatic changes in land use over the recent decades in Russia and Ukraine (*high confidence*) which have the potential to increase production and export of agricultural products, especially wheat, meat and milk (Swinnen et al., 2017).

A bias towards modelling of cereals, specifically wheat and maize, results in gaps in knowledge for fruit and vegetables, especially for temperate regions in Europe (Bisbis et al., 2019). The assessment of irrigation needs and the impact of CO_2 and O_3 tend to focus on individual species and processes hindering upscaling to multiple stressors and mixed production (Challinor et al., 2016; Webber et al., 2016) (*high confidence*).

There is a lack of actionable adaptation strategies for European fisheries and aquaculture. 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

Urban areas in Europe offer home to 547 million inhabitants, corresponding to 74% of the total European population (UN/DESA, 2018). In the EU-28, 39% of the total population lives in metropolitan regions (i.e., areas with at least one million inhabitants) where 47% of the total GDP is generated (Eurostat, 2016). Apart from urban settlements, this section also covers energy and transport systems, as well as tourism, industrial and business sectors which are key for livelihood, economic prosperity and well-being of residents.

13.6.1 Observed Impacts and Projected Risks

13.6.1.1 Energy Systems

The energy sector in Europe already faces impacts from climate extremes (*high confidence*). Significant reductions and interruptions of power supply have been observed during exceptionally dry and/or hot years of the recent 20-year period, e.g. 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., 2016b; Abi-Samra, 2017; Vogel et al., 2019). Heating degree days decreased and cooling degree days increased during 1951-2014, with clearer trends after 1980 (De Rosa et al., 2015; Spinoni et al., 2015; EEA, 2017b). Projected climate risks for energy supply are summarized in Figure 13.16.

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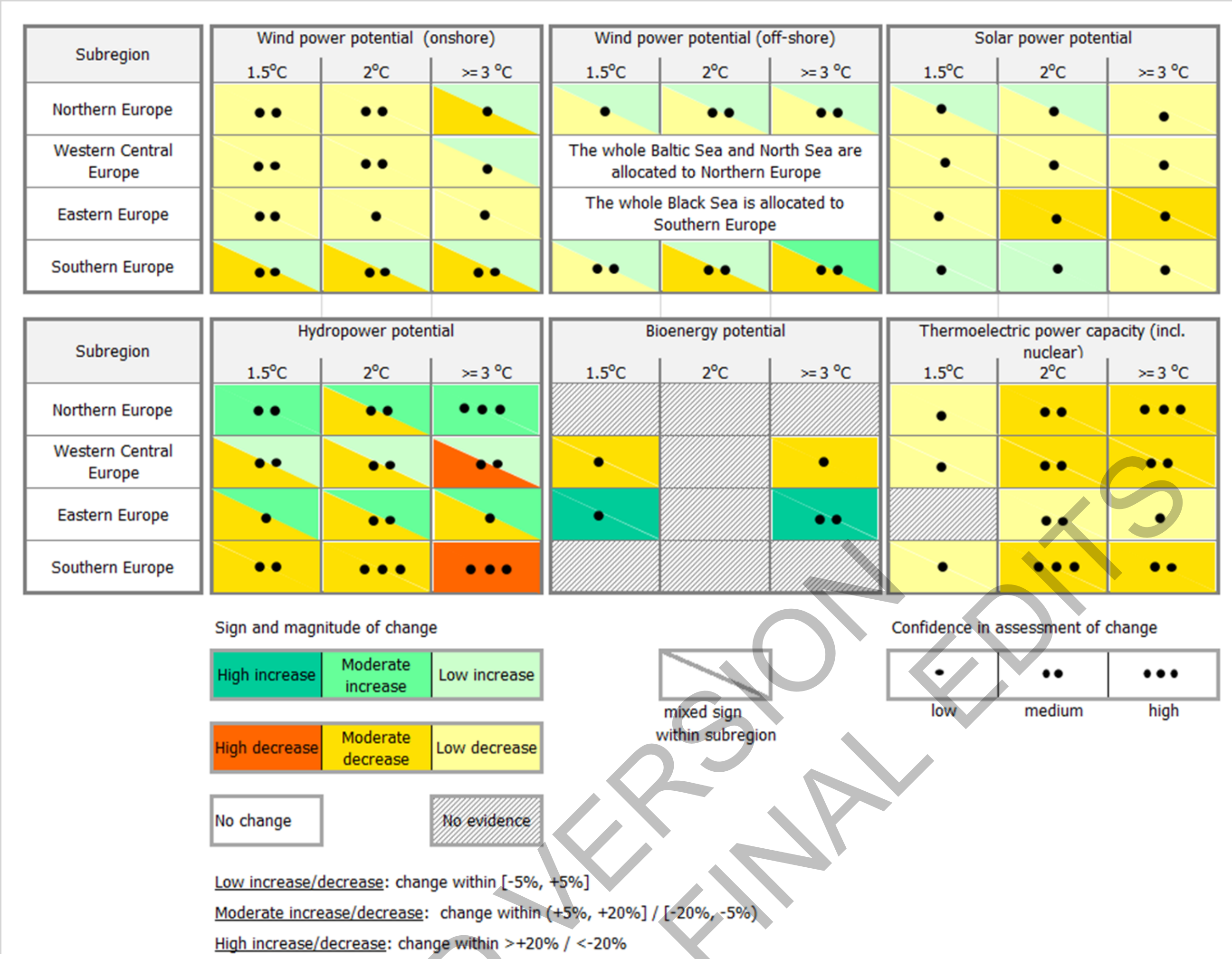

Figure 13.16: Projected climate change risks for energy supply in Europe for major sources and under 1.5 °C, 2 °C and >3 °C GWL (Tables SM13.5.6-13).

New studies reinforce the findings of AR5 on risks for thermoelectric power and regional differences between NEU and SEU regarding risks for hydropower (Figure 13.16). In NEU and EEU, extremely high water inflows to dams are projected to increase flooding risks for plant and nearby settlements (Chernet Haregewoin et al., 2014; Porfiriev et al., 2017), while increasing temperatures could reduce the efficiency of steam and gas turbines (Porfiriev et al., 2017; Cronin et al., 2018; Klimenko et al., 2018a). Water scarcity may limit onshore carbon capture and storage in some regions (Byers et al., 2016; Murrant et al., 2017; EEA, 2019a).

Reduced surface wind speeds during 1979-2016 (Frolov et al., 2014; Perevedentsev and Aukhadeev, 2014; Tian et al., 2019) support projected trends in decreasing onshore wind energy potential. Seasonal changes may result in reductions in many areas in summer (by 8-30% in Southern Europe) and increases in most of NEU during winter. Increasing probabilities and persistence of high winds over the Aegean and Baltic Seas (Weber et al., 2018a) could create new opportunities for offshore wind. The future configuration of the wind fleet will affect the spatial and temporal variability of wind power production (Tobin et al., 2016). 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 *low evidence* and *limited agreement* on projections of solar power potential due to differences in the integration of aerosols and the estimated cloud cover between climate models (Bartok et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020). Studies on climate risks for bioenergy are also limited.

Energy demand is projected to display regional differences in response to global warming beyond 2°C GWL, with a the significant southwest-to-northeast decrease of heating degree days by 2100 (particularly in northern Scandinavia and Russia), and a smaller north-to-south increase of cooling degree days (Porfiriev et

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al., 2017; Spinoni et al., 2018; Coppola et al., 2021). Under present population numbers, total energy demand would decrease in almost all Europe, whereas it could increase in some countries (e.g. UK, Spain, Norway) when considering Eurostat's population projections (Klimenko et al., 2018b; Spinoni et al., 2018).There is *medium confidence* that peak load will increase in SEU and decrease in NEU (Damm et al., 2017; Wenz et al., 2017; Bird et al., 2019). Beyond 2ºC GWL, a shift of peak load from winter to summer in many countries is possible (Wenz et al., 2017). Together with water-cooling constraints for thermal power, this change in load may challenge the stability of electricity networks during heatwaves (EEA, 2019a). Technological factors, increased electricity use and adaptation 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). Potential power curtailments or outages during climatic extremes may increase electricity prices (Pechan and Eisenack, 2014; Steinhäuser and Eisenack, 2020).

13.6.1.2 Transport

Heatwaves in 2015 and 2018 in parts of WCE and NEU caused road melting, railway asset failures, and speed restrictions to reduce the likelihood of track buckling (Ferranti et al., 2018; Vogel et al., 2019). Recent studies on projected risks focus mainly on infrastructure and much less on transport flows and disruptions.

Sea level rise (section 13.2) may disrupt port operations and surrounding areas, mainly in parts of NEU and WCE (Christodoulou et al., 2018), while changes of waves agitation could increase non-operability hours of some Mediterranean ports beyond 2°C GWL (Sierra et al., 2016; Camus et al., 2019; Izaguirre et al., 2021). Low water level days at some critical locations for inland navigation at the Rhine river are projected to increase beyond 2ºC GWL, while decreases at the Danube river are possible (van Slobbe et al., 2016; Christodoulou et al., 2020).

Risks of rutting and blow-ups of roads (particularly in low altitudes) due to high summer temperatures are expected to increase in WCE and EEU at 3ºC GWL (*medium confidence*) (Frolov et al., 2014; Matulla et al., 2018; Yakubovich and Yakubovich, 2018). In EEU and northern Scandinavia, the higher number of freezing-thawing cycles of construction materials will increase risks for roads (Frolov et al., 2014; Yakubovich and Yakubovich, 2018; Nilsen et al., 2021) while warming beyond 2ºC GWL could significantly reduce road maintenance costs in NEU (Lorentzen, 2020), but limiting off-road overland transport in north-western Russia (Gädeke et al., 2021). Beyond 3ºC GWL, more frequent hourly precipitation extremes are projected over WCE and NEU in summer (e.g. 2-fold and 10-fold increase for events exceeding the present-day 99.99th percentile in Germany and UK) but more widely across Europe in autumn and winter (increase higher than 10-fold for 99.99th percentile events in southern Europe in autumn (Chan et al., 2020), potentially severely damaging roads as happened in Mandra, Greece in 2017 (Diakakis et al., 2020). Landslide risks in WCE and SEU could increase beyond a 2ºC GWL, threatening road networks (Schlogl and Matulla, 2018; Rianna et al., 2020).

Current flood risk for railways could double or triple at 1.5-3°C GWL, particularly in WCE, increasing public expenditure for rail transport in Europe by €1.22 billion annually under 3°C GWL and no adaptation (Bubeck et al., 2019). Thermal discomfort in urban underground railways is expected to increase, even at a high level of saloon 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 and Mediterranean coasts (Christodoulou and Demirel, 2018). Rising temperatures reducing lift generation could impose weight restrictions for large aircraft at 2ºC GWL and beyond in airports of France, UK and Spain (Coffel et al., 2017). There is a lack of studies quantifying the effect of future extreme events on flight arrivals at and departures from European airports.

13.6.1.3 Business and Industry

European industrial and service sectors contribute 85% to Gross Value Added in EU-28 (Eurostat, 2020); while their direct exposure and vulnerability is smaller compared to sectors directly reliant on weather, they are directly and indirectly affected by heat, flooding, water scarcity and drought (Weinhofer and Busch, 2013; Gasbarro and Pinkse, 2016; Meinel and Schule, 2018; Schiemann and Sakhel, 2018; TEG, 2019). Heat

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reduces the productivity of labour particularly in construction, agriculture and manufacturing (García-León et al., 2021; Schleypen et al., 2021) (section 13.7.1). Direct losses from floods in Europe are highest for manufacturing, utilities, transportation; indirect losses arise e.g. for manufacturing, construction, and banking and insurance (Koks et al., 2019a; Sieg et al., 2019; Mendoza-Tinoco et al., 2020). Drought and water scarcity directly affect European industries in the sectors of pulp and paper, chemical and plastic manufacturing and food and beverages (Gasbarro et al., 2019; Teotónio et al., 2020); additionally, drought may indirectly affect sectors relying on shipping, hydropower, or public water supply (Naumann et al., 2021). The European financial and insurance sector is affected by climate change impacts via 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).

The vulnerability to climate hazards varies by European region, type of risk, sector and business characteristics (Gasbarro et al., 2016; Forzieri et al., 2018; ECB, 2021a; Kouloukoui et al., 2021). Current damages are mainly related to river floods and storms, but heat and drought will become major drivers in the future (*medium confidence*); until 2050, the probability of default of firms located in particularly exposed locations may increase to up to four times of that of an average firm in all sectors (ECB, 2021a).

Many European sectors are exposed to multiple and cross-cutting risks (Gasbarro et al., 2019; Schleypen et al., 2021). Indirect effects via supply chains, transport and electricity networks can be as high as or substantially higher than direct effects (*medium confidence*) (Koks et al., 2019a; Koks et al., 2019b; Knittel et al., 2020).

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; Matiu et al., 2021). Despite snowmaking, the number of skiers to French resorts at low elevations during the extraordinary warm/dry winters of 2006/2007 and 2010/2011 was 12-26% lower (Falk and Vanat, 2016).

Due to reduced snow availability and hotter summers, damages are projected for the European tourism industry, with larger losses in SEU (*high confidence*) and some smaller gains in the rest of Europe (*medium confidence*) (Ciscar et al., 2014; Roson and Sartori, 2016; Dellink et al., 2019).

At 2°C GWL, the operation of low altitude resorts without snowmaking will *likely* be discontinued, while beyond 3°C GWL snowmaking will be a necessary but not always sufficient for most resorts in many European mountains and parts of NEU (Pons et al., 2015; Joly and Ungureanu, 2018; Scott et al., 2019; Spandre et al., 2019). Expanding snowmaking is capital-intensive and will strongly increase water and energy consumption, particularly at 3°C GWL and beyond (Spandre et al., 2019; Morin et al., 2021), adversely affecting the financial stability of small resorts (Pons et al., 2015; Falk and Vanat, 2016; Spandre et al., 2016; Joly and Ungureanu, 2018; Moreno-Gené et al., 2018; Steiger and Scott, 2020). Permafrost degradation due to rising temperatures is expected to create stability risks for ropeway transport infrastructure at high-altitude Alpine areas (Duvillard et al., 2019).

Climatic conditions from May to October at 1.5-2°C GWL are projected to become more favourable for summer tourism in NEU and parts of WCE and EEU, while there is *medium confidence* on opposite trends for SEU from June to August (Grillakis et al., 2016; Scott et al., 2016; Jacob et al., 2018; Koutroulis et al., 2018). The amenity of European beaches may decrease as a result of sea level rise amplifying coastal erosion and inundation risks, although less in NEU (Ebert et al., 2016; Toimil et al., 2018; Lopez-Doriga et al., 2019) (Section 13.2 and Ranasinghe et al., 2021 Section 12.4.5).

13.6.1.5 Built Environment, Settlements and Communities

Expected shift of European residents to large cities and coastal areas will increase assets at risk (Section 13.2). The share of urban population in Europe is projected to increase from 74% in 2015 to 84% in 2050, corresponding to 77 million new urban residents (UN/DESA, 2018), with most of this increase in SEU and WCE (particularly in Turkey and France). In the EU-28, urban residents in 2100 may increase by about 30 million under SSP1 and SSP5, and decrease by 90-110 million under SSP3 and SSP4 (Terama et al., 2019).

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About 32% of 571 European cities in the GISCO Urban Audit 2014 dataset show a medium to high or relatively high vulnerability against heatwaves, drought and floods (Tapia et al., 2017). Under current vulnerabilities, future climate hazards will augment climate risks for several cities, particularly beyond 3°C GWL (Figure 13.17). In many NEU cities, a high increase in pluvial flooding risk by the end of the century is possible, while in WCE cities may face a high increase in pluvial flooding risks, moderate to very high increase in extreme heat risk, and to some extent moderate to high increase in drought risk. Many SEU cities could face a high to very high increase in risks from extreme heat and meteorological drought.

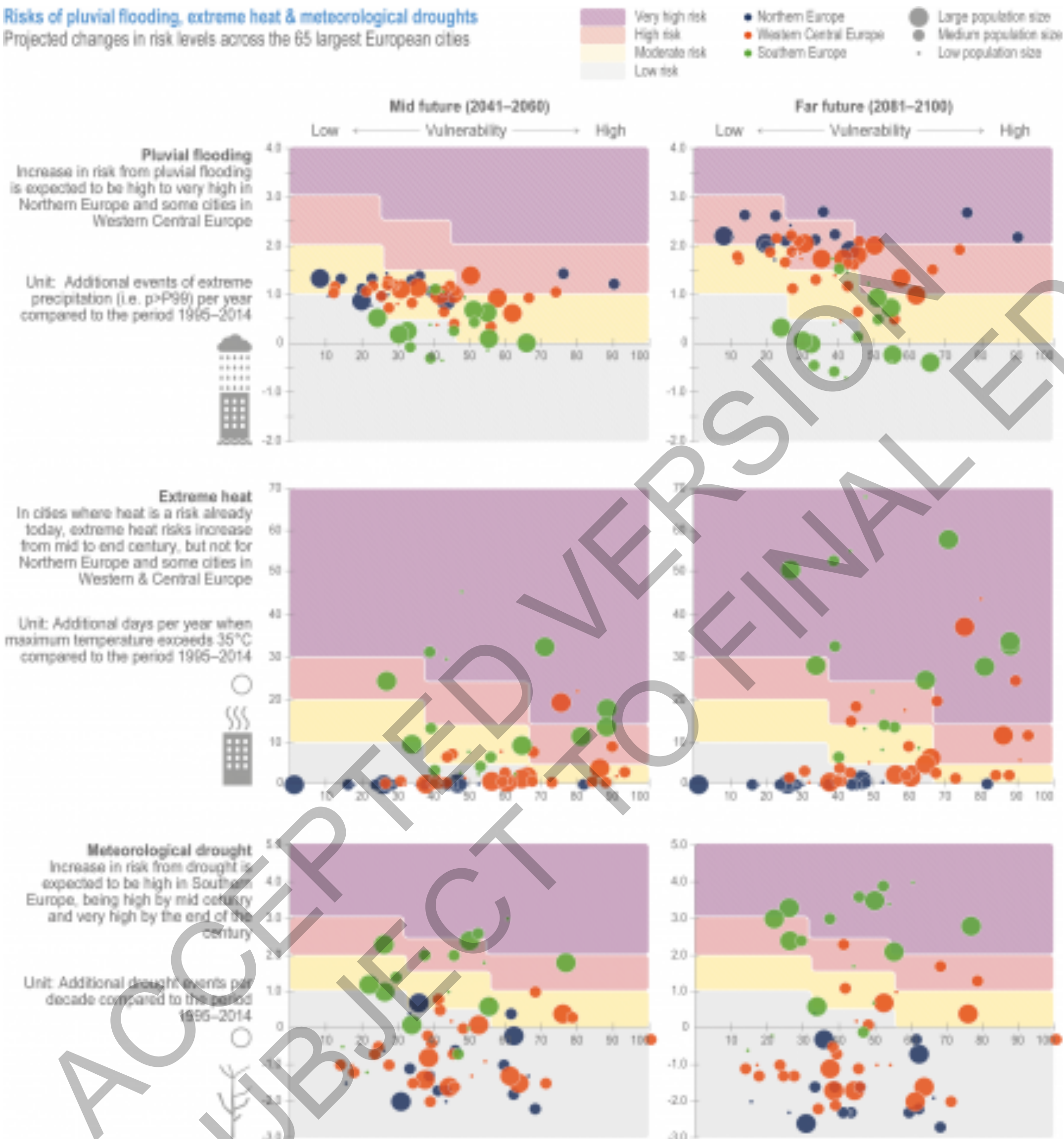

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Figure 13.17: Projected changes in pluvial flooding, extreme heat and meteorological drought risks for the 65 largest cities in EU-28 plus Norway and Switzerland for 2.5°C GWL and 4.4°C GWL compared with the baseline (1995-2014) (Tapia et al., 2017). Exposure is expressed in terms of current population. Values of climatic impact-drivers are derived from the Euro-CORDEX regional climate model ensemble.

13.6.1.5.1. Risks from coastal, river and pluvial flooding

New studies increase confidence in AR5 statements that flood damages will increase in coastal areas due to sea level rise and changing social and economic conditions (section 13.2.1.1). Except for areas affected by land uplift, 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).

In many cities, the sewer system is older than 40 years, potentially reducing their capacity to deal with more intense pluvial flooding (EEA, 2020c). Apart from climate change, urbanization is an important driver for increases in flooding risks as it results in growth of impervious surfaces. Flash floods are particularly challenging, causing the overburdening of drainage systems (Dale et al., 2018), urban transport disruptions, and health and pollution impacts due to untreated sewage discharges (Kourtis and Tsihrintzis, 2021).

More than 25% of the population in nearly 13% of the EU-cities lives within potential river floodplains. In many of these, e.g. 50% of UK cities, a significant increase of the 10-year high river flow is possible beyond 2°C GWL under a high-impact scenario (i.e. 90th percentile of projections) (Guerreiro et al., 2018; EEA, 2020c).

13.6.1.5.2 Risks from heatwaves, cold waves and drought

Heatwave days and number of long heatwaves increased in most capitals from 1998-2015 compared to 1980-1997 (Morabito et al., 2017; Seneviratne et al., 2021). In the summer of 2018, many cities suffered from heatwaves attributed to climate change (Vogel et al., 2019; Undorf et al., 2020). As a result, indoor overheating and reduced outdoor thermal comfort, often coupled with urban heat island (UHI) effect, have already impacted European cities (Di Napoli et al., 2018; EEA, 2020c) (see also Section 13.7.1).

Heatwaves are *likely* to become a major threat not only for SEU but also for WCE and EEU cities (Russo et al., 2015; Guerreiro et al., 2018; Lorencova et al., 2018; Smid et al., 2019).At 2ºC GWL and SSP3, half of1.1 the European population will be under very high risk of heat stress in summer (Rohat et al., 2019). The UHI effect will further increase urban temperatures (Estrada et al., 2017). In many cities, hospitals and social housing tend to be located within the intense UHI, thus increasing exposure to vulnerable groups (EEA, 2020c). There is *high confidence* that overheating during summer in buildings with insufficient ventilation and/or solar protection will increase strongly , with thermal comfort hours potentially decreasing by 74% in locations of southern Europe at 3ºC GWL (Jenkins et al., 2014a; Hamdy et al., 2017; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019; Shen et al., 2020). Highly insulated buildings, following present building standards, will be vulnerable to overheating, particularly under high GWL levels, unless adequate 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 NEU and WCE are more vulnerable due to limited solar shading and fewer air conditioning installations (Ward et al., 2016; Thomson et al., 2019). Cooling energy demand in SEU buildings has been projected to increase by 81-104% by 2035 and by 91-244% after 2065 compared to 1961-1990 depending on GWL (Cellura et al., 2018). Increases of 31-73% by 2050 and by 165-323% by 2100 compared to 1996-2005 were estimated for buildings in NEU (Dodoo and Gustavsson, 2016) with risks modified by adaptation (Viguié et al., 2020) (see section 13.6.2). Cold waves beyond 3ºC GWL will not represent an effective threat for European cities at the end of the century, and only a marginal hazard under 2ºC GWL (Smid et al., 2019).

