# 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*). Impacts of 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, the 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 in 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 are 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 global warming levels (GWL) compared with 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}.

**KR1: The number of deaths and people at risk of heat stress will increase two- to threefold at 3°C compared with 1.5°C GWL (*high confidence*).** 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, 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 NbS) 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 if warming does not exceed 2°C (*medium confidence*).

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[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 is 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.

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*). For Western Central and Southern Europe, and for many cities, the risk of water scarcity will be strongly increasing 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 (SLR), 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 the accelerating pace of SLR 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 tenfold 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 impacts 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}.

**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 socioeconomic 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 with 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 inter-regional 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 are a growing range of adaptation options available today to deal with future climate risks (*high confidence*).** Examples of 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 SLR (*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 Southern Europe (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 prevent path dependencies and maladaptation, and ensure timely action (*high confidence*). Monitoring climate change, socioeconomic developments and progress on implementation is critical in assessing 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}.

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[2] In this Report, the following terms are 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*).

**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 citizen 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 socioeconomic 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 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 programmes). These windows can be used to accelerate action through mainstreaming and transformational actions (*medium confidence*). This 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; Box 13.3; 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 CRD. Such pathways require consideration of SDGs, gender and Indigenous knowledge and local knowledge (IKLK) 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 mobilisation 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}.

## 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 socioeconomic developments, land-use change and other non-climatic drivers. Compared with AR5 and in the context of the Paris Agreement (2015), we place emphasis on the planned and implemented solutions, assess their feasibility and effectiveness, and consider the Sustainable Development Goals (SDG) and shared socioeconomic pathways (SSPs). Global warming level (GWL) refers to global climate-change emissions relative to pre-industrial levels, expressed as global surface air temperature (Section 1.6.2; Chen et al., 2021).

The chapter generally follows the overall structure of AR6 WGII. We first present our point of departure (the present section) followed by the key sectors, starting with water, as water is interconnected and of fundamental importance to subsequent sections (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 (Section 13.10). The chapter ends with an assessment of the adaptation solution space, CRD pathways and SDGs (13.11), although recognising 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 prioritises systematic reviews, meta-analyses, and synthesis papers and reports. Feasibility and effectiveness assessments use revised methods developed for the Special Report of Global warming of 1.5°C (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.

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 with the assessment in this chapter (SEU). The European part of the Arctic region is not