At 2ºC GWL and beyond, cities in SEU and large parts of WCE would exceed the historical maximum 12-month Drought Severity Index of the past 50-years (on drought risks see Section 13.2) and 30% will have at least 30% probability of exceeding this maximum every month (Guerreiro et al., 2018). This could adversely affect the operation of municipal water services (Kingsborough et al., 2016). For example, under 2ºC GWL, the reservoir storage volume is predicted to decrease for all of England and Wales catchments, resulting in a probability of years with water use restrictions doubling by 2050 and quadrupling by 2100 compared to 1975-2004 (Dobson et al., 2020). 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 (13.3.1.3). High fuel load combined with proximity of the built environment to wildland highly increases fire risks (EEA, 2020c).

Extreme heat and drought causes shrinking and swelling of clays, threatening the stability of small houses in peri-urban environments (Pritchard et al., 2015), with damage costs of € 0.9-1 billion during the 2003 heatwave (Corti et al., 2011). In WCE and SEU, mean annual damage costs could increase by 50% for 2°C GWL, and by a factor of 2 for 3°C GWL (Naumann et al., 2021).

13.6.1.5.3 Risks from thaw of permafrost and mudflows

Increasing temperatures in NEU and the Alps lead to accelerated degradation of permafrost, negatively affecting the stability of infrastructures (Stoffel et al., 2014; Beniston et al., 2018; Duvillard et al., 2019). In

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the Caucasus, glacial mudflows due to permafrost degradation and modern tectonic processes pose a significant danger to the infrastructure (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, resulting to damages of buildings, roads and pipelines and to significant expenditure for stabilizing soils (Porfiriev et al., 2017; Konnova and Lvova, 2019). Beyond 3°C GWL, 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 northern EEU (Shiklomanov et al., 2017; Streletskiy et al., 2019). Increasing number of cycles of freezing and thawing, observed in EEU, led to accelerated aging of building envelopes (Frolov et al., 2014) (13.8.1.4). Permafrost degradation due to higher temperatures could increase the potential of debris flow detachment in Alpine locations (13.6.1.4, Damm and Felderer, 2013).

Increased precipitation falling on local topography can increase landslide and mudflow risks, as seen in settlements at the Caucasus mountainous region (Marchenko et al., 2017; Efremov and Shulyakov, 2018; Kerimov et al., 2020). At the Umbria region in Italy, landslide events could increase by 16-53% under 2°C GWL and by 24-107% beyond 3°C GWL, mostly during winter (Ciabatta et al., 2016). Risks from shallow landslides are expected to increase in the Alps and Carpathians if no adequate risk mitigation measures are in place (CCP5.3.2, Gariano and Guzzetti, 2016).

13.6.2 Solution Space and Adaptation Options

Monetary assessments of future damages from climate extremes on critical infrastructures show a sevenfold escalating figures by 2080s (Figure 13.18) compared to the baseline (Forzieri et al., 2018), highlighting the need for adaptation.

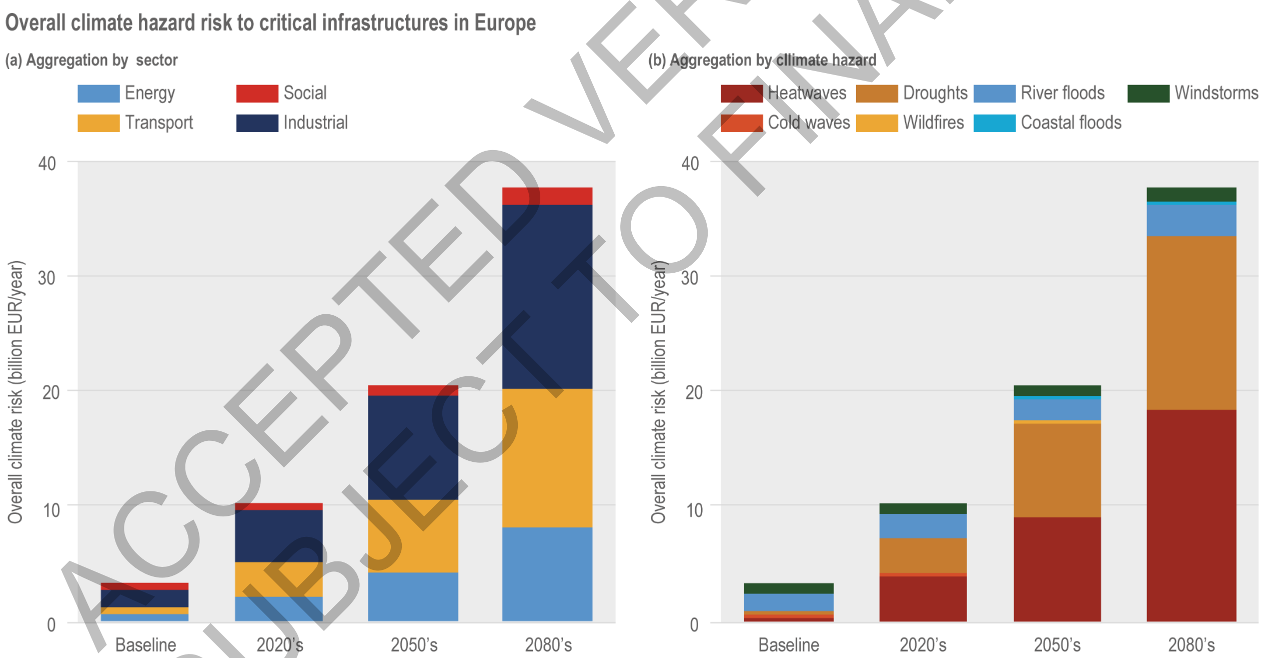

Figure 13.18: Climate risks to critical infrastructures, aggregated at European (EU+) level under the SRES A1B scenario (Forzieri et al., 2018). Baseline: 1981-2010. 2020s: 2011–2040. 2050s: 2041–2070. 2080s: 2071–2100.

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 13.1; Box 13.3; Figure 13.36), adaptation by private actors and by cities against sea level rise (Chapter 16; CCP2).

Table 13.1: Present status of planned and implemented adaptation in cities, energy sector, tourism sector, transport and industry in Europe

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	General commitments / Adaptation Plans	Implemented adaptation actions
Cities	• Increasing number of cities acknowledging the critical role of adaptation in building resilience to climate change. • Of 9609 European municipalities in the Covenant of Mayors for Climate & Energy (CoM), 2221 reported on adaptation through the CoM platform, 429 provided some information on adaptation goals, risk and vulnerability assessments/action plans, and 230-290 reported adaptation goals and funds for adaptation. Extreme heat, droughts and forest fires are the most often reported hazards. • Most urban adaptation plans include ecosystem-based measures (but often with insufficient baseline information and lack of convincing implementation actions). • Adaptation to risks from climate extremes (mostly flooding) is often addressed through municipal emergency plans.	• Large cities are in the process of implementation (e.g., Helsinki, Copenhagen, Rotterdam, Barcelona, Madrid, London, Moscow). • 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 Nature-based Solutions (NbS) and ecosystem-based adaptation (EbA) to address urban heating and the discontinuity of the urban water cycle due to surface sealing and limited infiltration. • Strategic, tactical, and emergency measures applied for drought management (e.g., London, Istanbul)
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)
		• Measures undertaken by some distribution system operators (DSOs) and energy companies, focusing on adaptation of transmission lines, water cooling, dams for avoiding flooding during intense precipitation events, actions to avoid flooding and to secure fuel supply.
Tourism	• Consideration of tourism in national adaptation strategies is limited, and national tourism strategies rarely mention adaptation. • Tourism operators do not consider longer term adaptation strategies to be relevant. • 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, and 45% in Spain apply snowmaking. • Resorts offering nocturnal skiing (e.g., Spain) and other snow-based activities. Transformation to all-year mountain resorts (e.g., 70% of Spanish ski resorts).
		• Some diversification of tourism products offered in Mediterranean coastal destinations. • Implementation of water saving measures, primarily for cost reduction.
Transport	• Only 10 countries have started coordination activities or identified adaptation measures. • An integrated, trans-modal approach to adaptation is lacking. • Few countries are mainstreaming of adaptation within transport planning and decision-making (e.g., the 'Low-water Rhine' action plan and in Germany).	• Only in 5 countries. • Majority of actions are preparatory. • Actions mostly focus on infrastructure and much less on services, although the latter have started gaining ground (e.g., operational forecasts for water levels in rivers). • Transport modes often compete for public funds, and political priorities for specific modes often influence adaptation
	• 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).
Industry and business	• Recommendation of the High Level Expert Group on Sustainable Finance ((HLEG) that the European Commission endorses and implements the guidelines provided by the Task force on Climate-Related Financial Disclosure in 2019.	• 50 of European large listed companies publicly disclosed their climate risks in 2020; yet only a small share provided specifics on sectoral risks, how risks differ over time and by different climate scenarios • Large national/multinational companies, and companies regulated by mitigation policy are first movers in corporate adaptation, while small and medium-sized enterprises often lack knowledge and resources to address risks and adaptation options. • Development of different tools (stress testing, scenario analysis, value at risk) by climate service providers, insurance companies and central banks

	Well-established adaptation		Advancing adaptation		Low adaptation

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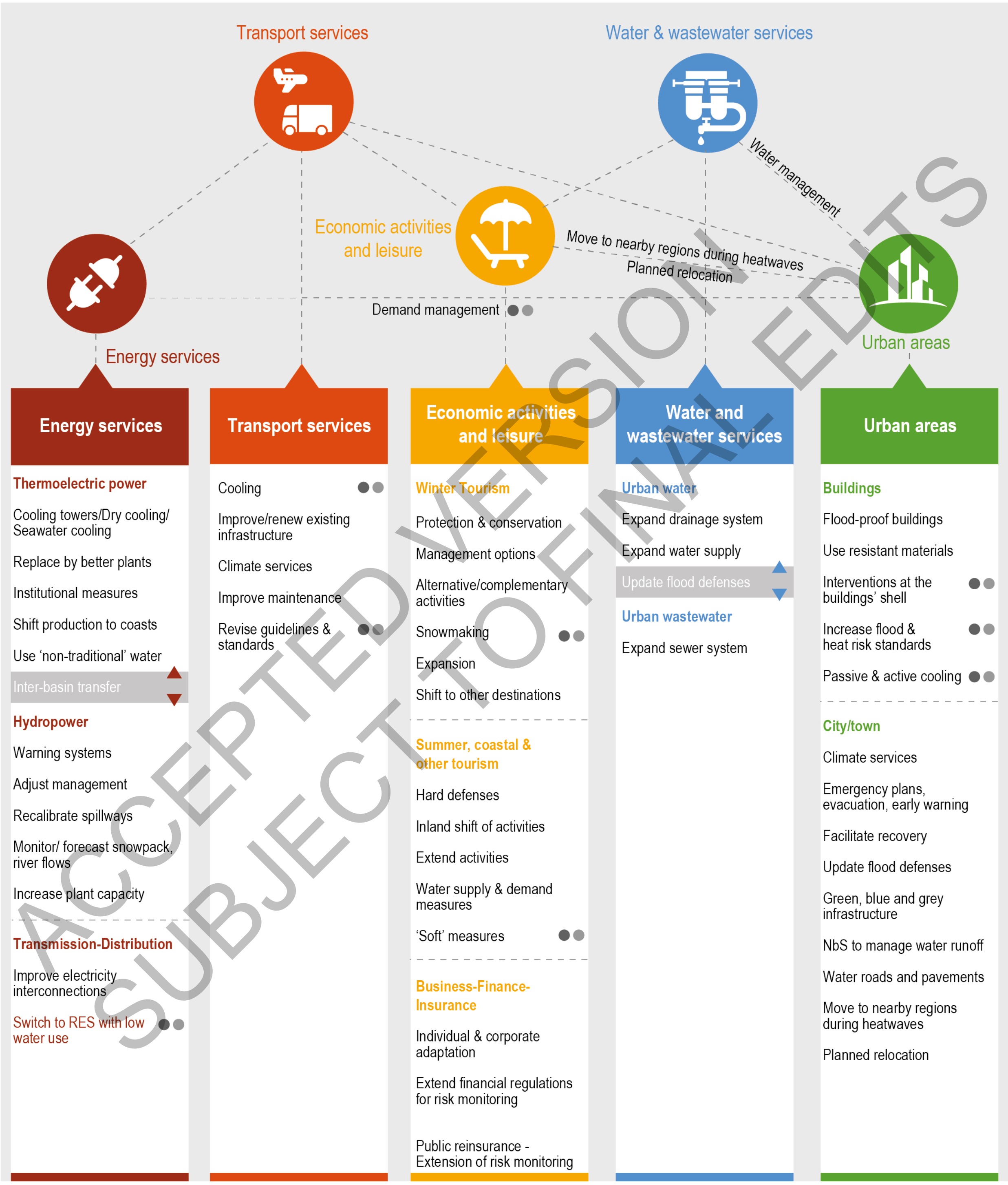
Although urban adaptation is underway, many small, economically weak (i.e. with low GDP/capita) or cities facing high climate change risks lack adaptation planning (Reckien et al., 2015; EEA, 2016). While almost all large municipalities in NEU and WCE report implemented actions at least in one sector, this is not the case for 39% of municipalities in SEU (Aguiar et al., 2018). In the UK, the legal requirement to develop urban adaptation plans has been a significant driver for their widespread adoption (Reckien et al., 2015). The availability of and access to funding for adaptation is also crucial for plan development (section 13.11.1). Network membership (e.g., ICLEI, C40, Covenant of Mayors for Climate & Energy) is an important driver for city planning and transfer of best practices (Heikkinen et al., 2020a). Stakeholder engagement is key for successful adaptation (Bertoldi et al., 2020)(see Chapter 17).

Only 29% of local adaptation plans are mainstreamed in cities, which could reduce the effectiveness of implementing adaptation (Reckien et al., 2019) (13.11.1.2). Although large municipalities usually fund the implementation of their adaptation plans, smaller and less populated municipalities (particularly in SEU and EEU) often depend on intergovernmental, international and national funding.

13.6.2.2 Adaptation Options as a Function of Impacts

Examples of adaptation options in Europe are presented in Figure 13.19.



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Potential synergies and 4 trade-offs with mitigation

Figure 13.19: Adaptation options in cities, settlements, and key infrastructure in Europe (Table SM13.7).

Nature-based solutions (NbS) and ecosystem-based adaptation (EbA) such as green spaces, ponds, wetlands and green roofs for urban stormwater management and vegetation for heat mitigation represent an emerging adaptation option in cities. Combined with traditional water infrastructure, they can contribute to managing urban flood events (Kourtis and Tsihrintzis, 2021), playing a role in mitigating flood peaks (Pour et al., 2020) and protecting critical urban infrastructure (Ossa-Moreno et al., 2017). For example, in the Augustenborg district of Malmö, Sweden, using nature to manage stormwater runoff 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, 2020c). Urban greening 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). The scale and relative degree of management or integration of approaches drawing on nature 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 approaches) provides greater opportunity for human intervention to ensure the survival of urban vegetation during droughts or heatwaves.

When selecting and combining adaptation options, challenges remain on how to address uncertainties of climate projections and climatic extremes (Fowler et al., 2021) and to translate scientific input into practical guidance for adaptation (Dale, 2021) (Section 13.11.1.3).

An assessment of the feasibility and effectiveness of main adaptation options, based on literature, is presented in Figure 13.20; for adaptation to flood risk, see Figure 13.6.

Effectiveness & feasibility of main adaptation options to climate impacts & risk for cities, settlements & key infrastructure in Europe

Impact types	Adaptation options	Effectiveness	Feasibility						Confidence	
			Economic	*Technological*	*Institutional*	*Socio-cultural*	*Ecological*	*Geophysical*	*Evidence*	*Agreement*
Reduction of thermal comfort due to increasing temperatures & extreme heat	Interventions in the building shell	M	M	L	M	L	NL	M	M	M
	Ventilation (natural/mechanical, incl. night)	M	M	H	M	L	NL	M	H	M
	Air conditioning	H	L	NL	NL	L	NL	M	L	M
	Shading	M	L	H	L	M	NL	L	M	M
	Green roofs, green walls	L	M	M	L	M	M	M	M	M
	Urban green spaces	L	L	M	L	M	M	M	L	M
	Use of 'cool' paints & coatings	L	H	M	L	M	NL	H	M	M
	Escape to nearby non-urban destinations	NL	NL	NL	NL	M	NL	NL	L	H
Loss of critical services due to heatwaves & drought	Improvements in cooling systems	M	L	M	M	NL	NL	M	H	M
	Shifting production to less water-intensive plants	M	M	M	L	NL	NL	NL	L	H
	Regulatory measures	L	M	NL	M	NL	NL	NL	L	M
	Management measures	M	M	M	M	NL	L	M	M	M
	Use of heat-resilient materials	L	H	L	M	M	NL	NL	L	H
	Replace vulnerable infrastructure with resilient one	L	M	NL	NL	NL	NL	NL	L	H

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.20: Effectiveness and feasibility of main adaptation options for cities, settlements and key infrastructure in Europe (SM13.9 and Table SM13.8).

There are gaps of knowledge on the social, environmental and geophysical dimension of feasibility for many options and a holistic assessment of different options is largely lacking. This latter could reveal unintended impacts from and synergies or trade-offs between options, as in water and wastewater services (Dobson and Mijic, 2020).

13.6.2.3 Adaptation Limits, Residual Risks, Incremental and Transformative Adaptation

Adaptation in cities, settlements and key infrastructure in Europe faces technical, environmental, economic and social limits (Figure 13.21).

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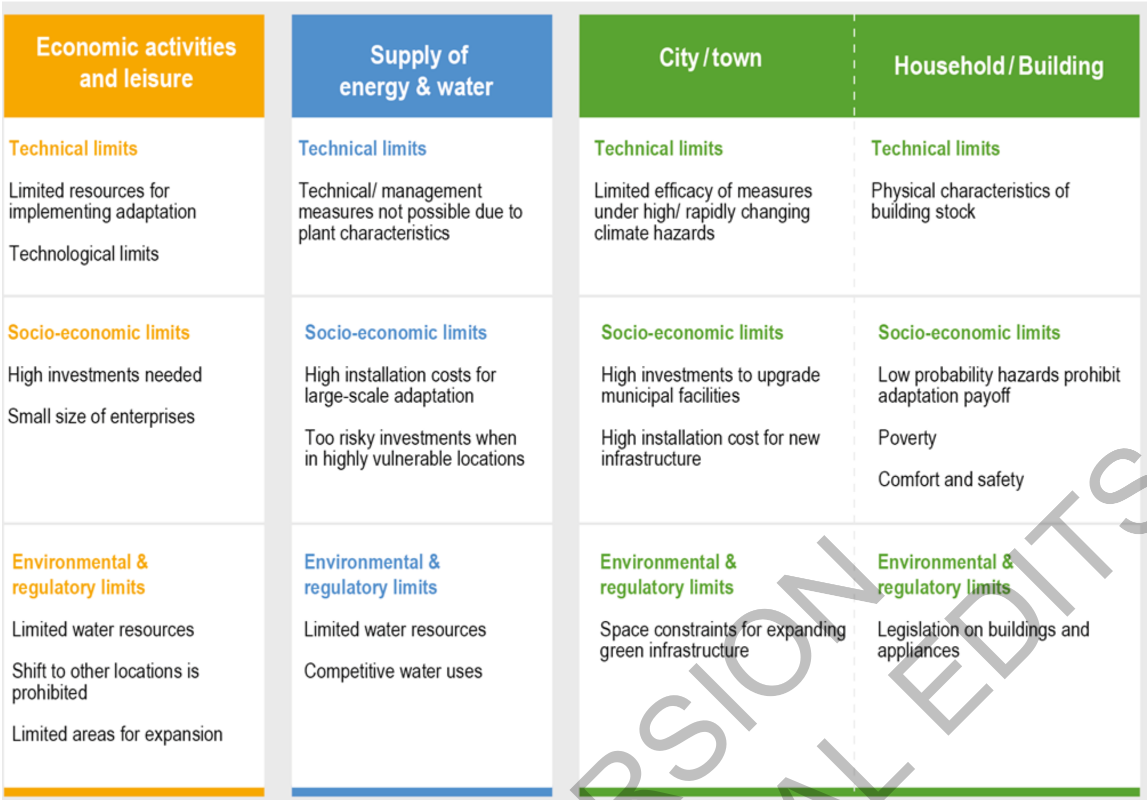

Figure 13.21: Indicative adaptation limits in cities, settlements and key infrastructure in Europe (Table SM13.16).

Adaptation options for many sectors will not be sufficient to remove residual risks, e.g. regarding overheating in buildings under high GWL, (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); snowmaking beyond 3°C GWL (Scott et al., 2019; Steiger et al., 2020; Steiger and Scott, 2020); 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., 2014a); and flood mitigation in cities (Skougaard Kaspersen et al., 2017; Umgiesser, 2020). Some adaptation actions in a sector may also have side-effects on others, increasing their vulnerability (Pranzini et al., 2015) (sections 13.2.2 and 13.2.3).

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 and prove challenging to upscale (Jacob, 2015; Restemeyer et al., 2015; Restemeyer et al., 2018; Holscher et al., 2019). The active involvement of local stakeholders, public administration and political leaders 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).

13.6.2.4 Governance and Insurance

Urban adaptation plans can enhance resilience and their development is mandatory in the UK, France, and Denmark (Reckien et al., 2019). There is *medium confidence* 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., 2018). A high organizational capacity in a municipality may not be a necessary condition for forward-looking investment decisions 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 policy mixes utilized by local governments for supporting adaptation (Lesnikowski et al., 2019). In early adapter cities (e.g., Rotterdam), adaptation is institutionally embedded in climate, resilience and sustainability-related actions and collaboration between city departments, government levels, businesses, and rest stakeholders (Holscher et al., 2019). In most other cities however, adaptation planners

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rarely consider collaborations with citizens 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 (Wiering et al., 2017; Alkhani, 2020). For example, in flood management (also section 13.2), 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 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 institutional 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 European insurance industry has developed tailored products for specific climate risks threatening cities, settlements and key infrastructure, such as risk-based flood insurance for homeowners and companies (section 13.2.3). The European insurance industry is developing new services (such as risk analysis and catastrophe modelling embedding climate change, early warning and post-event recovery recommendations) and it has recently started to play a role as communicator of future risks and as institutional investor with the aim of risk reduction (Jones and Phillips, 2016; Marchal et al., 2019).

13.6.2.5 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 future climate scenarios (Aparicio, 2017). Without rapid decarbonization of electricity supply, greenhouse gas emissions will increase due to the increased use of air-conditioning installations in cities. This trade-off can be reduced to some extent through use of more efficient cooling technologies (IEA, 2018) and complementary adaptation measures such as large-scale urban greening, building policies and behavioural changes in air conditioning use (Viguié et al., 2020; Sharifi, 2021; Viguié et al., 2021). Greenhouse gas emissions from transport may increase due to the temporary relocation of city residents to cooler locations during heatwaves (Juschten et al., 2019), and from increased energy use for snowmaking in European ski resorts (Scott et al., 2019).

13.6.3 Knowledge Gaps

A key knowledge gap is the lack of a quantitative European-wide integrated assessment of future climate change risks on water and energy, including different socio-economic futures. Models capable of representing integrated policies for energy and water are lacking (Khan et al., 2016) including quantitative modelling of impacts on energy transmission and coastal energy infrastructure (Cronin et al., 2018). These lacks are especially pertinent when combined with the small number of studies considering SSP population projections, and adaptation tipping points. The limited social vulnerability assessments, mapping, and validation (Rufat et al., 2019) contribute further to these knowledge gaps.

While compound, concurrent, and consecutive climate extremes become more frequent, there is limited knowledge on sectoral risks or on cascading risks for through transport, telecommunications, water, and banking and finance. While heat is well studies, studies on risks for cities and key infrastructure from hailstorms and lightning are missing.

Empirical data on the damage of transport infrastructure (e.g., railways) covering different European countries is not systematically collected and indirect economic effects of interruptions of transport networks are not well studied (Bubeck et al., 2019). These deficits result in uncertainties associated with impacts of climate change on transport flows and indirect impacts (delays, economic losses).

There is limited knowledge on interactions created by synchronous adaptation in ski tourism supply and demand, and models are not yet including individual snowmaking capacity and a higher time resolution (Steiger et al., 2019). Furthermore, there is no European-wide assessment of coastal flooding risks on tourism.

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Many studies lack consideration of market characteristics (e.g., competitors) in their risk assessment which would be improved by location- and sector-specific knowledge on climate risks for firm assets, operations, business, industry, finance and insurance needed to inform adaptation actions (de Bruin et al., 2020; Feridun and Güngör, 2020; Monasterolo, 2020).

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

Attribution studies show that human-induced climate change is increasing the frequency and intensity of heat waves and has already impacted human health in Europe (Section 13.10.1, Vicedo-Cabrera et al., 2021); for example the 2010 heatwave in EEU resulted in 55,000 heat-related deaths (Barriopedro et al., 2011; Russo et al., 2015); the 2018 heatwave in NEU (Ebi et al., 2021) and the 2019 heatwave in WCE and NEU both had significant health impacts (Cross-Chapter Box DISASTER in Chapter 4, Vautard et al., 2020; Watts et al., 2021). Elderly, children, (pregnant) women, socially isolated people and those with low physical fitness are particularly exposed and vulnerable to heat-related risks, as are those people suffering from pre-existing medical conditions, including cardiovascular disease, kidney disorders, diabetes and respiratory diseases (de'Donato et al., 2015; Sheridan and Allen, 2018; Naik et al., 2021). An aging population in Europe is increasing the pool of vulnerable individuals, resulting in higher risk of heat-related mortality (Montero et al., 2012; Carmona et al., 2016b; WHO, 2018b; Watts et al., 2021).

1.5°C GWL warming could result in 30,000 annual deaths due to extreme heat, with up to three-fold the number under 3°C GWL (*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 development (Rohat et al., 2019; Ebi et al., 2021) (Figure 13.22). Heat stress risks will be lower under SSP1 than SSP3 or SSP4 scenarios (*high confidence*) (Hunt et al., 2017; Rohat et al., 2019; Wang et al., 2020; Ebi et al., 2021). The incidence of heat-related mortality and morbidity will be highest in SEU, where their magnitude is also expected to increase more rapidly (Forzieri et al., 2017; Gasparrini et al., 2017; Guo et al., 2018; Díaz et al., 2019; Vicedo-Cabrera et al., 2021). WCE, NEU, SEU will experience accelerating negative consequences beyond 1.5°C GWL, particularly under SSP3 and SSP4 due to higher vulnerability compared with SSP1 (Figure 13.22, Rohat et al., 2019). The number of heat-related respiratory hospital admissions is projected to increase from 11,000 (1981-2010) to 26,000 annually (2021-2050), particularly in SEU mainly due to a relative increase in the number of extremely hot days (Åström et al., 2013). Cold spells are projected to decrease across Europe, particularly in southern Europe, but do not compensate for the additional heat related deaths projected (Lhotka and Kysely, 2015; Carmona et al., 2016a; Martinez et al., 2018).

74% of Europeans live in urban areas (section 13.6), where the effect of heat waves on human health is exacerbated by microclimates due to buildings and infrastructure, heat island effects, and air pollution (WHO, 2018a; Smid et al., 2019). In large European cities, stabilizing climate warming at 1.5°C GWL would decrease premature deaths by 15–22% in summer compared with stabilization at 2°C GWL (Mitchell et al., 2018) (*high confidence*).

Although there is *very high confidence* that risk consequences will inevitably be more pervasive and widespread in a warmer Europe, evidence of higher heat tolerance is also 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 (Åström et al., 2017; Guo et al., 2018; Díaz et al., 2019). However, there are large uncertainties in the ability to adapt to future heat extremes which might fall outside of historical ranges (Vanos et al., 2020).

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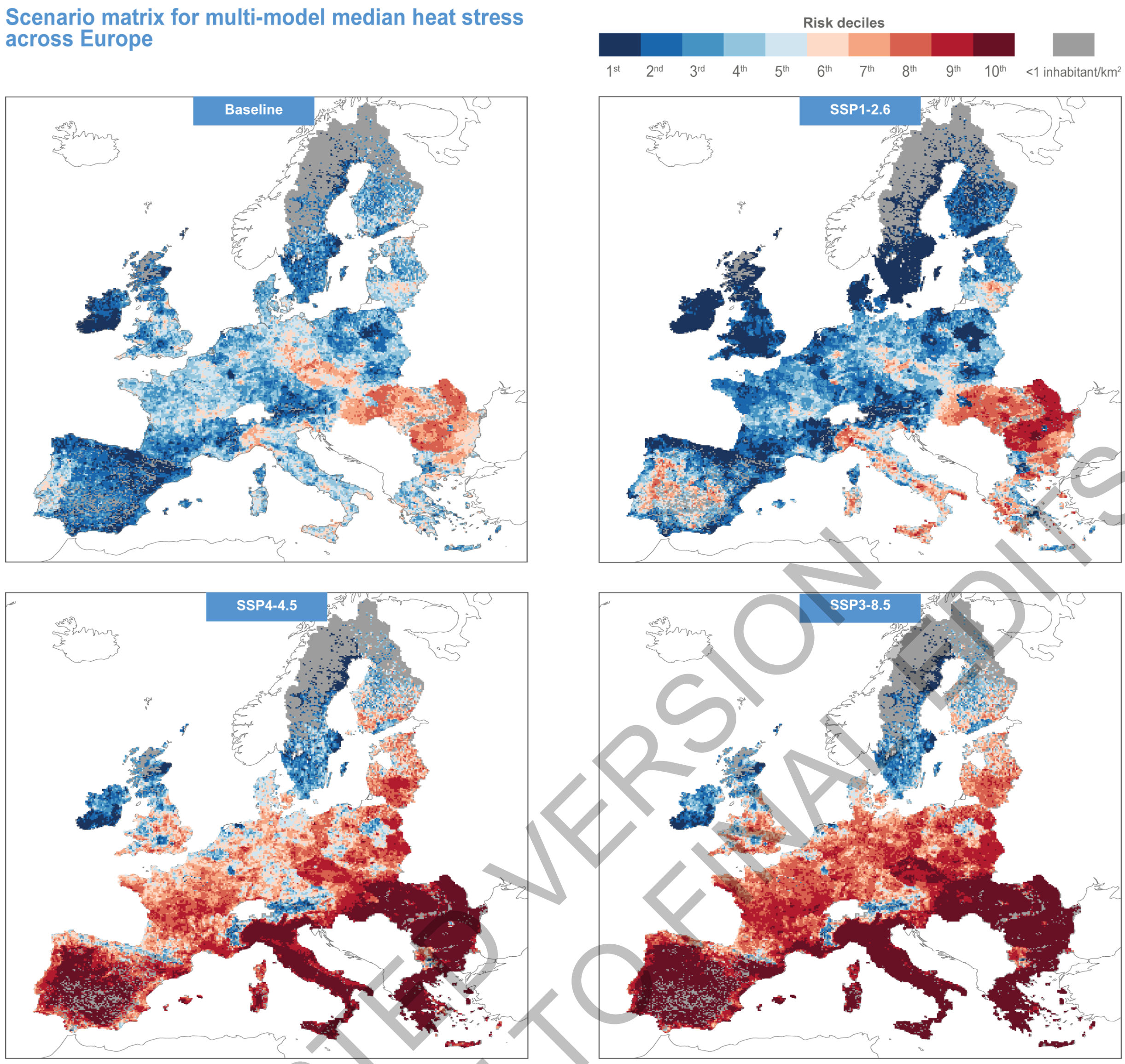

Figure 13.22: Scenario matrix for multi-model median heat stress risks for the baseline 1986-2005, and different SSP-RCP combinations for the period 2040-2060. SSPs are extended SSPs for Europe (EU28+). Heat stress risk is calculated by geometric aggregation of the hazard (heat wave days), population 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 and riverine flooding (13.2.2), wildfires (13.3.4), and windstorms could rise substantially by 2100 (Forzieri et al., 2017; Feyen et al., 2020). Lifetime exposure to extreme weather events for children born in 2020 will be about 50% larger at 3.5°C compared to 1.5°C GWL (Thiery et al., 2021).

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 due to long-term exposure to ambient PM2.5, 71,000 due to NO_2, and more than 15,000 premature mortalities occurred due to near surface ozone (EEA, 2019b; Lelieveld et al., 2019). Impacts of air pollution determined by air quality policies, changes to temperature, humidity, and precipitation (Naik et al., 2021). Climate change could increase air pollution health effects, with the size of the effect differing across European regions and pollutants (Jacob and Winner, 2009; Orru et al., 2017; Tarin-Carrasco et al., 2021) (*medium confidence*). Increases in temperature and changes in precipitation will impact future air quality due to increased risk of wildfires and related air pollution episodes. Data on the health impacts of wildfires in

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Europe is currently limited (Section 13.3.1.4), but examples such as the 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 2.5°C GWL, mortalities due to exposure to PM2.5 are projected to increase by up to 73% in Europe (*medium confidence*) (Silva et al., 2017; Lelieveld et al., 2019; Tarin-Carrasco et al., 2021). At 2°C GWL, annual premature mortalities due to exposure to near-surface ozone are projected to increase up to 11% in Western Central and Southern Europe and to decrease up to 9% in Northern Europe (under RCP4.5) (Orru et al., 2019) (*medium confidence*). Projected increase in wildfires and reduced air quality is expected to increase respiratory morbidity and mortality, especially in SEU (Slezakova et al., 2013; de Rigo et al., 2017). Constant or lower emissions combined with stricter regulations and new policy initiatives, might improve air quality in coming decades (*medium agreement, low evidence*). Aging population in Europe augments 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 allergies, asthma and rhinitis (EASAC, 2019; EEA, 2019b).

13.7.1.3 Climate Sensitive Infectious Diseases

Figure 13.23 summarizes the observed and projected changes in climatic suitability and assesses the risk for selected climate-sensitive infectious diseases in Europe.

Among the tick-borne diseases, Lyme disease is the most prevalent disease in Europe. There has been a temperature-dependent range expansion of ticks that is projected to expand further north in Sweden, Norway and the Russian Arctic. (Jaenson et al., 2012; Jore et al., 2014; Tokarevich et al., 2017; Waits et al., 2018) and to higher elevations in Austria and the Czech Republic (Daniel et al., 2003; Heinz et al., 2015) (*medium confidence).* A potential habitat expansion of these ticks of 3.8% across Europe, relative to 1990-2010, is projected for 2°C GWL (Porretta et al., 2013; Boeckmann and Joyner, 2014). In contrast, there are projected habitat contractions for these ticks in SEU due to unfavourable climatic conditions (Semenza and Suk, 2018).

The Asian tiger mosquito (*Aedes albopictus*) is present in many European countries and can transmit Dengue, Chikungunya and Zika (Liu-Helmersson et al., 2016; Tjaden et al., 2017; Messina et al., 2019). There is a moderate climatic suitability projected for chikungunya transmission, notably across France, Spain, and Germany but also contractions, particularly in Italy. Europe experienced an exceptionally early and intense transmission season of West Nile virus in 2018, with elevated spring temperature abnormalities (Haussig et al., 2018; Marini et al., 2020). Projections for Europe show West Nile virus risk to expand; by 2025 the risk is projected to increase in SEU and south and eastern parts of WCE (*medium confidence*) (Semenza et al., 2016). Although climatic suitability for malaria transmission in Europe is increasing and will lead to a northward spread of the occurrences of *Anopheles* vectors, the risk from malaria to human health in Europe remains low due to economic and social development and access to health care (*medium confidence*) (Sudre et al., 2013; Hertig, 2019).

Water-borne diseases are also associated with changes in climate such as heavy precipitation events (Semenza, 2020). Warming has been linked with elevated incidence of campylobacteriosis outbreaks in different European countries (Yun et al., 2016; Lake et al., 2019). Marine bacteria such as vibrio thrive under elevated sea surface temperature and low salinity such as the Baltic Sea. Under further warming, the number of months with risk of Vibrio transmission increases and the seasonal transmission window expands, thereby increasing the risk to human health in the future (*high confidence*) (Baker-Austin et al., 2017; Semenza et al., 2017).

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Climate sensitive infectious disease	Impact/Risk: Hazard	Impact/Risk: Vulnerability	Impact/Risk: Exposure		Overall risk for European society	Direction of Change of Climatic Suitability by European Regions: Europe	SEU	WCE	EEU	NEU
Tick-borne diseases (Tick-borne encephalitis & borreliosis)	Pathogens, ticks, hosts, climatic suitability	Recreation, low SES, disadvantaged groups, access to health care, forest gatherers	Affected by: ticks, hosts, geography, habitat encroachment, hunting	Observed	High	••	••	•••	••	••
				Projected: +1.5 °C	High	••	••	••	••	••
				Projected: +3.0 °C	Medium	•	•	•	•	••
West Nile fever	Pathogen, vector, bird hosts, vectorial capacity, precipitation	Age, housing (AC), poverty, lack of window/door screens, access to health care, naivity, vector control, lack of efficatious vaccine or medication	Affected by: mosquitoes, geography, land use, standing water	Observed	Medium	••	••	••	••	••
				Projected: +1.5 °C	Medium	••	••	••	NE	•
				Projected: +3.0 °C	Medium	••	••	••	NE	NE
Dengue, Chikungua, Zika	Pathogen, vector, vectorial capacity, precipitation, population mobility	Age, housing (AC), poverty, lack of window/door screens, access to health care, naivity, vector control, lack of efficatious vaccine or medication	Affected by: mosquitoes, geography, land use, urbanization, standing water	Observed	Low	••	•••	••	NE	•••
				Projected: +1.5 °C	Medium	••	•••	••	NE	••
				Projected: +3.0 °C	Medium	••	••	••	NE	••
Malaria	Pathogen, vector, vectorial capacity, precipitation, population mobility	Age, housing (AC), poverty, lack of bed nets and screens, access to health care, naivity, vector control, insecticide/drug resistance, lack of efficatious vaccine	Affected by: mosquitoes, geography, land use, standing water	Observed	Low	••	••	••	NE	••
				Projected: +1.5 °C	Low	••	••	••	NE	••
				Projected: +3.0 °C	Low	••	••	••	NE	••
Vibrio	Pathogen, Sea Surface Temperature, Sea Surface Salinity	Age, access to care, pre-existing medical conditions, open wounds, immunocompromized	Affected by: geography, recreational water use, sea food consumption	Observed	Medium*	•••*	•••	•••*	•••	•••*
				Projected: +1.5 °C	Medium*	•••*	•••	•••*	•••	•••*
				Projected: +3.0 °C	Medium*	•••*	•••	•••*	•••	•••*

LEGEND:		LEGEND:		LEGEND:	
increase		High confidence	•••	High weigthed risk for society	High
decrease		Medium confidence	••	Medium weighted risk for society	Medium
mixed: increase and decrease		Low confidence	•	Low weighted risk for society	Low
no observation (white)					
no change	NC				
no evidence (NE)	NE				

* only the case for the Baltic region

Figure 13.23: Assessment of climate sensitive infectious diseases. The assessment considers the main drivers of hazard (climatic impact drivers, pathogens and vectors), vulnerability (lack of safeguards and a predisposition to these hazards) and exposure (humans to be affected by these pathogens and vectors), the direction of change of climatic suitability (i.e. temperature, precipitation, relative humidity, extreme weather events) of observed changes and at 1.5°C and 3°C GWL, and assesses the overall infectious disease risks across Europe (Chapter 7.3 and 7.4, Lindgren et al., 2012; Semenza and Paz, 2021). The assessment does not consider incidence of disease infections through autochthonous transmission. (Table SM13.18).

13.7.1.4. Allergies and Pollen

The main drivers of allergies are predominantly non-climatic (e.g. increased urbanization, adoption of westernized lifestyles, social and genetic factor) 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, 2019). 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). Across Europe, sensitization to ragweed is expected to increase from 33 million people in 1986–2005 to 77 million people at 2°C GWL (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; EASAC, 2019; Revich et al., 2019). For instance in different parts of WCE and NEU, the start of the birch season flowering has 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 has a substantive impact, the pollen count could increase more than 3 to 3.5 times at

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2.5°C GWL 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 (Martinez-Solanas et al., 2018) and changes in labour productivity (Orlov et al., 2019; García-León et al., 2021) while evidence on the consequences of other extreme events is lacking. 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; Orlov et al., 2019) (13.6.1.3). The heatwaves of August 2003, July 2010 and July 2015 concentrated in SEU and led to reductions in monthly worker productivity of on average 3-3.5% in SEU, ranging up to 8-9% in Cyprus (2003, 2010) and in Italy (2015) (Orlov et al., 2019); in contrast, the heatwave of 2018 centred on NEU, but also led to pronounced productivity reductions in WCE and SEU (García-León et al., 2021); each of these major European heatwaves led to considerable economic losses in agriculture and construction (*high confidence*) and reduced GDP in Europe (except EEU) by 0.3-0.5% (García-León et al., 2021). At 2.5°C GWL and beyond, GDP losses are projected to increase fivefold compared to 1981-2010, ranging from 2-3.5% in SEU, to 0.5-1.5% in WCE, and below 0.5% in NEU and EEU (Roson and Sartori, 2016; Takakura et al., 2017; Szewczyk et al., 2018; Dellink et al., 2019; García-León et al., 2021) (13.10.3).

13.7.1.6. Food Quality and Nutrition

There is growing evidence that climate change will negatively 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 by income, 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, 2019; Loopstra, 2020). Reduced access to healthy and varied food could contribute to overweight and obesity which is a growing health concern across European countries (Springmann et al., 2016). Increased rates of obesity and diabetes further exacerbate risks from heat-related events (EASAC, 2019).

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).

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, 2019). 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

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level health adaptation is generally limited (Araos et al., 2015) , with most activities occurring in SEU (Paz et al., 2016) *(high agreement, medium evidence)*.

Figure 13.24 presents the assessment of the feasibility and effectiveness of key heat-related health adaptation actions. It shows that substantial social-cultural and institutional barriers complicate widespread 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 implementing health adaptation plans (van Loenhout et al., 2016; Macintyre et al., 2018; Martinez et al., 2019). Key barriers to mental health adaptation actions include lack of funding, coordination, surveillance, and training (e.g., psychological first aid) (Hayes and Poland, 2018). Existing health measures, such as monitoring and early warning systems, play an important role in detecting and communicating emerging climate risks and weather extremes (Confalonieri et al., 2015; Casanueva et al., 2019; 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).

Effectiveness & feasibility of main adaptation options to reduce heat related impacts & risks to human health in Europe

Impact Type	Adaptation Option	Effectiveness	Feasibility						Confidence	
			Economic	*Technological*	*Institutional*	*Socio-cultural*	*Ecological*	*Geophysical*	*Evidence*	*Agreement*
Mortality, morbidity, exposure, stress from heat	Behavior change measures	M	NL	NL	H	H	NL	NL	M	L
	Natural cooling	L	NL	M	NL	M	NL	NL	H	L
	Building interventions	M	M	M	NL	M	NL	H	H	L
	Green infrastructures	M	M	M	M	M	H	M	M	H
	Heat proof land management	H	NL	M	M	H	H	M	M	M
	Heat health action plans	H	NL	M	H	H	NL	NL	H	H
	Bundle of options	H	H	NL	NL	NL	NL	H	M	L

Legend
High = H
Medium = M
Low = L
No/Limited Evidence = NL

Figure 13.24: Effectiveness and feasibility of the main adaptation options to reduce heat related impacts and risks to human health in Europe. (SM13.9 and Table SM13.19).

The effectiveness of most options in reducing climate induced health risks is determined by many co-founding factors, including the extent of the risk, existing socio-political structure and culture, and other adaptation options in place (*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), improvements in health services, and infrastructure of homes (Vandentorren et al., 2006) (Section 13.10.2.1). A study of nine European cities, for example, showed lower numbers of heat-related deaths in Southern European 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). Physical fitness of individuals may increase resilience to extreme heat (Schuster et al., 2017). Combining multiple types of adaptation options into a consistent policy portfolio may have an amplifying effect in reducing risks, particularly at higher GWL (Lesnikowski et al., 2019) (*medium confidence*) (Chapter 7).

Health adaptation actions have demonstrable synergies and trade-offs (Cross-Chapter Box HEALTH in Chapter 7). For example, increasing green-blue spaces in Europe's densely populated areas can be effective in improving micro-climates, reducing the impact of heat waves, improving air quality, and improving mental health by increasing access to fresh air and green (restorative) environment (Gascon et al., 2015; Kondo et al., 2018; Kumar et al., 2019). Health adaptations can also have negative trade-offs, be inconsistent with mitigation ambitions, and could lead to maladaptation. Green-blue spaces, for example, may create new nesting grounds for carriers of vector-borne diseases, increase pollen and allergies (Kabisch et al., 2016),

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enlarge freshwater use for irrigation (Reyes-Paecke et al., 2019), and could raise climate equity and justice issues such as 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, raising energy costs which is particularly challenging for the poor (Section 13.8.1.1), enhancing the heat island effect, and increasing noise pollution (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 but these differ significantly across Europe, as do 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 of climate change is observed, particularly due to low societal pressure to change, confidence in existing health systems, and lack of awareness of links between human health and climate change (*medium confidence*) (Austin et al., 2016; WHO, 2018b; Watts et al., 2021). 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 include increasing the role for national and regional governments in facilitating knowledge sharing across scales, allocating dedicated financial resources, and creating dedicated knowledge and policy programs on climate and health (Wolf et al., 2014; Akin et al., 2015; Curtis et al., 2017). Investing in public healthcare systems more broadly increases their capacity to respond to climate-related extreme events and will ensure wider societal benefits as the COVID-19 pandemic has demonstrated (Cross-Chapter Box COVID in Chapter 7).

Despite a range of options available, there are limits to how much adaptation can take place and residual risks 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 heat waves are expected to stretch existing adaptation interventions well beyond levels observed in response to the observed events of 2003 and 2010 (Hanna and Tait, 2015), see Section 13.10.2.1.

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 on region-specific impacts (e.g., flood injuries in WCE, heatwaves in SEU). In general, attributing health impacts to climate change remains challenging, particularly for mental health and wellbeing, (mal)nutrition and food quality, and climate sensitive 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. However, these interactions seem to play an important role in better understanding projected risks and inform choices on adaptation planning.

Some climate-related health issues are emerging but evidence is too limited for a robust assessment, for example 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 effectiveness of levers for interventions, are hardly assessed. Although health adaptations are documented, these are particularly around mortality and injuries due to extreme events (predominantly floods (13.2.1) and heat waves (13.7.1.1). There are very few studies assessing the barriers and enablers of health adaptations, nor systematic assessment of the effectiveness of (portfolio of) options. Limited insights into what works and where hamper upscaling these insights across Europe and constrains the ability to evaluate whether investments in health adaptation have actually reduced risks.

13.8 Vulnerable Livelihoods and Social Inequality

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This section addresses social consequences of climate change for Europe, by looking into consequences for poor households and minority groups; migration and displacement of people; livelihoods particularly vulnerable to climate change (indigenous and traditional communities); and cultural heritage.

13.8.1 Observed Impacts and Projected Risks

13.8.1.1 Poverty and Social Inequality

While climate change is not the main driver of social inequality in Europe, poor households and marginalized groups in Europe are affected more strongly than other social groups by flooding, heat and drought and risks to spreading diseases (*medium confidence*).

Urban poor and ethnic minorities often settle in more vulnerable settlement zones, and are therefore impacted more by flooding (*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 disproportionately affected e.g. during heat waves in the Mediterranean (Jouzel and Michelot, 2016). Women, those with disabilities and the elderly are disproportionately affected by heat (Section 13.7.1). Floods in the Western Balkans in 2014 resulted in heavy metal pollution of water and land threatening the health condition of the poorer rural population (Filijović and Đorđević, 2014). Access to water and sanitation is less available to poorer households and marginalized groups in Europe (Ezbakhe et al., 2019; Anthonj et al., 2020) which could be intensified by increasing water scarcity in parts of Europe under future climate change (Section 13.10.3).

Food self-provisioning is a widespread practice in many parts of Europe (Aleynikov et al., 2014; Corcoran, 2014; Church et al., 2015; Mustonen and Huusari, 2020), reaching over half of German rural areas (Vávra et al., 2018). 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) and renews their local knowledge, 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., 2017b; Inuit Circumpolar Council, 2020), and after 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 Migration and Displacement of People

Most migration and displacement due to climate change is taking place within national borders and single regions (Cross-Chapter Box MIGRATE in Chapter 7). There is *low confidence* in climate change contributing to migration from outside Europe into Europe (Gemenne, 2011; Topilin, 2016; Gemenne and Blocher, 2017; Selby et al., 2017). Some economic models project that asylum applications to the EU might increase by a third at 2.5°C GWL and more than double beyond 4°C GWL by end of the century (Missirian and Schlenker, 2017), but empirical evidence shows that applications might decrease due to growing economic and legal barriers in the capacity of populations to emigrate from Africa or other regions (Kelley et al., 2015; Zickgraf, 2018; Borderon et al., 2019).

Migration of people within Europe is predominantly triggered by economic disparities among European countries (Fischer and Pfaffermayr, 2018). There is *limited* and *inconclusive* evidence for climate-driven impacts on these movements (Hoffmann et al., 2020). Small scale climate-induced displacement within Europe occurs in the aftermath of flood and drought disasters and over short distances (Cattaneo et al., 2019). The unequal distribution of future climate risks (13.1) and adaptive capacity across European regions

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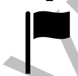
may increase pressure for internal migration (Williges et al., 2017; Forzieri et al., 2018). For instance, projected sea level rise (13.2.1, Cross-Chapter Box SLR in Chapter 3) may result in planned relocation of coastal settlements and inland migration in the UK, the Netherlands and the northern Mediterranean (Mulligan et al., 2014; Antonioli et al., 2017). The number of people living in areas at risk in Europe is projected to increase with future SSPs increasing exposure (Merkens et al., 2016; Byers et al., 2018; Harrison et al., 2019).

13.8.1.3 Loss and Damage to Vulnerable Livelihoods in Europe

A number of livelihoods maintaining unique cultures in Europe is particularly vulnerable to climate change (Table 13.2): indigenous communities in the European polar region because of their dependence on cryosphere ecosystems *(high confidence)* (CCP Polar, Hayashi, 2017; Huntington et al., 2017; Hock et al., 2019; Meredith et al., 2019; Inuit Circumpolar Council, 2020; Douville et al., 2021; Fox-Kemper et al., 2021) and communities dependent on small-scale fisheries, traditional farming and unique cultural landscapes (*medium confidence*) (Kovats et al., 2014; Ruiz-Díaz et al., 2020).

For Sámi reindeer herding impacts cascade due to a lack of access to key ecosystems, lakes and rivers thereby threatening traditional livelihoods, food security, cultural heritage (e.g. burial grounds, seasonal dwellings and routes), mental health (Box 13.2 and Figure 13.13, Feodoroff, 2021), and growing costs for example as a result of the need for artificial feeding of reindeer.

Table 13.2: Examples of losses and damages to vulnerable livelihoods in Europe, differentiating for different categories of non-economic loss and damage. (Table SM13.20.).

	Human life		Communal and production sites and intrinsic value
	Sense of place		Agency and identity
	Cultural artefacts		Psychological and emotional distress
	Biodiversity and ecosystems		

Climate hazard	**Change in exposure and vulnerability**	**Observed impact / projected risk**
Loss of livelihood, culture, health and wellbeing of the Sámi and the Nenets. 		
Decrease and alterations in snow and ice sheet, unstable winter weather, especially in the form of rain-on-snow events; increased precipitation and thawing permafrost, in tundra; unstable loss/flux of marine ice cover.	Land-use change (e.g. expansion of renewable energy) resulting in pasture loss and disconnection of ecosystems.	Loss of livelihood (e.g. reindeer herding), loss of food security (cold dependent species), culture, health (impact on safety; psychological impacts from stress to reindeer and Indigenous way of life), and cultural and linguistic wellbeing; release of anthrax from permafrost soils in the Nenets area.
Loss of key species in high-Arctic freshwater habitats, proliferation of introduced species and disruption of local food systems in Greenland, Finland, Sweden, NW Russia and Scotland. 		
Warmer water temperatures in high-Arctic freshwater habitats (13.3.1) increase productivity in oligotrophic systems and eventually	Introduced Pacific Pink Salmon has expanded in range since 1970s, affecting endemic species through competition and reducing their	Shifts in freshwater aquatic habitats and loss of endemic cold-dependent fish, such as Arctic Char and Arctic Salmon, cause disruptions to local

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lead to loss of oxygen in water; warming temperatures and changes to ice cover and cryosphere lead to access issues to freshwater fisheries.	abundance. Increased nutrient loading of rivers and rapid expansion of algae increase the risks for cold-dependent fish.	food supply, and local extinctions threatens livelihood safety and cultural well-being.
Warmer winters lead to loss of income from ice fishing and cultural heritage in Finland.		
The start of ice cover on lakes, e.g. lake Puruvesi (Finland), has changed from November to February; ice breakup occurs much earlier in the year.	The quality of the water in the lakes used for fishing depend on ice cover during most of the year, and the season of open water is now much longer, increasing nutrient flow and loss of water quality in these lakes.	Lack of winter ice combined with delayed freeze up and earlier ice breakup reduce fish harvest for important species by up to 50% and impacts local safety, ecosystems, oral history maintenance and the local economy.
Changes to marine food web results in loss of Indigenous knowledge and food insecurity in Greenland.		
Warmer ocean waters moving further north (so-called “atlantification” of Greenland waters); higher temperatures removing sea ice	Traditional practices and knowledge based on sea ice uses and hunting are being lost; species are being replaced with southern fish.	Loss of Indigenous knowledge of how to deal with and use sea ice regarding species and navigation, loss of access to seals and walruses, food insecurity.
Reduced yields on managed alpine grasslands decreases the self-sufficiency of pastoral livestock farming in the Austrian, French and Swiss Alps		
Increase in heat, precipitation variability and agricultural as well as hydrological drought; less snow on the ground, increase in glacier melt, landslides susceptibility and erosion	Land-use change resulting in natural reforestation of abandoned pastoral land; shifts in alpine plant communities; more intensive cultivation of grasslands; change in agricultural markets and support policy.	Abandonment of summer pastures and farms, with negative consequences for farming income, tourism, cultural and aesthetic values.
Reduced yields on semi-natural grasslands, compromising livestock feeding in winter, and ultimately decreasing viability of pastoralism in the Spanish Pyrenees		
Higher temperatures and more variable precipitation, less snow, change in seasonality and drought	Demographic change, change in policy and market conditions, simplification of pastoral practices and agroecosystems, land abandonment or afforestation of marginal pastoral lands and intensification of more favourable lands in the lowlands, troublesome coexistence with tourism and nature conservation initiatives	Decreasing viability of pastoralism, concentration of pastoral production on most profitable locations for intensive rearing of livestock with abandonment of the rest of the land; pastoral land encroachment both by shrubs and other activities; grassland degradation; biodiversity loss
Retreating glaciers and changes in the landscape lead to loss of identity, culture and self-reliance in the Italian Alps (Alto Adige)		

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Glacier volume loss from increasing temperatures	Vulnerability is mainly driven by reliance on tourism	Loss of sense of community through shared memories, and history. Sadness caused by the loss of what feels like "home". Loss of well-being due to uncertainty and fear of the future.
Drought results in a reduction of provisioning (water) and regulating services (protection against floods) in Western and Eastern Alps, Iberian Mountains, Dinaric Mountains		
Increase in drought, particularly under high-end GWL	Forest management strategies, including that of natural forests, can enhance or reduce vulnerability.	Critical importance of alpine natural forests and meadows for regulating services; Negative impacts of climate change are found mainly at low elevations and for specific species (Norway spruce); decrease in soil moisture due to abandonment of pastoralism result in reduced water provision for downstream water users
Increase of sea temperature leads to shifts in distribution of cold water species, reducing productivity at lower latitudes. Artisanal fisheries in Southern European coastal areas (Mediterranean) that rely on local, nearshore stocks can have difficulties to adapt		
Increase in sea temperature	Substitution of artisanal fisheries by industrial fisheries; less support by governments, shift in employment (e.g. tourism) which do not match the skill sets, education or desires of small-scale fishers; national quotas system leads to prices to high buy or lease quotas and immense amount of bureaucracy and regulations	Due to their low investment capacity and boat size, fishers are limited in their movement to other fishing places when local fish stocks decline. Increasing sea temperatures are increasing the threat of invasive species in coastal ecosystems.

[START BOX 13.2 HERE]

Box 13.2: Sámi 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 Sámi. Reindeer migrate between seasonal pastures that cover 55% of Sweden and are simultaneously used for multiple other purposes (Sandström et al., 2016). Reindeer herding is recognized as an indigenous right, protected by the UN Declaration on the Rights of Indigenous Peoples, several UN conventions and through Swedish national legislation.

Temperatures in Arctic and sub-Arctic regions have increased on average by 2°C over the last 30 years (*very high confidence*) (Ranasinghe et al., 2021). Future warming is expected to further increase winter precipitation (*high confidence*) (Ranasinghe et al., 2021) and rain-on-snow events, 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 forest fires and changes in plant community composition reduce pasture quality (*medium confidence*) (Mallory and Boyce, 2018) (Figure Box 13.2.1). High snow depth and rain-on-

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snow events 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).

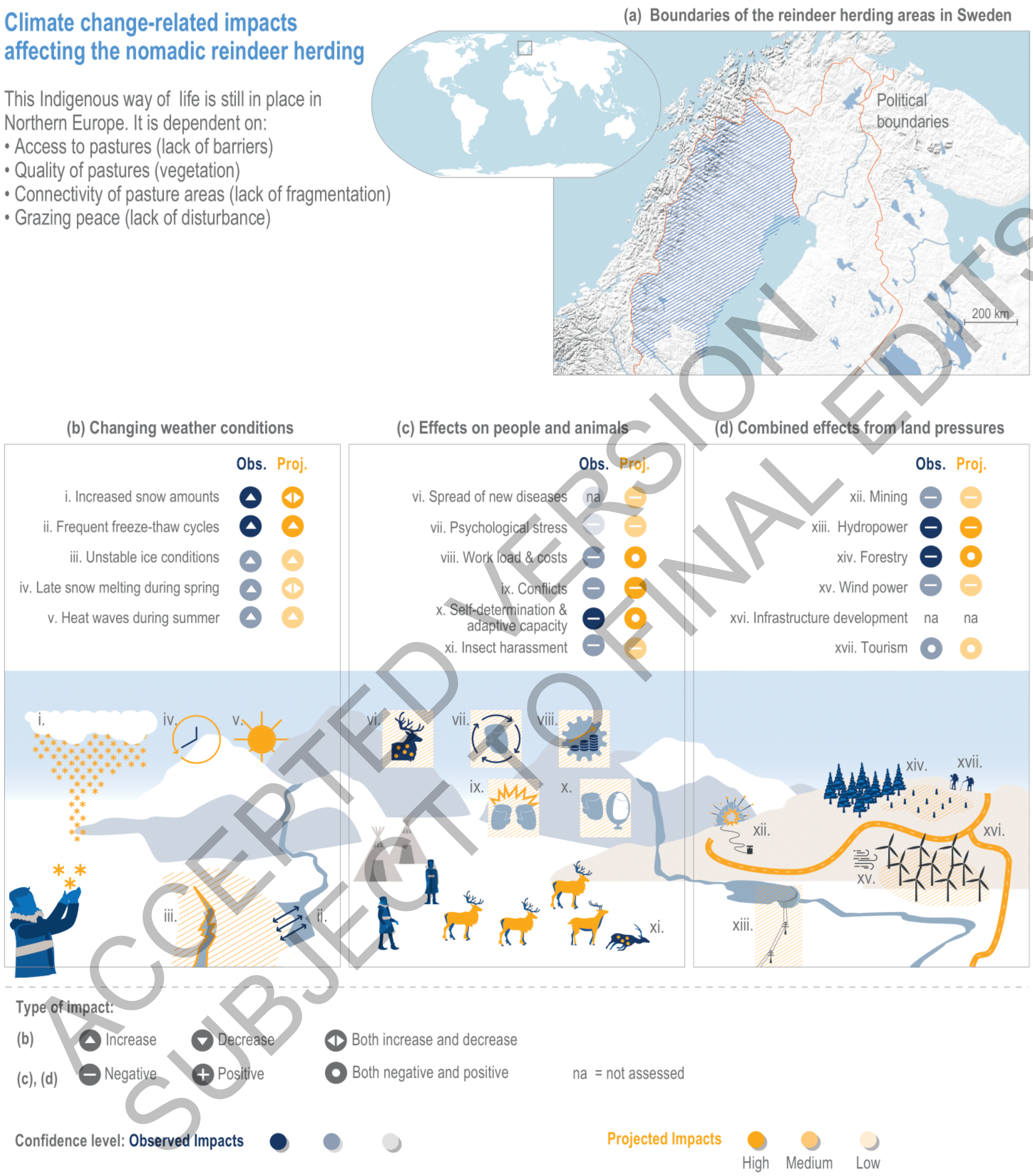

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Figure Box 13.2.1: Cumulative impacts of climate and land use change on reindeer herding as a traditional, semi-nomadic Sámi livelihood (Table SM13.21).

Reindeer herders 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., 2021). Supplementary feeding 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, and increasing human disturbance to animals *(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; Kløcker Larsen et al., 2018). Herding communities face strong barriers to protecting their rights and halting further degradation of pastures (*medium confidence*) (Allard, 2018; Kløcker Larsen 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 significantly affected by climate change directly and indirectly (Figure Box 13.2.1) (Pape and Löffler, 2012; Andersson et al., 2015). 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 (Andersson et al., 2015; Turunen et al., 2016; AMAP, 2017; Hausner et al., 2020). Lack of control over land use is the biggest and most urgent threat to the adaptive capacity of reindeer herding and the right of Sámi to their culture (*high confidence*) (Pape and Löffler, 2012; Andersson et al., 2015; Kløcker Larsen and Raitio, 2019).

[END BOX 13.2 HERE]

13.8.1.4 Cultural and Natural Heritage

Climate change poses a serious threat to preservation of cultural heritage in Europe, both tangible and intangible (*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). At higher GWL, building exteriors and valuable indoor collections become at risk (Leissner et al., 2015). Coastal heritage such along the North Sea and Mediterranean are under water-related threats (Reimann et al., 2018b; Walsh, 2018; Harkin et al., 2020) (Box 13.1 Venice; WGII AR6 CCP4).

Disappearing cultural heritage can reduce incomes due to loss of tourism (Hall et al., 2016), as exemplified by glacier retreat e.g. in the Swiss Alps and Greenland (Bjorst and Ren, 2015; Bosson et al., 2019) (CCP5.3.2.4). Glacier retreat can create a sense of discomfort, loss of sense of place, displacement and anxiety in people (Section 13.7) (Albrecht et al., 2007; Brugger et al., 2013; Allison, 2015; Jurt et al., 2015). Intangible cultural heritage, such as place names, and lost traditional practices can also be affected (Mustonen, 2018; Dastgerdi et al., 2019).

13.8.2 Solution Space and Adaptation Options

As climate change is interacting with many other drivers of poverty, improving the social position of the currently poor may increase their climate resilience (*low confidence*) (Hallegatte and Rozenberg, 2017; Fronzek et al., 2019). Some adaptation actions have the potential to alleviate poverty (Section 13.11.3), but adaptation can also increase social inequalities, e.g. when practices of disaster recovery focus on high visibility areas and not on low-income neighbourhoods or marginalized spaces (D'Alisa and Kallis, 2016). Risk communication and management reliant on new information technologies can exclude elderly and populations with lower educational attainment (Kešetović et al., 2017).

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Unlike migration within the European Union, migration from outside Europe to Europe is heavily constrained by restrictive migration and asylum policies (Fielding, 2011; Mulligan et al., 2014), eventually leaving people to stay in more exposed and risk-prone regions (Benveniste et al., 2020). To reduce vulnerability in these regions, Europe can contribute to adaptation and development in regions outside Europe (section 13.9.4).

Indigenous and local 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., 2019) (section 13.11.1.3). 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., 2019).

European cultural heritage in general and world heritage sites specifically lack 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). Key reasons are the underdeveloped adaptation actions available, resources for implementing them, and absence of overarching policy guidance (Phillips, 2015; Fernandes et al., 2017; Sesana et al., 2018; Daly et al., 2020) (Sesana et al., 2018; Fatorić and Biesbroek, 2020; Sesana et al., 2020).

13.8.3 Knowledge Gaps

There is limited understanding of how different social groups are affected by the four European key risks under future climate change (13.11.2), and by adaptation to them. Similarly, the interaction of multiple risks across sectors and how this interaction results in displacement, migration, or immobility of people both within and from outside Europe is insufficiently understood. For indigenous and traditional livelihoods in Europe, the understanding of how risks will change at different warming levels is very limited, due to complex interactions with socio-economic and political change. For European cultural heritage, there is also a lack of tailored knowledge and understanding of the impacts and how to translate these into adaptation measures.

13.9 Interregional Impacts, Risks and Adaptation

This section addresses interregional risks between Europe and other parts of the world. 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, 2016; Hedlund et al., 2018; Benzie et al., 2019) strengthens the confidence in the AR5 statement 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 depending on their territorial settings, national policies and position in the global supply chain (*high confidence*) (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 (Hedlund et al., 2018). The social and governance context in Europe make the region less vulnerable to conflicts driven by climate change than other regions, at least up to 2°C GWL (Buhaug et al., 2014; Mach et al., 2019; Ide et al., 2020).

Climate risks in other parts of the world can be transmitted to European economies via trade networks (Figure 13.25). 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 such as tropical fruits are highly

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vulnerable to future climate change (Brás et al., 2019). Simultaneous breadbasket failures, and trade restrictions increase risks to food supply (*medium confidence*) (Fellmann et al., 2014; d'Amour et al., 2016; Gaupp et al., 2017; Gaupp et al., 2020). There is *high confidence* that the European economy could be negatively affected by supply chain disruptions due to flooding destroying facilities, heatwaves and malaria reducing productivity in labour intensive industries and regions (13.7.1), and sea level rise affecting ports and cities along coastlines (13.6.1.2) (Nicholls and Kebede, 2012; Challinor, 2016; Wenz and Levermann, 2016; Hedlund et al., 2018; Koks, 2018; Szewczyk et al., 2018; Willner et al., 2018; Knittel et al., 2020; Kulmer et al., 2020; Carter et al., 2021).

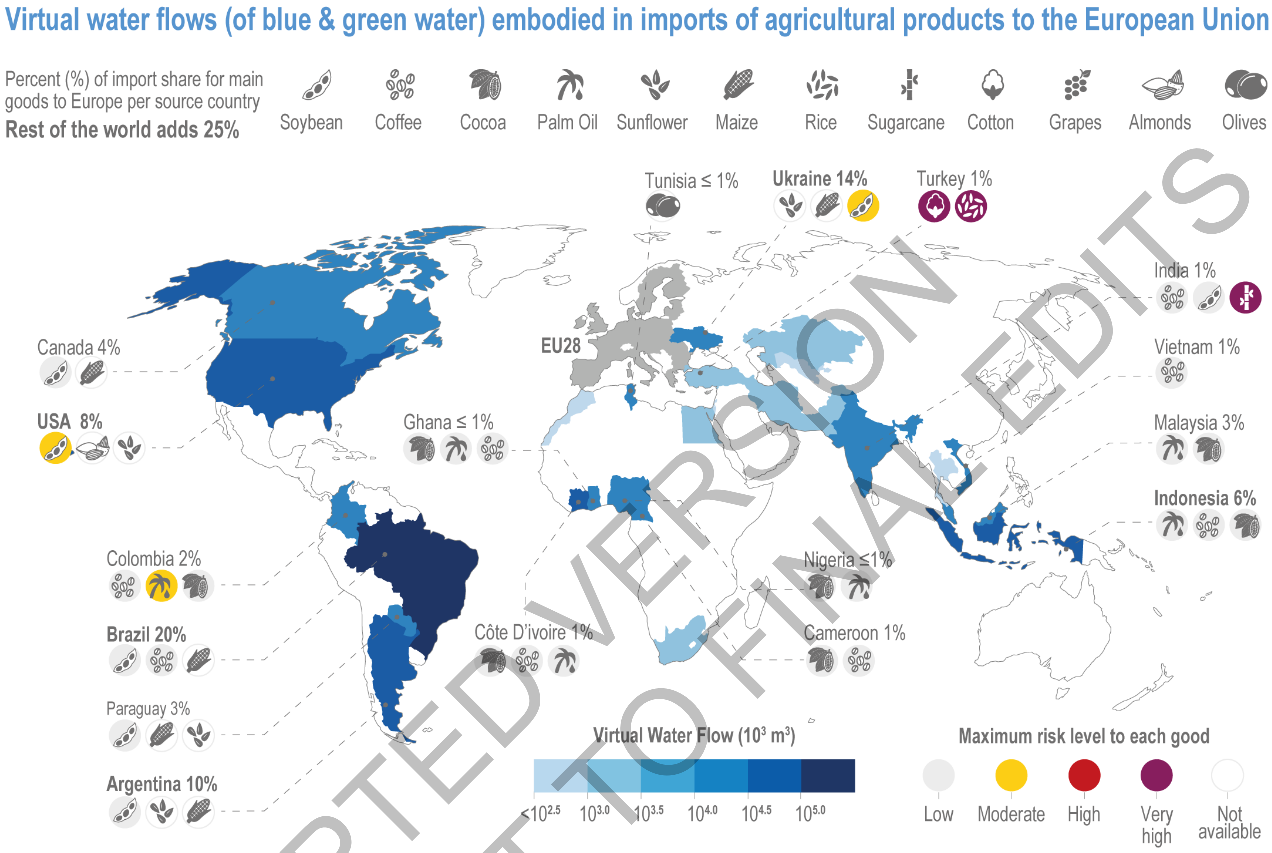

Figure 13.25: Trans-European climate risks in trade: virtual water flows embodied in agricultural imports to Europe in 2018 and the vulnerability to climate change of the most important crops in the originating countries (Dolganova et al., 2019; Ercin et al., 2019).

13.9.2 Interregional Consequences of Climate Risks and Adaptation Emerging from Europe

New literature since AR5 suggests that climate risks in Europe can propagate worldwide in response to 3°C GWL (*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 coastal and riverine flood risks in Europe could be amplified through the global financial system, and generate a systemic financial crisis (Mandel et al., 2021) (Figure 13.26). For 3°C GWL 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).

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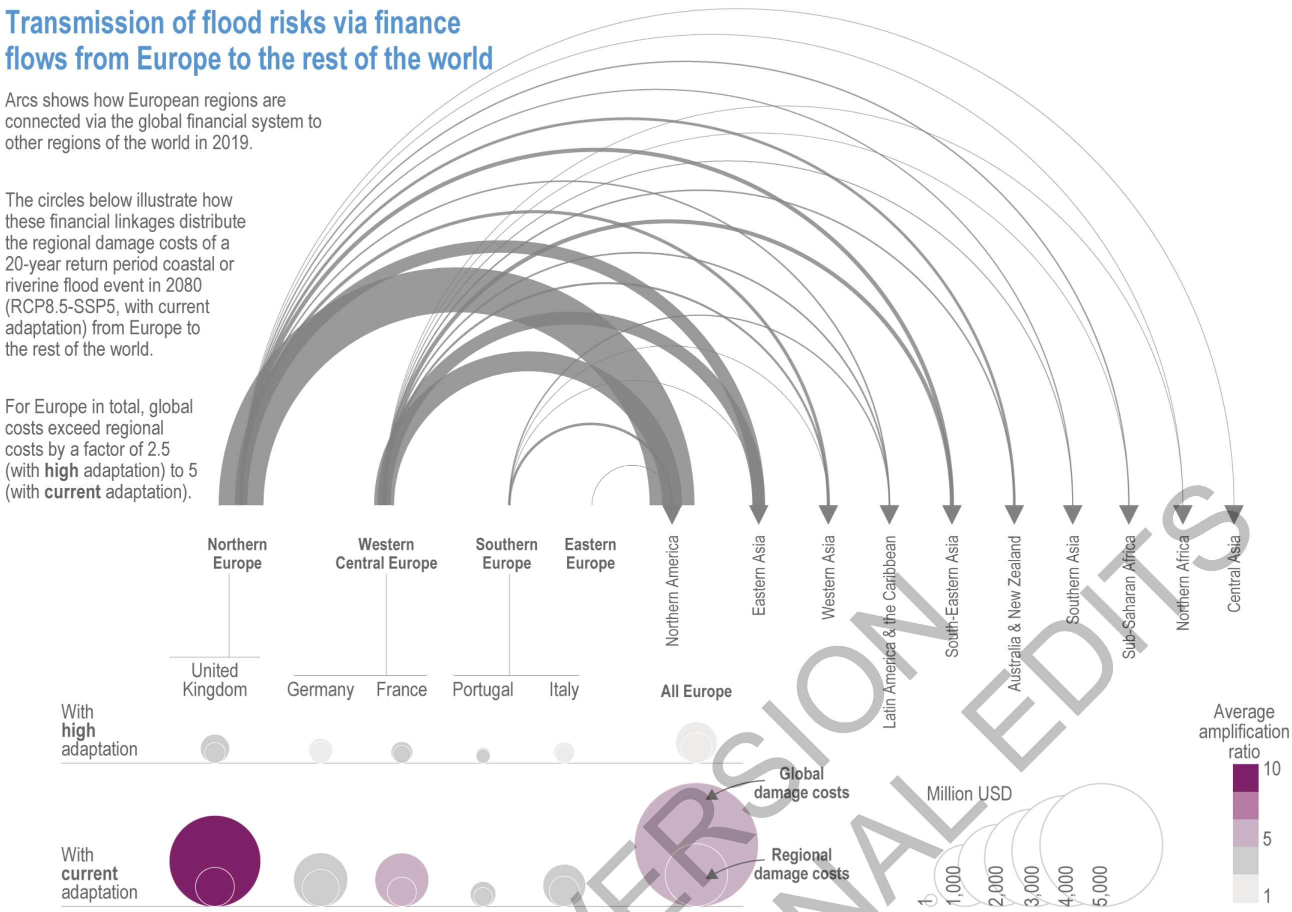

Figure 13.26: The transmission of coastal and riverine flood risks via finance flows from Europe to the Rest of the World. (Mandel et al., 2021).

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) (Chapter 10), 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) (Chapters 12 and 15). Climate risks emerging from these territories include 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, 13.4.3) in European overseas territories are increasingly affected by changes originating in far-field upstream areas. These changes ultimately undermine their ability to curb biodiversity losses and provide ecosystem services (Schaffner and Mathis, 2014; Robinson et al., 2017). Adaptation options and regulations developed within Europe apply in these territories, despite *low confidence* that they meet local and regional adaptation challenges and address the aspiration for social justice, promotion of local solutions and consideration of traditional knowledge (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; Benzie et al., 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) (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

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(e.g., Common Agricultural Policy, trade agreements) (Benzie et al., 2019; Benzie and Persson, 2019; Groundstroem and Juhola, 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).

13.10 Detection and Attribution, Key Risks and Adaptation Pathways

13.10.1 Detection and Attribution of Impacts

Since AR5, scientific documentation of observed changes attributed to global warming have proliferated (*high confidence*). These include 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 (*high confidence*), and impacts of heat on human health, and productivity (*high confidence*) (Figure 13.27 and Table SM13.22) (Vicedo-Cabrera et al., 2021). Formal attribution of impacts of compound events to anthropogenic climate change is just emerging for example in the recent crop failures due to heat and drought (Toreti et al., 2019a). Also, 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). In the recent decades (2000-2015), economic losses intensified in southern Europe (*high confidence*) and were detected for parts of WCE and NEU (*medium confidence*). The methodology for detection and attribution is presented in Chapter 16.2.

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Figure 13.27: Detected changes and attribution (D&A) of climate-related impacts 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 (Table SM13.22).

13.10.2 Key Risks Assessment for Europe

Key risks (KRs) are defined as a subset of climate risks which can potentially become or are already severe now (Section 16.5). The selection process included a review of KRs already identified in AR5 Chapter 23 and a review of the large number of new evidence on projected risks presented in Sections 13.2-13.9. Key risks are reinforced by evidence from the detection and attribution assessment (Section 13.10.1) and new evidence from WGI AR6 Chapters 11 and 12 on regional climatic impact drivers and extremes (Ranasinghe et al., 2021; Seneviratne et al., 2021). Several expert opinion workshops of lead and contributing authors led to further refinements, adjustment and consensus building around the key risks' characteristics, which ultimately guided the construction of the burning embers (Figures 13.28-13.32) (SM13.10). There is *high confidence* that under low or medium adaptation, high to very high risks are projected at 3°GWL (Figure 13.28 and Sections 13.10.2.1-13.10.2.4). Most risks are assessed as moderate up to 1.5°GWL (Figure 13.28).

This section also includes an assessment of the solution space using illustrative adaptation pathways which show alternative sequences of options to reduce risks as climate changes (SM13.10). Low effectiveness measures are followed by measures of a higher effectiveness, while accounting for path-dependency of decisions (Toreti et al., 2019b; Haasnoot et al., 2020a). The process to derive the pathways draws on evidence from the feasibility and effectiveness assessments (Sections 13.2, 13.5, 13.6, 13.7).

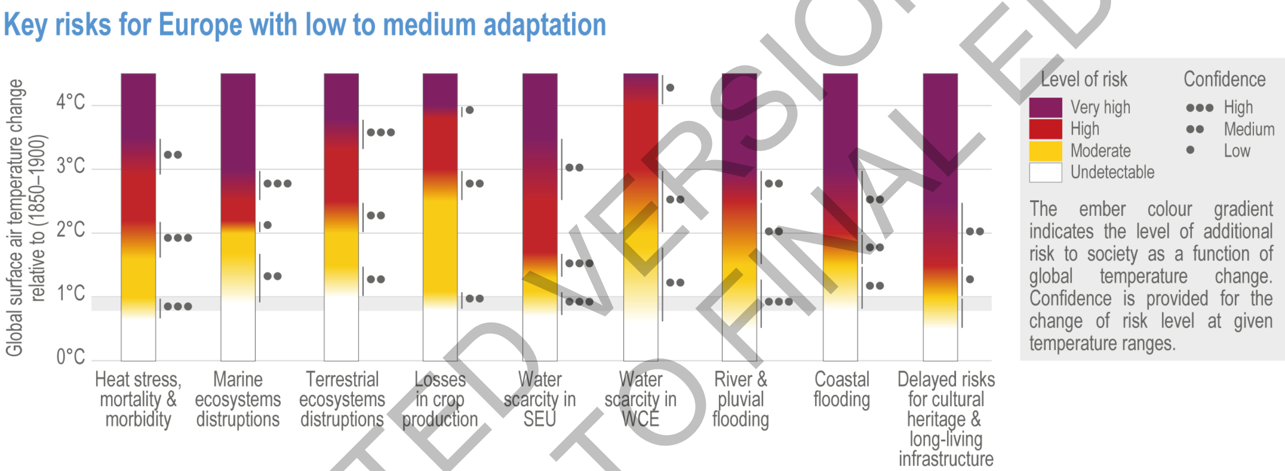

Figure 13.28: Burning ember diagrams for low to medium adaptation. More details on each burning ember are provided in Sections 13.10.2.1-13.10.2.4 and SM13.10. Some burning embers are shown again in Figure 13.29-13.34 alongside burning embers with high adaptation.

13.10.2.1 KR1: Risks of human mortality and heat stress and of ecosystems disruptions due to heat extremes and increase in average temperatures

This key risk cut across humans and ecosystems and severe consequences are mainly driven by an increasing frequency, intensity and duration of heat extremes and increasing average temperatures (*high confidence*) (Urban, 2015; Forzieri et al., 2017; Feyen et al., 2020; Naumann et al., 2020; Ranasinghe et al., 2021). The risk of human heat stress and mortality is largely influenced by underlying socio-economic pathways, with consequences being more severe under SSP3, SSP4 and SSP5 scenarios than SSP1 (*very high confidence*) (Figure 13.22, Section 13.6.1.5.2, Section 13.7.1.1, Hunt et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019; Casanueva et al., 2020). SSPs impact natural systems as well but are not yet well studied. The impact of warming in marine systems are often synergistic with SLR in coastal systems and ocean acidification driven by the rise in CO_2, while habitat fragmentation and land use have important synergies in terrestrial systems (Sections 13.3.1.2 and 13.4.1.2, *high confidence*). More intense heatwaves on land and in the ocean, particularly in Mediterranean Europe (Section 13.4, CCP 4, Darmaraki et al., 2019b; Fox-Kemper et al., 2021), are expected to cause mass mortalities of vulnerable species and species extinction, altering the provision of important ecosystem goods and services (Marbà and Duarte, 2010).

The burning embers on risks for humans (Figure 13.29a) differentiate between present and medium adaptation conditions, drawing on SSP2 and SSP4 (and to a lesser extent SSP3), and high adaptation

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conditions, drawing on SSP1 and papers using various temperature adjustment methods (Table SM13.25). There is *high confidence* that the risk is already moderate now because it has been detected and attributed with *high confidence* (13.10.1). The transition from moderate to high risk for human health is assessed to happen after 1.5°C GWL in a scenario with present to medium adaptation and implies 2- 3 fold increase (compared to moderate risk levels) in magnitude of consequences such as mortality, morbidity, heat stress and thermal discomfort (Rohat et al., 2019; Casanueva et al., 2020; Naumann et al., 2020). At this level, the risk will also become more persistent across the continent due to increase in heat events exceeding critical thresholds for health (Ranasinghe et al., 2021) (*high confidence* on the direction of change and temperature transition, but *medium confidence* on the magnitude).

The burning embers on risk for terrestrial and marine ecosystems and some of their services is shown in Figure 13.28, second and third ember from left (Tables SM13.26 SM13.27). The transition to moderate risk is currently happening as warming already results in changes in timing of development, species 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; Figure 13.8 and 13.12) (*high confidence*). While some terrestrial ecosystems are already impacted today such as Alpine, cryosphere and peatlands, the impacts are not widespread and severe yet across a wide range of terrestrial systems. Around 2°C GWL, losses accelerate in marine ecosystem and appear across systems, including habitat losses especially in coastal wetlands (Roebeling et al., 2013; Clark et al., 2020), biodiversity and biomass losses (Bryndum-Buchholz et al., 2019; Lotze et al., 2019) and ecosystem services such as fishing (Raybaud et al., 2017) (*high confidence* on the direction of change, but *medium confidence* on the local and regional magnitude). The transition is happening at slightly higher warming in terrestrial systems due to higher number of thermal refugia in terrestrial systems causing relocation but not already severe impacts (*medium confidence*) (Chapter 2).

There is *medium confidence* that high adaptation or conditions posing low challenges for adaptation (e.g. SSP1) in the context of human health can delay the transition from moderate to high risk (Åström et al., 2017; Ebi et al., 2021). The illustrative adaptation pathways in Figure 13.29b,c show the sequencing of options to a high adaptation future for NEU and SEU. Whether or not adaptation measures are effective to reduce risk severity for people's health depends on local context (*high confidence*) (Figure 13.29, Section 13.6.2 and 13.7.2). Some adaptation options are found to be 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; Åström et al., 2017; Dino and Meral Akgül, 2019; Venter et al., 2020), although air conditioning increasingly faces some feasibility constraints (Figure 13.20). Building interventions alone have low to medium effectiveness independent of the region. Many behavioural changes such as personal and home heat protection have already been implemented in SEU (Section 13.7.2, Martinez et al., 2019). To reach high adaptation, a combination of low, medium, and high effectiveness measures in different sectors and sub-regions is needed, many of which entail systems' transformations (Chapter 16) (e.g., heat proof land management) and remain effective at higher warming levels (*medium confidence*) (Díaz et al., 2019). These transformations have long lead times, therefore requiring timely start of implementation including regions that are not yet experiencing high heat stress (e.g. NEU) (*high agreement, medium evidence*).

Autonomous adaptation of species via migration in response to climate change is well documented in contemporary, historical and geological records (Chapter 2, Cross-Chapter Box PALEO in Chapter 1). However, the projected rate of climate change can exceed migration potential, leading to evolutionary adaptation or increased extinction risk (Chapters 2 and 3; Sections 13.3 and 13.4). 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 (Sections 13.3 and 13.4, Ramírez et al., 2018) (*high confidence*). A major governance tool to reduce climatic and non-climatic impacts is the establishment of networks of protected areas (Sections 13.3.2 and 13.4.2) especially when aggregated, zoned or linked with corridors for migration (*high confidence*), as well as a cost-effective adaptation strategy with multiple additional co-benefits (Berry et al., 2015; Roberts et al., 2017). Reforestation, rewilding and habitat restoration are long term strategies for reducing risk for biodiversity loss supported by assisted migration and evolution (Section 13.3.2, 13.4) though current laws and regulations do not include species migration (*high confidence*) (Prober et al., 2019; Fernandez-Anez et al., 2021).

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Very high risks are expected beyond 3°C GWL due to the magnitude and increased likelihood of serious consequences, as well as to the limited ability of humans and ecosystems to cope with these impacts. There is *high confidence* that even under high adaptation scenarios for human systems or autonomous adaptation of natural systems, the risk will still be high at 3°C GWL and beyond (Section 13.7.2, Hanna and Tait, 2015; Spencer et al., 2016) with *medium confidence* on the temperature range of the transition. Projected sea level rise will strongly impact coastal ecosystems (*high confidence*), minimising their contribution to shoreline protection (Section 13.10.2.4).

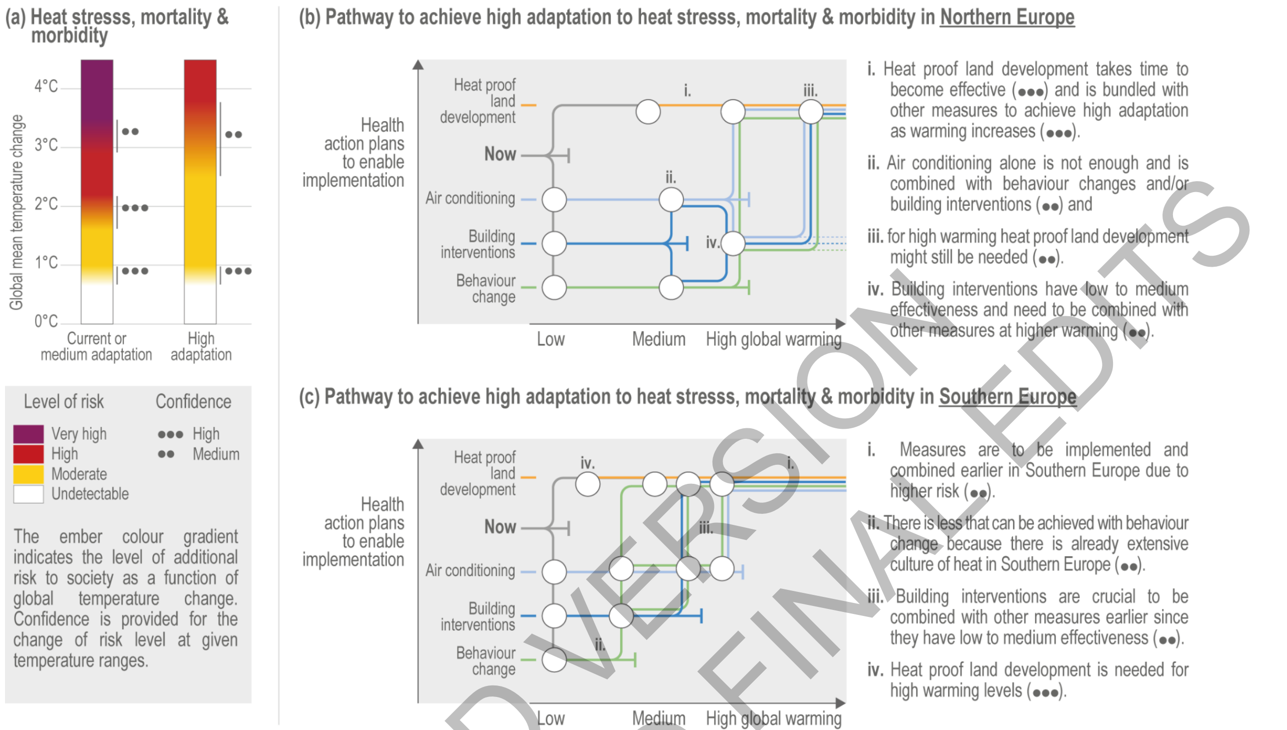

Figure 13.29: (a) Burning ember diagrams for the risk to human health from heat. The low/medium adaptation scenario corresponds to present, SSP2 and SSP4 socio-economic conditions. The high adaptation includes SSP1 and adaptation needed to maintain current risk levels. (b-c) Illustrative adaptation pathways for NEU (top) and SEU (bottom) and key messages based on the feasibility and effectiveness assessment in Figures 13.20 and 13.24. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point. (Tables SM13.24, SM13.25)

13.10.2.2 KR2: Risk of losses in crop production, due to compound heat and dry conditions, and extreme weather

KR2 encompasses agriculture productivity (Figure 13.30a). It is mainly driven by the increase in the likelihood of compound heat and dry conditions and extremes and their impact on crops. There is *high confidence* that climate change will increase the likelihood of concurrent extremely dry (Table SM13.28) and hot warm seasons with higher risks for WCE, EEU (particularly north-western Russia) and SEU leading to enhanced risk of crop failure and decrease in pasture quality (Section 13.5.1) (Zscheischler and Seneviratne, 2017; Sedlmeier et al., 2018; Seneviratne et al., 2021). The risk is already moderately severe due to multiple crop failures in the last decade in WCE and Russia (Section 13.5.1, Hao et al., 2018; Pfleiderer et al., 2019; Vogel et al., 2019). Under high-end scenarios, heat and drought extremes are projected to become more frequent and widespread as early as mid-century (Toreti et al., 2019a). For present to moderate adaptation and at least up to 2.5°GWL, negative consequences are mostly in SEU (Bird et al., 2016; EEA, 2019c; Moretti et al., 2019; Feyen et al., 2020). The transition from moderate to high risk is projected to happen around 2.7°C GWL when hazards and risk will become more persistent and widespread in other regions (Section 13.1, Deryng et al., 2014; Donatelli et al., 2015; Webber et al., 2018; Ceglar et al., 2019; Ranasinghe et al., 2021; Seneviratne et al., 2021). This temperature increase will trigger shift of agricultural zones, onset of early heat stress, losses in maize yield of up to 28% across EU-28, and regional disparity in losses and gains in wheat, which are not able to offset losses across the continent (Deryng et al.,

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2014; Szewczyk et al., 2018; Ceglar et al., 2019). There will be also broader adverse impacts such as reduction of grassland biomass production for fodder, increases in weeds and reduction in pollination (Castellanos-Frias et al., 2016; Nielsen et al., 2017; Brás et al., 2019) (*medium confidence*). Combined with socio-economic development, increased heat and drought stress and reduced irrigation water availability in SEU are projected to lead to abandonment of farmland (Holman et al., 2017). Around 4°C GWL, the risk is very high due to persistent heat and dry conditions (Ben-Ari et al., 2018) and the emergence of losses also in NEU which would be much higher without the assumed CO_2 fertilisation (Deryng et al., 2014; Szewczyk et al., 2018; Harrison et al., 2019).

Farmers have historically adapted to environmental changes and such autonomous adaptation will continue. Higher CO_2 levels have a fertilisation effect on plants that is considered to decrease production risks (Deryng et al., 2014). Adaptation solutions to heat and drought risks include changes in sowing and harvest dates, increased irrigation, changes in crop varieties, the use of cover crops, and mixed agricultural practices (Section 13.5.2; Figure 13.14 and Figure 13.30b). Under high adaptation, the use of irrigation can substantially reduce risk by both reducing canopy temperature and drought impacts (*high confidence*) (Section 13.5.2, Webber et al., 2018). Some reductions of maize yields in SEU are still possible, but are balanced by gains in other crops and regions (Deryng et al., 2014; Donatelli et al., 2015; Webber et al., 2018; Feyen et al., 2020). At 3°C GWL and beyond, the adaptive capacity is reduced (Ruiz-Ramos et al., 2018). Crop production is a major consumer of water in agriculture (Gerveni et al., 2020), yet a potentially scarcer supply of water in some regions must be distributed across many needs (KR3, Section 13.10.2.3), limiting availability to agriculture which is currently the main user of water in many regions of Europe (Section 13.5.1) (*high confidence*). Where the ability to irrigate is limited by water availability, other adaptation options are insufficient to mitigate crop losses in some sub-regions, particularly at 3°C GWL and above, with an increase of risk from north to south and higher risk for late-season crops such as maize (*high confidence*). Under these conditions, land abandonment is projected (Holman et al., 2017) (*low confidence*).

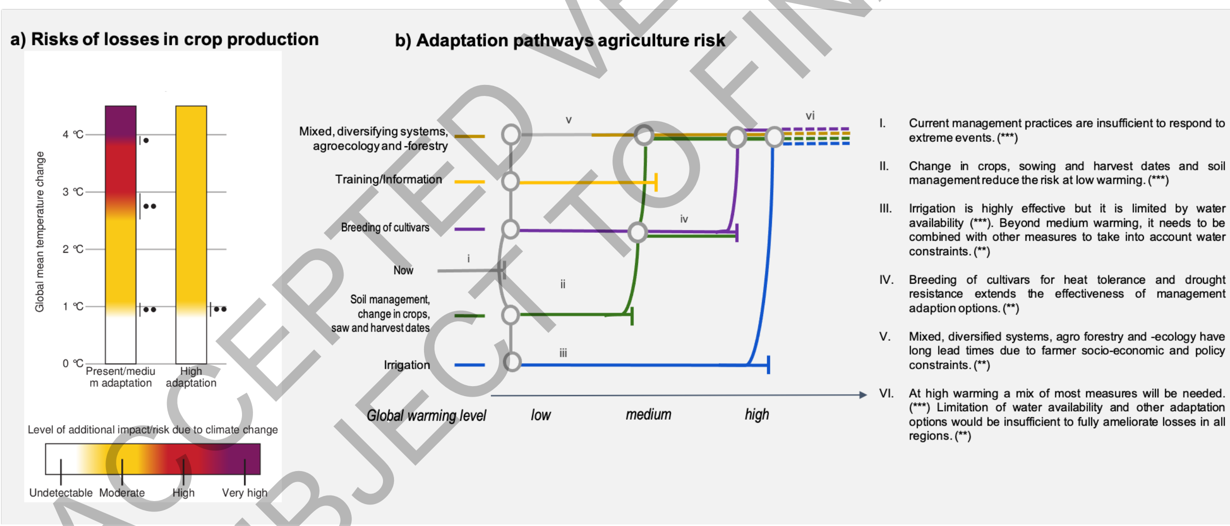

Figure 13.30: (a) Burning ember diagrams for losses in crop production with present or medium adaptation condition and with high adaptation. Panel (b) Illustrative adaptation pathways and key messages based on the feasibility and effectiveness assessment in Figure 13.14. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point (Table SM13.28).

13.10.2.3 KR3: Risk of water scarcity to multiple interconnected sectors

Risks related to water scarcity across multiple sectors can become severe in WCE and to a much larger extent in SEU based on projections of drought damage, population and sectors exposed and increases in water exploitation (Figure 13.31a; Table SM13.29). In EEU, uncertainty in hydrological drought projections and risk consequences is higher (Greve et al., 2018; Ranasinghe et al., 2021; Seneviratne et al., 2021) and the available number of publications is lower, not allowing a conclusion on how risk levels change with GWL. Yet, there is emerging evidence that drought related risks increase with warming beyond 3°C GWL also in

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EEU (Seneviratne, 2021 #12291for hydrological drought and 4°C GWL, Kattsov and Porfiriev, 2020). Evidence from the D&A assessment suggests that the risk is already moderate in SEU (e.g. 48 million people exposed to moderate water scarcity between 1981-2010) (Section 13.10.1, Figure 13.31a) (*high confidence*).

Risks have a high potential to lead to cascading impacts well beyond the water sector since water scarcity affects a number of highly interconnected sectors in Europe, from agriculture and livestock farming to 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). Extensive water extraction will augment pressures on water reserves, impacting the ecological status of rivers and ecosystems dependent on them (Grizzetti et al., 2017). Socioeconomic conditions contributing to severe consequences are when more residents settle in drought-prone regions, or when the share of agriculture in GDP declines (*high confidence*). For Europe, risks of water scarcity will be higher under SSP5 and SSP3 than under SSP1 (*medium confidence*) (Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019). Transition to high risks is projected to occur below 2°C GWL in SEU and associated with more persistent droughts (Section 13.1.3) and at 2°C GWL with 54% increase of the population facing at least moderate levels of water shortage (Byers et al., 2018). This transition will happen at higher warming in WCE since risks are projected to increase less rapidly (transition between 2-3°C GWL) (*medium confidence*) (Section 13.2.1.2, Byers et al., 2018). At 3°C GWL and beyond, water scarcity will become much more widespread and severe in already water scarce areas in SEU (*high confidence*) and will expand to currently non-water scarce regions in WCE (*medium confidence*) (Section 13.2.1.2, Bisselink et al., 2018; Naumann et al., 2018; Harrison et al., 2019; Koutroulis et al., 2019; Cammalleri et al., 2020; Spinoni et al., 2020). Decrease in hydropower potential in SEU and WCE are expected beyond 3°GWL (Figure 13.16).

To reduce risk severity, adaptation measures both at supply and demand level have been suggested (Section 13.2.2, Figure 13.6, Figure 13.31b, Garnier and Holman, 2019; Hagenlocher et al., 2019). Several measures are already in place, showing high technical and institutional feasibility (Section 13.2.2.2 and 13.5.2.1). The effectiveness of options varies regionally (in particular between northern and southern regions). For example, in SEU many water reservoirs are already in place. Irrigation is used to support agriculture where rainfed supplies are not sufficient (13.5.2). Their future extension depends on available precipitation. Also, wastewater reuse can only be effective if sufficient wastewater is available. Improvements in water efficiency and behavioural changes are very effective in SEU (>25% of damages avoided) (Section 13.2.2.2). Investments in large water infrastructures and advanced technologies (incl. storage), water transfer, water recycling and reuse and desalination allow to buy time and therefore to cope with additional warming (Papadaskalopoulou et al., 2016; Greve et al., 2018). Beyond 2.5°C GWL, transformational adaptation is needed to lower risk levels, such as planned relocation of industry, abandonment of farmland or the development of alternative livelihoods (Holman et al., 2017). In WCE the solution space to water scarcity is expanding with considerable potential for investments in large water infrastructure and advanced technologies (incl. storage), for reducing risks above 3°C GWL (Greve et al., 2018). Under medium warming a larger portfolio of measures might be needed in SEU in particular, although it may not be able to completely avoid water shortages at high warming.

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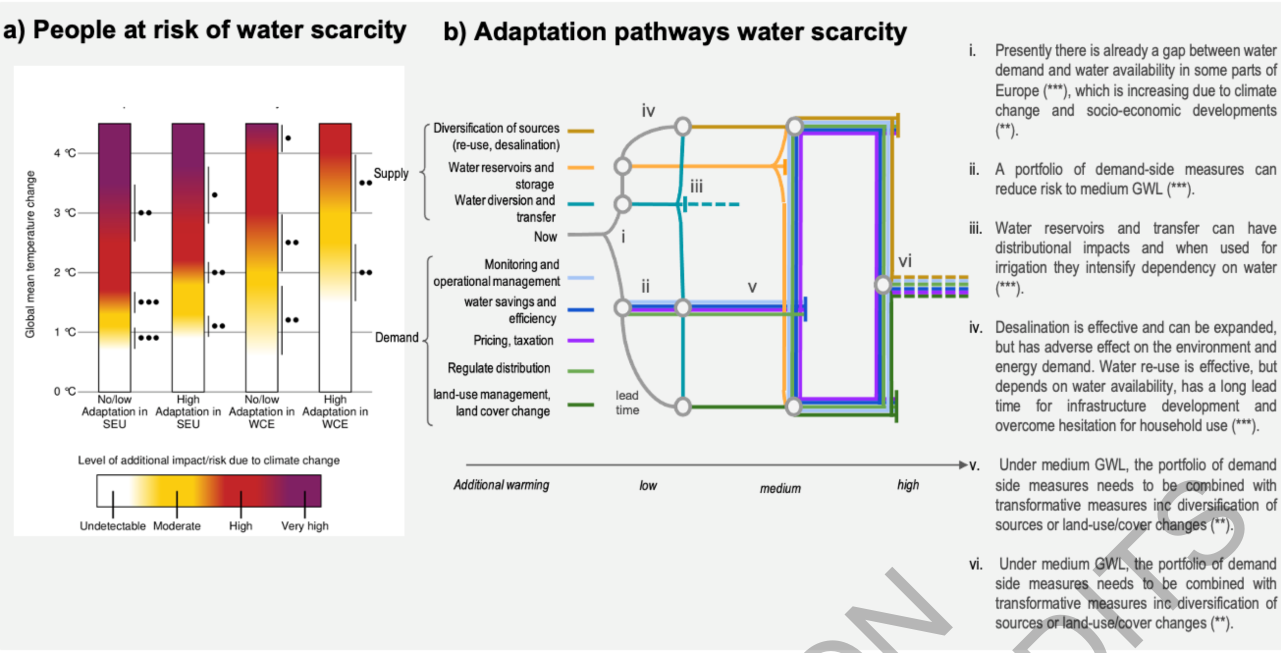

Figure 13.31: (a) Burning ember diagrams for the risk of water scarcity with no/low adaptation and with high adaptation for SEU and WCE. (b) Illustrative adaptation pathways and key messages (see Figure 13.6). Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point (Table SM13.29).

13.10.2.4 KR4: Risks to people, economies and infrastructures due to coastal and inland flooding

Damages and losses from coastal and river floods are projected to increase substantially in Europe over the 21st century (*high confidence*) (Section 13.2.1, SM13.10). Coastal areas have already started to be affected by sea level rise (Box13.1; Section 13.10.1) and human exposure to coastal hazards is projected to increase in the next decades (*high confidence*), but less under SSP1 (20%) than SSP5 (50%) by the end of the century (*medium confidence*) (Merkens et al., 2016; Reimann et al., 2018a). Under low adaptation (i.e. coastal defences are maintained but not further strengthened), severe consequences include increase in expected annual damage by a factor of at least 20 for 1.5-2.1°C GWL (i.e.. high risks) and by 2-3 orders of magnitude between 2 and 3°C GWL in EU-28 (i.e. very high risk) (*medium confidence*) (Figure 13.28, 13.34c; Section 13.2.1.1); (Vousdoukas et al., 2018b; Haasnoot et al., 2021b). Under high adaptation (i.e. lowlands are protected where it is economically efficient), expected annual damages still increase by a factor of 5 above 2°C GWL (Section13.2, Vousdoukas et al., 2020). Sea-levels are committed to rise for (Fox-Kemper et al., 2021), submerging at least 10% of the territory in 12 countries in Europe after millennia if GWL exceed 1.5-2.5°C (Clark et al., 2016), and this represents a major threat for the European and Mediterranean cultural heritage (Figure 13.28, Cross-Chapter Box SLR in Chapter 3, CCP4, Marzeion and Levermann, 2014; Reimann et al., 2018b).

Pluvial and riverine flood events in Europe have been attributed to climate change, but the associated damages and losses also depend on land use planning and flood risk management practices (*medium confidence*) (Section 13.10.1, Ranasinghe et al., 2021). Exposure to urban flooding will increase with urbanization (Jongman et al., 2012; Jones and O'Neill, 2016; Dottori et al., 2018; Paprotny et al., 2018b). Flooding is projected to rise with temperature in Europe, with e.g. a doubling of damage costs and people affected from river flood for low adaptation above 3°C GWL (Alfieri et al., 2018). Inland flooding represents a key risk for Europe due to the extent of settlements exposed, the frequency of the hazards, the risks to human lives associated with flash floods and the limited adaptation potential to pluvial flooding (e.g. difficulty to upgrade urban drainage systems (Dale et al., 2018; Dale, 2021). Hence, risks can become very high from 3°C GWL (Figure 13.32a).

A range of adaptation options to coastal flooding exists and adaptation is possible in many European regions if started on time (Section 13.2 and Figure 13.32d). Continuing a protection pathway is cost-effective in urbanized regions for this century (Vousdoukas et al., 2020), but there is *high agreement* that it comes with

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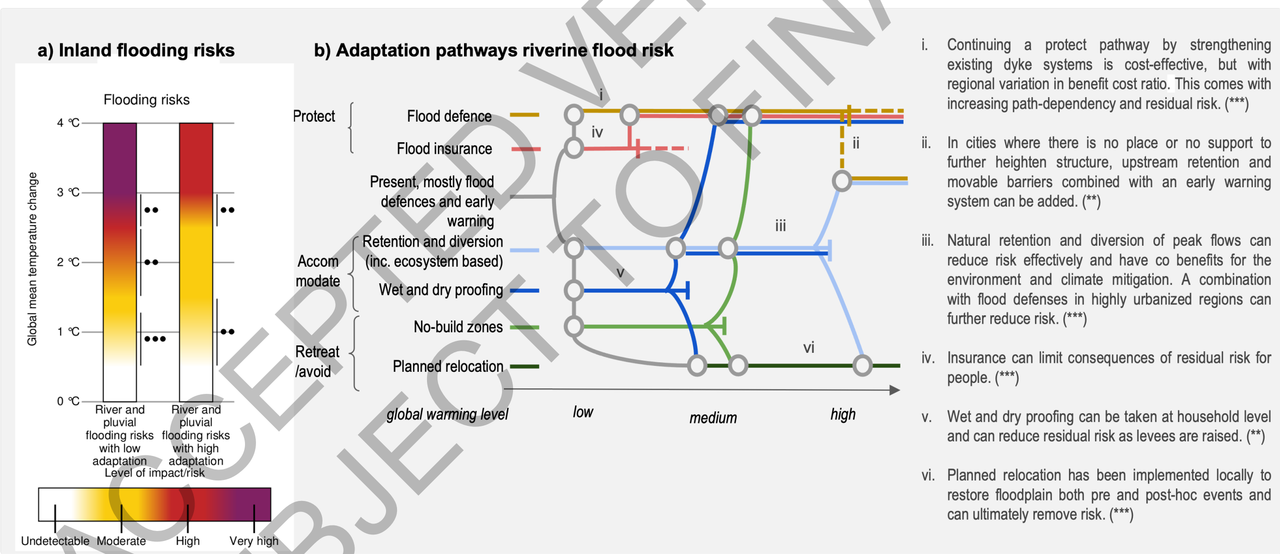
residual risk if coastal defences fail during a storm. This residual risk can be reduced through early warning and evacuations, insurance and accommodate measures (Section 13.2.2). Soft limits to protection have been identified under high GWL, in particular due to the rate of change and delayed impacts of long-term SLR (*medium confidence*) (Hinkel et al., 2018; Haasnoot et al., 2020a). Ecosystem based solutions such as wetlands can reduce waves' propagation, provide co-benefits for the environment and climate mitigation, and reduce costs for flood defences (*medium confidence*) (Section 13.2.2.1). At higher GWL, ecosystems are projected to experience reduced effectiveness due to temperature increase and increased rate of SLR combined with lack of sediment and human pressures (Cross-Chapter Box SLR in Chapter 3). Retention and diversion can be effective for compound flooding or for estuaries with a limited storm surge duration, but there is lack of knowledge on their effectiveness (Sections 13.2.2).

In the case of river flooding, adaptation has the potential to contain damage and losses up to 3°C GWL (Figure 13.32b, Jongman et al., 2014; Alfieri et al., 2016), provided they are implemented on time and that the technical, social and financial barriers are addressed (Sections 13.2.2 and 13.6.2). Residual risks can be reduced through early warning and evacuations, insurance and accommodate measures (see Section 13.2.2, Kreibich et al., 2015). Accommodation strategies such as retention and ecosystem-based solutions require space, which is not always available in cities. Both protection and flood retention are effective in reducing inland flooding risk across Europe, but with regional variation in the benefit-to-cost ratio (Alfieri et al., 2016; Dottori et al., 2020) (*medium confidence*). Furthermore, upgrading drainage systems to accommodate increase in pluvial flooding is costly, technically complex and requires time (Dale et al., 2018; Dale, 2021).

Avoiding developments in risk-prone areas can reduce both coastal and inland flooding risks and can be followed by planned relocation, particularly in less-populated areas. To align relocation with social goals and to achieve positive outcomes long lead times are needed (Haasnoot et al., 2021a).



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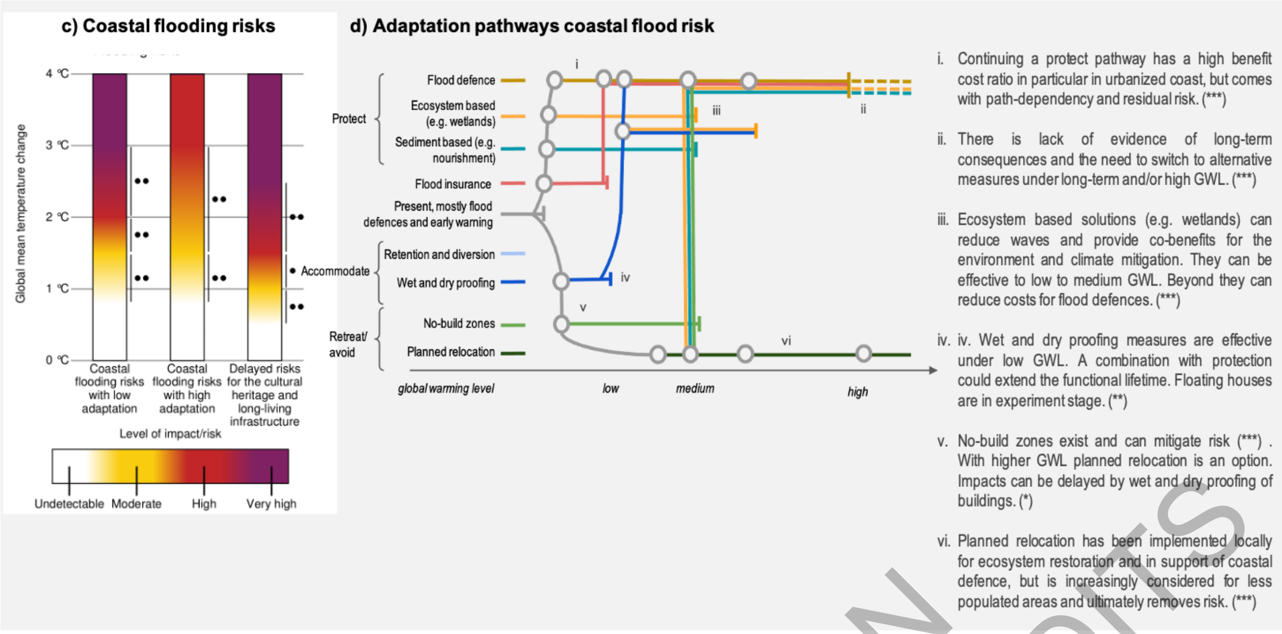

Figure 13.32: (a) Burning ember diagram for the risks from riverine and pluvial flooding with and without adaptation. (b) Illustrative adaptation pathways to riverine flooding risks. (c) Burning ember diagram for the risks from coastal flooding with and without adaptation. (d) Illustrative adaptation pathways to coastal flooding risks. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars that the measure have reached a tipping point.(Tables SM13.30, SM13.31)

13.10.3 Consequences of Multiple Climate Risks for Europe

European regions are affected by multiple key risks simultaneously; while there is a wide range in quantifications, there is high agreement that consequences for socio-economic and natural systems can be substantial, with more severe consequences in the south than in the north *(very high confidence*); there is some indication also for a west to east gradient, with higher uncertainty in eastern part of WCE and EEU which makes adaptation more challenging (*medium confidence*). Furthermore, the food-water-energy-land use nexus plays an important role in amplifying overall risk levels in Europe (*medium confidence*) (Forzieri et al., 2016; Harrison et al., 2016; Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019; Kebede et al., 2021). Southern Europe, European cities and coastal areas are projected to become hotspots of multiple risks (Cramer et al., 2018; Forzieri et al., 2018; Guerreiro et al., 2018) (*high confidence*). The number of people exposed to multiple KRs in Europe are projected to at least double at 3°C GWL compared to 1.5°C GWL (Forzieri et al., 2017; Byers et al., 2018; Arnell et al., 2019), but risk levels are already higher at 1.5°C GWL than today for a number of KRs (Figure 13.28) (*medium confidence*).

Economic losses and damages for European economies from multiple KRs are projected increase (*high confidence*) (Figure 13.34, Szewczyk et al., 2018; Feyen et al., 2020; Kalkuhl and Wenz, 2020), potentially quadruple at 3°C GWL compared to 1.5°C GWL (Feyen et al., 2020). Existing estimates of projected economic costs for Europe, based on integrated assessment or computable general equilibrium models, are however *likely* to be underestimations of the true costs because of incomplete coverage of biophysical impacts, in particular low-probability high impact events, and disruptive risk propagation channels (Lamperti et al., 2018; Stoerk et al., 2018; Schewe et al., 2019; Piontek et al., 2021). The main driver for this increase in economic losses and damages is mortality due to heat stress (*medium confidence*), followed by reduced labour productivity, coastal and inland flooding, water scarcity and drought (*medium confidence*) (Figure 13.33; Section 13.6.1.3). While losses are highest in SEU for both 1.5°C and 3°C GWL and increase by a factor of more than three between these GWLs, the projected economic damages and losses also increase significantly in WCE (by a factor of 4 from 1.5°C to 3°C GWL; 40% of total losses in EU-28 at 3°C GWL) and in NEU (almost 10% of total losses at 3°C GWL) (Szewczyk et al., 2018; Szewczyk et al., 2020). Adaptation is projected to reduce macroeconomic costs, but residual costs remain, particularly for warming above 3°C GWL (*medium confidence*) (De Cian et al., 2016; Bosello et al., 2018; Parrado et al., 2020).

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Economic risk	Key Risk	GWL	NEU	WCE	EEU	SEU	references (n)
Change in agricultural yields	KR1, KR2	1.5°C	••	••	LE	••	3
		3°C	••	•	••	•••	6
Change in labour productivity	KR1	1.5°C	••	••	••	••	5
		3°C	••	••	•	•••	6
Change in energy demand	KR1	1.5°C	•	•	LE	•	2
		3°C	••	••	•	••	3
Change in mortality due to heat	KR1	1.5°C	••	••	LE	••	2
		3°C	••	••	•	••	5
Damage to economic sectors from water scarcity ad drought	KR3	1.5°C	•	•	LE	••	4
		3°C	•	••	LE	••	2
Change in energy supply	KR3	1.5°C	•	•	LE	•	2
		3°C	•	•	•	•	3
Damage to infrastructure from coastal flooding	KR4	1.5°C	••	••	LE	••	4
		3°C	••	••	••	•••	8
Damage to infrastructure from inland flooding	KR4	1.5°C	••	••	•	••	6
		3°C	••	••	•	••	7

Economic damage/loss (% of GDP or welfare)						Economic gain (% of GDP or welfare)
very high >1%	high 0.1% - 1%	moderate 0.01% - 0.1%	no <0.01%	moderate 0.01% - 0.1%	high 0.1% - 1%	very high >1%
Confidence: high (•••), medium (••), low (•)					both	LE (limited evidence)

Figure 13.33: Economic losses/damages and gains due to projected climate risks, for 1.5°C and 3°C GWL relative to no additional warming; macroeconomic effects measured in GDP or welfare. Effect for EEU report for Russia as a whole country, deviating from the definition of EEU in this chapter. Effects may deviate from sectoral assessments in Sections 13.2-13.7 due to different degree of coverage of risk channels (Table SM13.23).

13.10.4 Knowledge Gaps

Information on risk levels and development are available for 1.7°C, 2.5°C and > 4°C GWL, making the determination of transitions for the burning embers challenging and impairing a comprehensive assessment across key risks. Further efforts to extend the SSP narratives to Europe can contribute to a more disaggregated understanding of risk severity for different vulnerability and exposure conditions, but the evidence to date remains limited to few sectors (CCP4, Kok et al., 2019; Pedde et al., 2019; Rohat et al., 2019). There is only very *limited evidence* on the extent and timing of residual risks under different GWL, even with high adaptation.

There is *medium confidence* on the effectiveness of adaptation beyond 3°C GWL particularly where risks are high to very high (Figures 13.28-13.32). There is *limited evidence* on the effectiveness of specific adaptation options at different levels of warming that also include consideration of lead and lifetimes. An integrated assessment, which projects the impacts on crop production by examining the potential availability of water for agricultural purposes together with other adaptation measures, is missing.

Transboundary risks, interactions between commodity and financial markets, market imperfections, non-linear socio-economic responses, and loss of ecosystem services, may amplify losses for European economies. Available models may underestimate the full costs of climate change as they generally neglect systemic risks, tipping points, indirect and intangible losses and limits to adaptation (Dafermos et al., 2018; Lamperti et al., 2018; van Ginkel et al., 2020; Dasgupta et al., 2021; Ercin et al., 2021; Piontek et al., 2021). With increasing global warming, compound, low likelihood, or unprecedented extremes such as the European dry and hot summer 2018 or the extreme rainfall following storm Desmond in the UK in 2015, become more frequent (AR6 WGI Cross-Chapter Box 11.2). These events can have catastrophic

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consequences for Europe, but the extent of economic and non-economic damages and losses remain largely uncertain.

13.11 Societal Adaptation to Climate Change across Regions, Sectors and Scales

Building on our sectoral analysis in previous sections, this section looks across European sectors, vulnerable groups, and regions to assess how climate change impacts are being responded to in general by state (Section 13.11.1) and non-state (Section 13.11.2) 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).

13.11.1 Policy Responses, Options and Pathways

13.11.1.1 Progress on Adaptation Planning and Implementation

The solution space for climate change adaptation has expanded across European regions since AR5 (*high confidence*). European countries are increasingly planning to adapt to observed impacts and projected climate risks across scales of government (Lesnikowski et al., 2016; Russel et al., 2020) (*high confidence*). Whereas in 2009, only nine EU countries had developed a National Adaptation Strategy (NAS) (Biesbroek et al., 2010; EEA, 2014), by mid-2020 all EU Member States and several other European countries had adopted at least a NAS and/or revised and updated prior strategies (Figure 13.34, bottom, Klostermann et al., 2018; EEA, 2020a). Progress is also observed at the level of the European Union with the adoption of the new EU strategy on adaptation to climate change in 2021 (European Comission, 2021a) and regionally, particularly in federalist and decentralised states (Steurer and Clar, 2018; EEA, 2020c; Pietrapertosa et al., 2021), and locally, with an increasing number of European cities planning for climate risks (Aguiar et al., 2018; Reckien et al., 2018; Grafakos et al., 2020) (Section 13.6.2.1;Box 13.3;Chapter 6) (*high confidence*). There is evidence of action across sectors and scales, even in European countries where national adaptation frameworks are absent (Figure 13.34) (De Gregorio Hurtado et al., 2015; Pietrapertosa et al., 2018; Reckien et al., 2018) (*medium confidence*). However, 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, persists in Europe (Aguiar et al., 2018; Russel et al., 2020; UNEP, 2021).

The drivers of adaptation progress in Europe differ across sectors and regions. Common drivers include: experienced climatic events, improved climatic information, societal pressures to act, projected economic and societal costs of climate change, participation in (city) networks, societal and political leadership, and changes in national and European policies and legislation (*medium evidence, high agreement*) (EEA, 2014; Massey et al., 2014; Reckien et al., 2018). The availability of human, knowledge, and financial resources appears important for proactive adaptation(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018)(Termeer et al., 2012; Sanderson et al., 2018), while adaptation is also strongly dependent on economic and social development (Sanderson et al., 2018) (*high confidence*). How adaptation is governed differs substantially across Europe (Clar, 2019; Lesnikowski et al., 2021). Political commitment, persistence and consistent action across scales of government is critical to move beyond planning for adaptation (Step A to C in Figure 13.34) and to ensure adequacy of implementation (Step D and E in Figure 13.34) (Howlett and Kemmerling, 2017; Lesnikowski et al., 2021; Patterson, 2021).

The scope of climate risks included in European adaptation policies and plans (Step B in Figure 13.34) is generally broad (EEA, 2018a). Systemic and cascading risks (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 (Cross-Chapter Box GENDER in Chapter 18, Boeckmann and Zeeb, 2014; Allwood, 2020).

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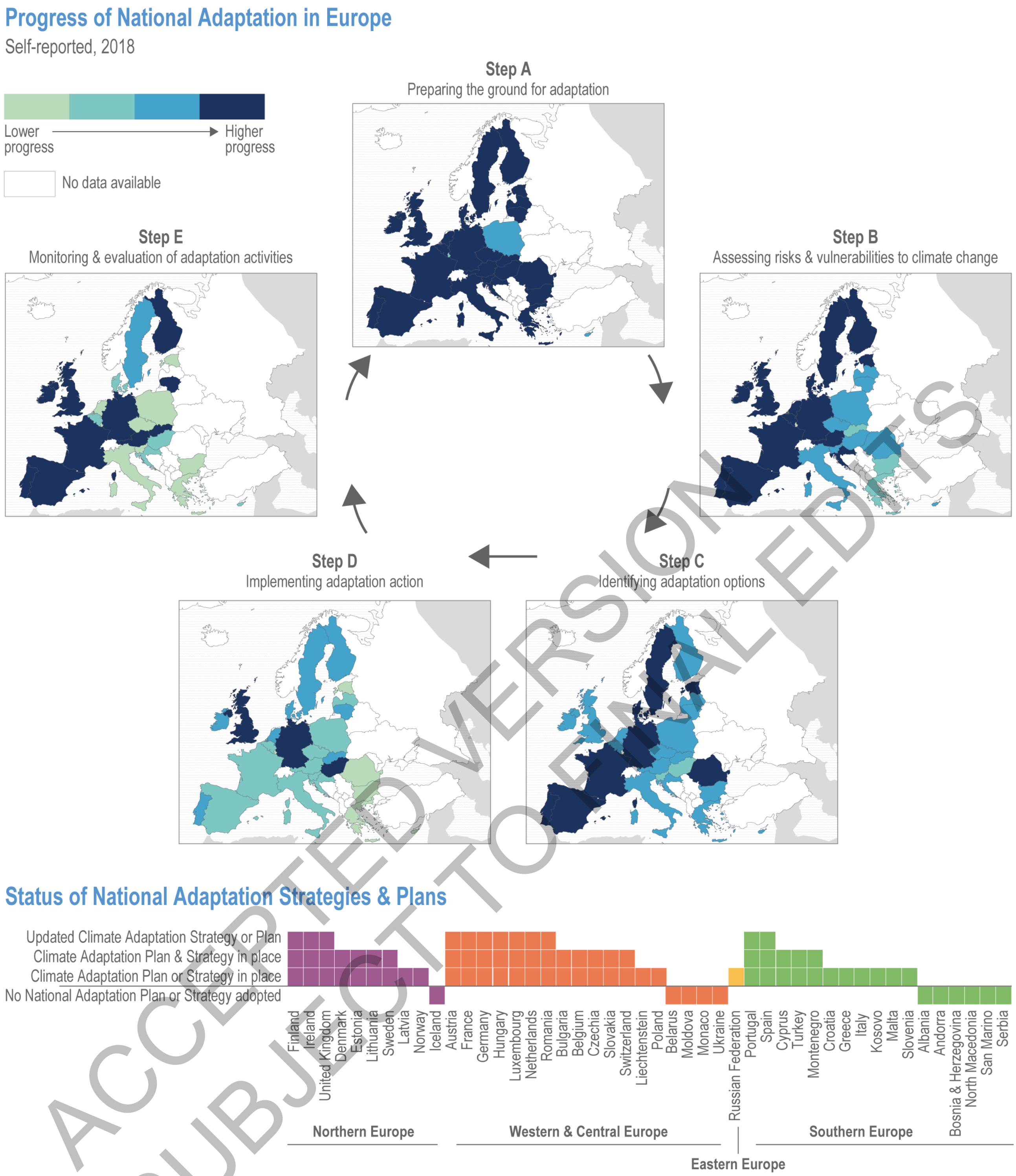

Figure 13.34: Progress of National Adaptation in Europe in 2018 and Status of National Adaptation Plans and Strategies in 2020. Data on the progress of national adaptation are from the self-reported status of EU members, as documented in the Adaptation Scoreboard for Country fiches (SWD(2018)460). The status of national adaptation plans and strategies data are from EEA Report 6/2020 (2020a), the ClimateADAPT portal (EEA, 2021a) and from the Grantham Institute database Climate Change Laws of the World (Grantham Research Institute, 2021).

Many near-term investment decisions have long-term consequences, and planning and implementation (Step C and D in Figure 13.34) can take up to decades, particularly for critical infrastructure planning in Europe (Zandvoort et al., 2017; Pot et al., 2018). Consequently, there are calls to expand planning horizons, to consider long-term uncertainties to prevent lock-in decision dependencies, to seize opportunities and synergies from other investments (e.g., socio-economic developments and systems transitions) and to broaden the range of considered possible impacts (e.g. Frantzeskaki et al., 2019; Marchau, 2019;

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Oppenheimer et al., 2019; Haasnoot et al., 2020b). Yet, high GWL scenarios beyond 2100 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; Taylor et al., 2020). High GWL 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). Extending planning horizons to beyond 2100 increases deep uncertainties for 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 (Fox-Kemper et al., 2021).

Adaptive planning and decision making are still limited across Europe (*high confidence*). Prominent examples of adaptive plans include the flood defence systems for the City of London (Ranger et al., 2013; Kingsborough et al., 2016; Hall et al., 2019) and the Netherlands (Van Alphen, 2016; Bloemen et al., 2019) Adaptation pathways have been also developed for planning of urban water supply (Kingsborough et al., 2016; Erfani et al., 2018), urban drainage (Babovic and Mijic, 2019) and wastewater systems (Sadr et al., 2020) (Cross-Chapter Box DEEP in Chapter 17). 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), but require appropriate design to be effective (Metzger et al., 2021).

Monitoring and evaluation of adaptation action is only done in some European countries (Figure 13.34, part E), but is important for adjusting planning, if needed (Hermans et al., 2017; Haasnoot et al., 2018), and enhancing transparency and accountability of progress (Mees and Driessen, 2019). In the Netherlands, a comprehensive monitoring system has been put in place, including signals for adaptation that support decisions on when to implement adaptation options or to adjust plans (Hermans et al., 2017; Haasnoot et al., 2018; Bloemen et al., 2019).

13.11.1.2 Mainstreaming and Coordination

Coordinated responses are necessary to prevent inefficient and costly action (Biesbroek, 2021), balance under- and over-reaction to climate risks (Peters et al., 2017; Biesbroek and Candel, 2019), avoid redistributing vulnerability and maladaptive actions (Atteridge and Remling, 2018; Albizua et al., 2019; Neset et al., 2019), and ensure timely implementation (Benson and Lorenzoni, 2017) (*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 SEU, WCE depending on impact) (Lesnikowski et al., 2016; Biesbroek and Delaney, 2020; Booth et al., 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 mainstreaming adaptation (Runhaar et al., 2018) (*high confidence*).

While mainstreaming of adaptation into other policy domains has been advocated as an enabler for adaptation, it may have resulted incremental rather than transformational adaptation, and may not be sufficient to close the adaptation gap (Andersson and Keskitalo, 2018; Remling, 2018; Scoville-Simonds et al., 2020).

13.11.1.3 Climate Services and Local Knowledge

Climate services to support adaptation decision-making of governments and businesses across Europe have rapidly increased since AR5, partly as a result of national and EU investments such as the Copernicus C3S service (*high confidence*) (Street, 2016; Soares and Buontempo, 2019). These services are increasingly used in NEU, SEU and WCE for example in energy and risk prevention in coastal and riverine cities, stimulating regulations and bottom-up initiatives (Cavelier et al., 2017; Le Cozannet et al., 2017; Reckien et al., 2018; Howard et al., 2020). However, climate service efficacy is rarely systematically evaluated (Cortekar et al., 2020). Barriers to use include: lack of perceived usefulness of climate information to organisations and expertise to use the information, outdated statistics, mismatch between needs and type of information made available, insufficient effective engagement between providers and recipients of climate information and lack of business models to sustain climate services over time (*high evidence, medium agreement*) (Cavelier et al., 2017; Räsänen et al., 2017; Bruno Soares et al., 2018; Christel et al., 2018; Oberlack and Eisenack,

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2018; Hewitt et al., 2020). Adaptation decision support platforms also face challenges regarding updating, training and engagement with users (EEA, 2015; Palutikof et al., 2019).

In addition to scientific knowledge, traditional and local knowledges can enable adaptation action (Huntington et al., 2017) as is the case with indigenous-led ecosystem restoration in the European Arctic (Brattland and Mustonen, 2018). There is a need to draw on surviving Indigenous knowledge systems in Europe (Greenland, Nenets, Khanty, Sámi, Veps, Ingrian) as unique, endemic ways of knowing the world that can position present and historical change in context and offer unique reflections of change in the future (Ogar et al., 2020; Mustonen et al., 2021).

13.11.1.4 Financing Adaptation and Financial Stability

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 (EEA, 2020b). Current adaptation spending varies greatly across and within European countries, partly reflecting (sub-)national adaptation priorities or financing sources targeting investment projects (López-Dóriga et al., 2020; Russel et al., 2020) and competing statutory priorities (Porter et al., 2015). European government budgets are also burdened by climate change damages today, particularly after huge flooding events, and austerity following financial crises, limiting anticipatory action (Penning-Rowsell and Priest, 2015; Miskic et al., 2017; Schinko et al., 2017; Slavíková et al., 2020). National adaptation funding in EU member states is complemented by EU funding (e.g. European Structural and Investment Funds (ESIF), European Regional Development Funds, and LIFE program). While the EU spending target on climate action increased from 20% in 2016-2020 to 25% in 2021-2026, most spending is going into mitigation, not adaptation (Berkhout et al., 2015; Hanger et al., 2015; EEA, 2020b).

With higher warming levels, financing needs are *likely* to increase (*high 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 et al., 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 (EEA, 2020b).

Since AR5, new evidence has emerged that climate change may deteriorate financial stability both at the global and European scale (Campiglio et al., 2018; Dafermos et al., 2018; Lamperti et al., 2019; ECB, 2021a). The European Central Bank, the European Systemic Risk Board, and several national central banks in NEU and WCE have started to systematically assess the consequences of climate risks for financial stability and plan to integrate climate stress testing into their supervisory tools (Batten et al., 2016; ECB, 2021a; ECB, 2021b).

13.11.2 Societal Responses, Options and Pathways

13.11.2.1 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 (Trawöger, 2014; Dannevig and Hovelsrud, 2016; Ray et al., 2017; Ricart et al., 2018). Whereas some sectors such as flood management, banking and insurance, and energy (Bank of England, 2015; Gasbarro and Pinkse, 2016; Bank of England, 2019; Wouter Botzen et al., 2019) have generally made moderate progress on adaptation planning across

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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., 2016; Gasbarro et al., 2017). For instance, following the implementation of the recommendations of the Task Force on Climate-Related Financial Disclosure (TFCD) by the European Commission in 2019, 50 publicly listed companies revealed their exposure to their physical climate risks in 2020 (CDSB, 2020). But even if companies experience extreme weather events or stakeholder pressure, they may not adapt because they underestimate their vulnerability (Pinkse and Gasbarro, 2019) (Table 13.1). For example, key barriers to adaptation among Greek firms include both external (e.g., lack of support/guidance) and internal factors (e.g., few resources, managerial perceptions (Halkos et al., 2018). Lack of knowledge, feeling climate change is not a salient risk, and lack of social learning or collaboration, appear to be key 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).

13.11.2.2 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) (Sections 13.2.1, 13.6.1); 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) (Section 13.2). Amongst the adaptation responses recorded, few are perceived as opportunities (Taylor et al., 2014; Simonet and Fatorić, 2016). There is currently little European research on public responses to risks other than flooding, heat stress and drought, such as vector-borne disease, and to multiple and cascading risks (van Valkengoed and Steg, 2019) (Section 13.7).

Perceived personal responsibility for tackling climate change remains low across the EU (Figure 13.35) 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 Box 13.2.1, 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), have low awareness of adaptation options, and confuse adaptation and mitigation (Harcourt, 2019), suggesting a need for improved climate literacy amongst the public. Indeed, fostering learning and coping capacity supports robust adaptation pathways (Jäger et al., 2015).

There is strong public support for adaptation policy (e.g., building flood defences), particularly within the UK, France, Norway and Germany (Doran et al., 2018). Although, in some cases such public adaptation can undermine motivation for householders to take adaptation measures (Section 13.2), public adaptation can also increase householder motivations, 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

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barriers to adoption; while lack of standards as well as societal hesitation may explain low levels of water reuse in Europe (EEA, 2017c) (Section 13.2). Conversely, water meters and higher tariffs have been found to reduce water consumption only in combination with other measures (EEA, 2017c; Bryan et al., 2019).

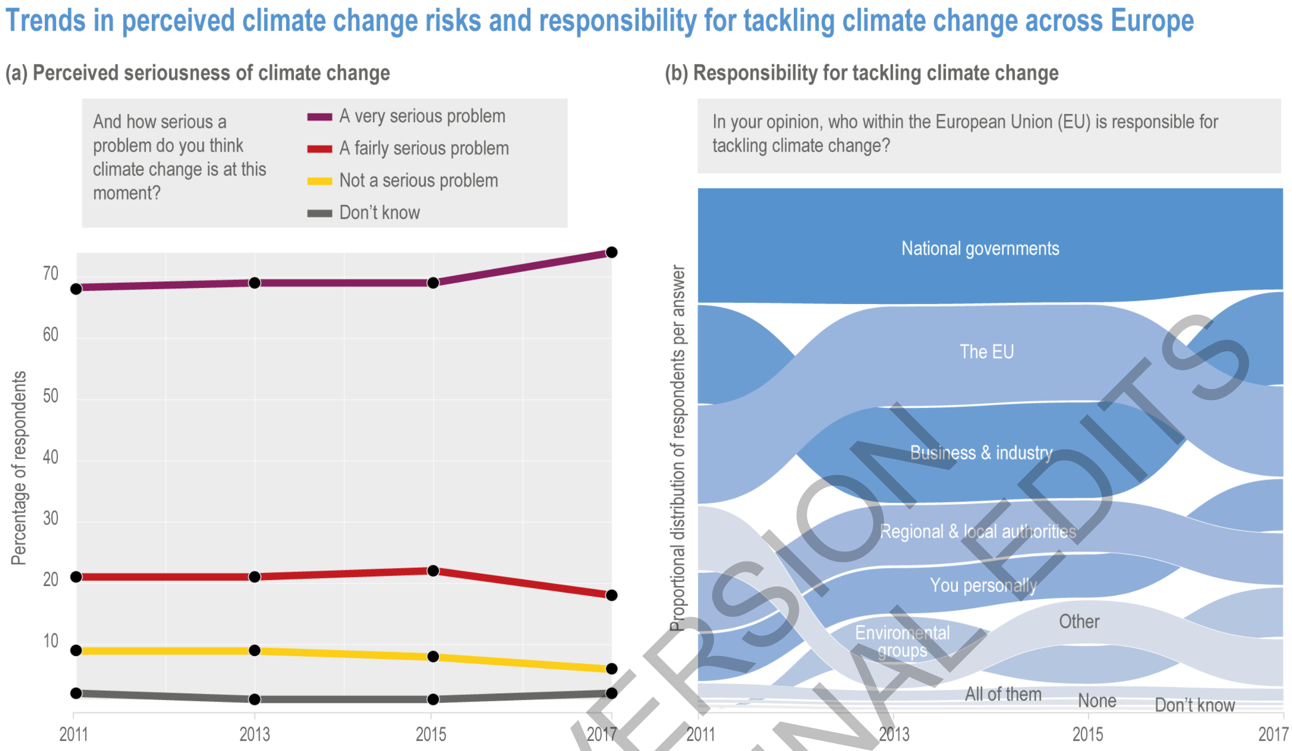

Figure 13.35: Trends in perceived climate change risks and responsibility for tackling climate change across EU-28; data collected from around 1,000 respondents per country for each year surveyed (European Comission, 2017)

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; Duijndam and van Beukering, 2021). 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 waterside residents in flood-prone regions of France and Austria were more resistant to relocation, due to higher place attachment (Adger et al., 2013; Rey-Valette et al., 2019; van Valkengoed and Steg, 2019; Seebauer and Winkler, 2020). Migration from threatened regions is discussed in Section 13.8.1.3.

13.11.3 Adaptation, Transformation and Sustainable Development Goals

The implementation of far-reaching and rapid systemic changes, including both adaptation and mitigation options (de Coninck et al., 2018) remains less researched in societal systems than natural ones (Salomaa, 2020) that enhance multilevel governance and institutional capabilities, and enables lifestyle/behavioural change and technology innovation. Adaptation responses across European regions and sectors, are more often incremental than transformative (*medium confidence*), with possible exceptions including water-related examples in for example the Netherlands (Section 13.2.2) and some cities (Box 13.3). Transformative options may be better able to exploit new opportunities and co-benefits (EEA, 2019a) (Box 13.3) (Cross-Chapter Box HEALTH in Chapter 7). Transitions towards more adaptive and climate resilient systems are

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often the result of responses to crises which create windows of opportunity for systemic changes (Johannessen et al., 2019) (cf. Chapter 18). This includes extreme weather events, financial crises (e.g., Malmö; (Anderson, 2014; Isaksson and Heikkinen, 2018)) and the COVID-19 pandemic (e.g., Milan), which have disrupted the status quo and accelerated innovation and implementation (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., Horizon Europe), European and national legislation, international treaties, and the identification of co-benefits, contribute to the prioritisation of climate action in European cities (Heidrich et al., 2016; Reckien et al., 2018; CDP, 2020). Still, mitigation and adaptation remain largely siloed and sectoral (Heidrich et al., 2016; Reckien et al., 2018; 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 cities (Reckien et al., 2018).

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), such as urban greening, 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). 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) are two examples to illustrate the strategies and challenges of two European cities attempting to implement CRDP.

Malmö (population 0.3M): Since the 1990s, Malmö has been transitioning toward an environmentally, economically and socially sustainable city, investing in eco-districts (redeveloped areas that integrate and showcase the city's sustainability strategies) 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 Stad, 2018). Malmö has developed 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 eco-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 its 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 Stad, 2018). Malmö also engages stakeholders via dialogue with residents, collaboration with universities and partnerships with industry and service providers (Kanters and Wall, 2018; Parks, 2019). Despite measurable and monitored targets, and supportive institutional arrangements, sustainability outcomes for the flagship districts have been tempered by developers' market-oriented demands (Holgersen and Malm, 2015; Isaksson and Heikkinen, 2018) and there is limited low-income housing in climate-resilient districts (Anderson, 2014; Holgersen and Malm, 2015).

Milan (population 1.4M): Milan is taking a CRD approach to new developments (Comune di Milano, 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 Milano, 2019) focus on low-carbon, inclusive and equitable development. The CAP is directed at municipal and

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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 neighbourhood-scale disaster response and reallocating street space for walking and cycling (Comune di Milano, 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 Milano, 2019). Implementation of Milan's plans remains a challenge, despite dedicated resources and commitment.

[END BOX 13.3 HERE]

Considerable barriers exist that prevent system transitions from taking place in Europe, 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*). For example, near-term and sectoral decision-making constrains transformative options for water-related risks (Section 13.2). Breaking through these lock-ins requires substantive (political) will, (un)learning of practices, resources, and evidence of what works. 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 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 the NAP's 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 and supplied with water, reducing the incentive for autonomous adaptation (de Moel et al., 2011; Hartmann and Spit, 2016; Di Baldassarre et al., 2018). 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). There are also trade-offs between large-scale mitigation measures (e.g., wind farms) and adaptation options that rely on ecosystem services (e.g., water regulation; Section 13.3-13.4); and conversely, some adaptation options (e.g., air conditioning) may negatively impact mitigation. Figure 13.36 summarises the synergies between adaptation and SDGs as identified by 167 European cities in 2019; particularly prominent are reported biodiversity and health benefits most often arising from societal (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).

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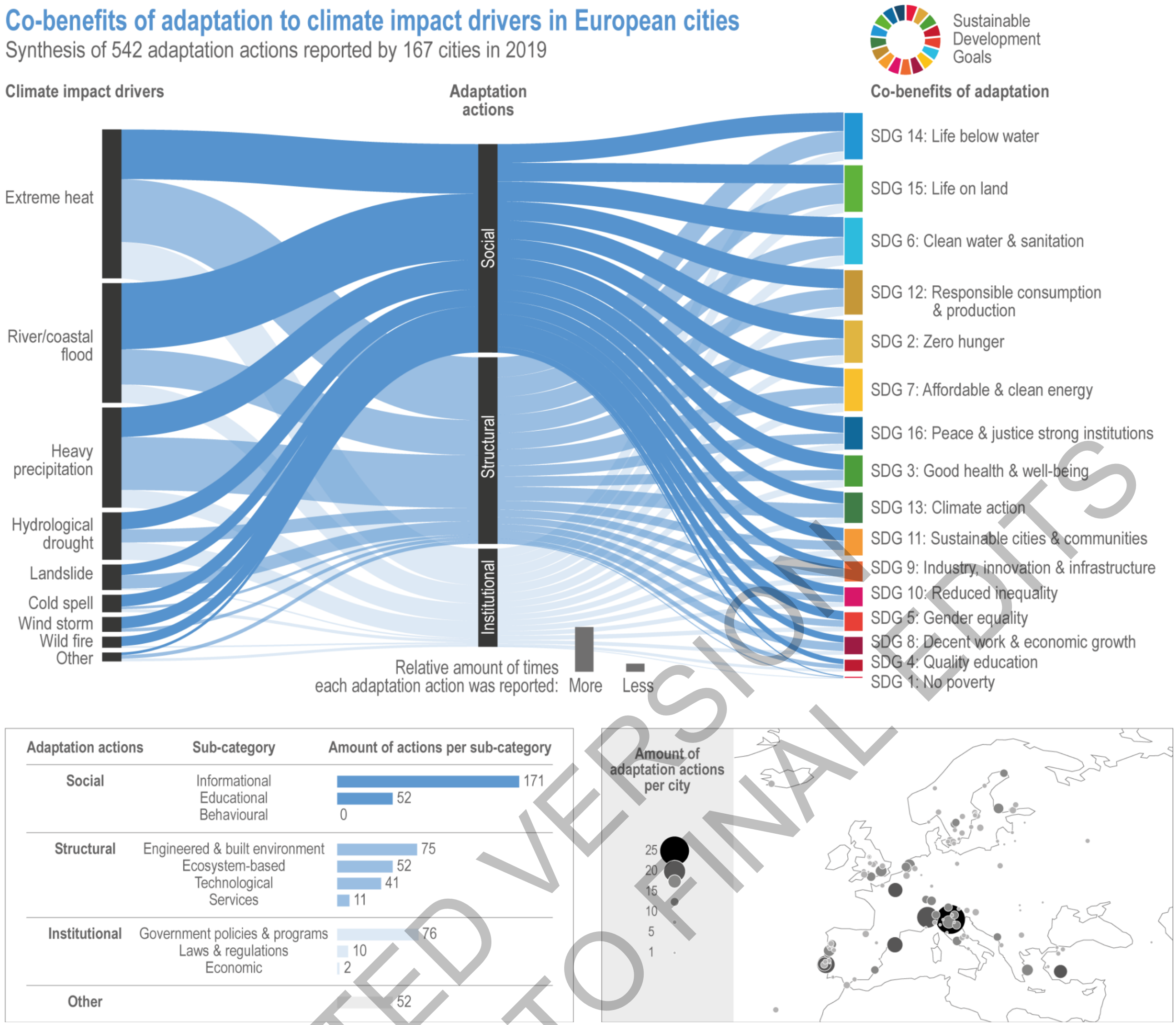

Figure 13.36: Co-benefits for SDGs from adaptation actions. Shows how European cities have assessed the sustainability co-benefits of taking adaptation actions. Data was extracted from the Carbon Disclosure Project (CDP) database using the 2019 dataset; of the 861 European cities submitting data, 167 provided data on their adaptation actions and so this data is shown here (CDP, 2019). CDP categories of climate hazards were recategorized into WG1 Climate Impact Drivers (e.g., cold spell, heavy precipitation); CDP adaptation actions were reclassified into AR5 adaptation options ('social', 'structural' and 'institutional'; 'other' includes actions falling outside these AR5 categories); and CDP co-benefits were recategorized as SDGs. Panel 2 shows that all SDGs except one (SDG 17) were identified as a co-benefit of adaptation, although more environmental co-benefits were identified than social or economic ones. Panel 2 shows that societal actions were most common, followed by structural, then institutional. Informational measures were particularly common. Panel 3 shows how many actions were taken by different European cities.

[START FAQ13.1 HERE]

FAQ 13.1: How can climate change affect social inequality in 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. 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. In the European Union, about a fifth of the population (109 million people) at present, live under conditions of poverty or social exclusion. Moreover, poverty is unequally distributed across Europe,

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with higher poverty levels in the eastern parts of Europe. The oldest and youngest in society are often most vulnerable.

The poor and those practising traditional livelihoods are particularly vulnerable and exposed to climate risks. Many depend on food self-provisioning from lakes, the sea, and the land. With higher temperatures, the availability of these sources of food is *likely* to be reduced, particularly in southern Europe. Poorer households often settle in flood-prone areas and are therefore more exposed to flooding. Traditional pastoralist and fishing practices are also negatively affected by climate change across Europe. Semi-migratory reindeer herding, a way of life among Indigenous and traditional communities (Komi, Saami, Nenets) in the European Arctic, is threatened by reduced ice and snow cover. Almost 15% of the EU population (in some countries more than 25%) already cannot meet their healthcare needs for financial reasons, while they are at risk of health impacts from warming.

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 the South and East of Europe live in dwellings that cannot be cooled to comfortable levels during summer. These people are particularly vulnerable to risks from increasing heatwave days in European cities e.g. when they already face energy poverty. They may also lack the means to protect against flooding or heat, e.g., when they do not own the property. 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 of resources, particularly when in competition with economic interests such as resource mining, oil and gas, forestry, and expansion of bioenergy.

Adaptation actions by governments can both increase and decrease social inequality. The installation of new or the restoration of existing green spaces may increase land prices and rents due to a higher attractiveness of these areas, leading to potential displacement of population groups who cannot afford 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 which integrate a gender-inclusive perspective in its sustainable urban planning, including designing public spaces and transit to ensure women, disabled people and other groups can access and feel safe using these public amenities (see Box 13.3).

[END FAQ13.1 HERE]

[START FAQ13.2 HERE]

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

Land, freshwater and ocean organisms and ecosystems across Europe are facing increasing pressures from human activities. Climate change is rapidly becoming an additional and, in the future, a primary threat. Ongoing and projected future changes are too severe and happen too fast for many organisms and ecosystems to adapt. More expensive and better implemented environmental conservation and adaptation measures can slow down, halt, and potentially reverse biodiversity and ecosystem declines, but only at low or intermediate warming.

Ecosystem degradation and biodiversity loss have been evident across Europe since 1950, mainly due to land use and overfishing. However, climate-change is becoming a key threat. The unprecedented pace of environmental change has already surpassed the natural adaptive capability of many species, communities, and ecosystems in Europe. For instance, the space available for some land ecosystems has shrunk, especially in Europe's polar and mountain areas, due to warming and thawing of permafrost. Across Europe, heatwaves and droughts and their impacts such as wildfires add further acute pressures, as seen in the 2018 heatwave, which impacted forest ecosystems and their services. In the Mediterranean Sea, plants and animals cannot shift northward and are negatively affected by marine heatwaves. Food-web dynamics of European ecosystems are disrupted as climate change alters the timing of biological processes, such as spawning and migration of species, and ecosystem composition. Moreover, warming fosters the immigration of invasive species that compete with–and can even out-compete–the native flora and fauna.

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In a future with further and even stronger warming, climate change and its many impacts will become increasingly more important threats. Several species and ecosystems are projected to be already at high risk at 2°C global warming, including fishes and lake and river ecosystems. At 3°C global warming, many European ecosystems, such as coastal wetlands, peatlands, and forests, are projected to be at much higher risk of being severely disrupted than in a 2°C warmer world. For example, Mediterranean seagrass meadows will *very likely* become extinct due to more frequent, 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 dry conditions, especially in boreal and Arctic ecosystems.

Current protection and adaptation measures, such as the Natura 2000 network of protected areas, have some positive effects for European ecosystems. However, these policies are not sufficient to effectively curb overall ecosystem decline, especially for the projected higher risks above 2°C global warming. Nature-based solutions, such as the restoration of wetlands, peatlands, and forests, can serve both ecosystem protection and climate-change mitigation through strengthening carbon sequestration. Some climate change mitigation measures such as reforestation and restoration of coastal ecosystems can strengthen conservation measures. These approaches are projected to reduce risks for European ecosystems and biodiversity, especially when internationally coordinated.

Not all climate-change adaptation options are beneficial to ecosystems. When planning and implementing adaptation options and Nature-based Solutions, trade-offs and unintended side effects should be considered. On one hand, engineering coastal protection measures (seawalls, breakwaters, and similar infrastructure) in response to sea level rise reduce the space available for coastal ecosystems. One the other hand, Nature-based Solutions can also have unintended side effects, such as increased methane release from larger wetland areas and large-scale tree planting changing the albedo of the surface.

[END FAQ13.2 HERE]

[START FAQ13.3 HERE]

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

Heatwaves will become more frequent, more intense and will last longer. A range of adaptation measures are available for communities and individuals before, during and after a heat wave strikes. Implementing adaptation measures are important to reduce the risks of future heat waves.

Heat waves will affect people in different ways, risks are higher for the elderly, pregnant women, small children, people with pre-existing health conditions and low-income groups. By 2050, about half of the European population may be exposed to high or very high risk of heat stress during summer, particularly in Southern Europe and increasingly in Eastern and Western and Central Europe. The severity of heat-related risks will be highest in large cities, due to the urban heat island effect.

In southern Europe people are already aware of the risks of heat extremes. Consequently, governments and citizens have implemented a range of adaptation responses to reduce the impacts of heat waves. However, there are limits to how much adaptation can be implemented. At 3°C global warming there will be substantial risks to human lives and productivity, which cannot be avoided. In the parts of Europe where heat waves are a relatively new phenomena, such as many parts of North and Western and Central Europe, public awareness of heat extremes is increasing and institutional capacity to respond is growing.

Preparing for heat waves is an important first step. Implementing and sustaining effective measures, such as national or regional early warning and information systems, heat wave plans and guidelines, and raising public awareness through campaigns are successful responses. Evidence suggests that such measures have contributed to reduced mortality rates in Southern and Western and Central Europe. At city level, preparing for heat waves can sometimes require urban redesign. For example, green-blue spaces, such as recreational parks and ponds in cities, have been shown to reduce the average temperature in cities dramatically and to provide co-benefits, such as improved air quality and recreational space. The use of cool materials in asphalt,

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increasing reflectivity, green roofs, and building construction measures are being considered in urban planning for reducing heat risks. Citizens can prepare themselves by using natural ventilation, using approaches to stay cool in heat waves, green roofs and green facades in their buildings.

During heat waves, public information that is targeted at people and social care providers is critical, particularly for the most vulnerable citizens. Governments and NGOs play an important role in informing people about how to prepare and what to do to avoid health impacts and reduce mortality. Coordination between vital emergency and health services is critical. Individuals can take several actions to effectively protect themselves from heat: 1) decreasing exposure to high temperatures (e.g., avoid outdoor during hottest times of the day, access cool areas, wear protective and appropriate clothing); 2) keep hydrated (e.g., drink enough proper fluids, avoid alcohol, etc.), 3) 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, evaluation of what worked well and how improvements can be made is key to prepare for the next heat wave. Governments can, for example, evaluate whether the early warning systems provided timely and useful information, whether coordination went smoothly, or assess estimated number of lives saved as results of the measures implemented. Sharing these lessons learned is critical to allow other cities and regions to plan for heat extremes. After the heatwave, citizens can reflect if their responses were sufficient, whether investments are needed to be better prepared, and draw key lessons about what (not) to do when the next heat wave strikes.

[END FAQ13.3 HERE]

[START FAQ13.4 HERE]

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

Not all climate change impacts across Europe pose challenges and threats to natural communities and human society. In some regions, and for some sectors, opportunities will emerge . Although these opportunities do not outweigh the negative impacts of climate change, considering these in adaptation planning and implementation is important to benefit from them. Nevertheless, Europe will face difficult decisions balancing the trade-offs between the adaptation needs of different sectors, regions and adaptation and mitigation actions.

Opportunities of climate change can be 1) positive effects of warming for specific sectors and regions, such as agriculture in northern Europe and 2) co-benefits of transformation of cities or transport measures that reduce the speed and impact of climate-change while improving air quality, mental health and wellbeing. Windows of action for transformation opportunities for large-scale transitions and transformation of our society may be accelerated through new policy initiatives in response to the COVID crisis, such as the European New Green Deal and Building Back Better.

As warming and droughts impact southern Europe most strongly, direct opportunities from climate change are primarily in northern regions, thereby increasing existing inequalities across Europe. Across Europe, positive effects of climate change are fewer than negative impacts and are typically limited to some aspects of agriculture, forestry, tourism, and energy sectors. In the food sector, opportunities emerge by the northward movement of food production zones, increases in plant growth due to CO_2 fertilisation, and reduction of heating costs for livestock during cold winters. In the energy sector, positive effects include increased wind energy in the southwestern Mediterranean, and reduced energy demand for heating across Europe. While climatic conditions for tourist activities are projected to decrease for winter tourism (e.g. lacking sufficient snow) and summer tourism in some parts of Europe (e.g. too hot), conditions may improve during spring and autumn in many European locations. Fewer cold waves will reduce risks on transport infrastructure, such as cracking of road surface, in parts of Northern and Eastern Europe particularly by the end of the century.

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Indirect opportunities emerge from the co-benefits of implementing adaptation actions. Some of these co-benefits are wide-spread but need careful consideration in order to be utilized. For example, Nature-based Solutions to adaptation can make cities and settlements more liveable, increase the resilience of agriculture, and protect biodiversity. Ecosystem-based adaptation can attract tourists and create recreational space. There are opportunities to mainstream adaptation into other developments and transitions, including the energy or agricultural transitions and COVID19 recovery plans. Transformative solutions to achieve sustainability may be accelerated through larger changes of, for example behaviour, energy, food or transport, to better exploit new opportunities and co-benefits. Implementation of adaptation actions can also help to make progress towards achieving the Sustainable Development Goals.

Inclusive, equitable and just adaptation is critical for climate resilient development considering SDGs, gender, as well as Indigenous knowledge and local knowledge and practices. Implementation requires political commitment, persistence and consistent action across scales of government. Upfront mobilization of political, human and financial capital in implementation of adaptation actions is key, even when the benefits are not immediately visible.

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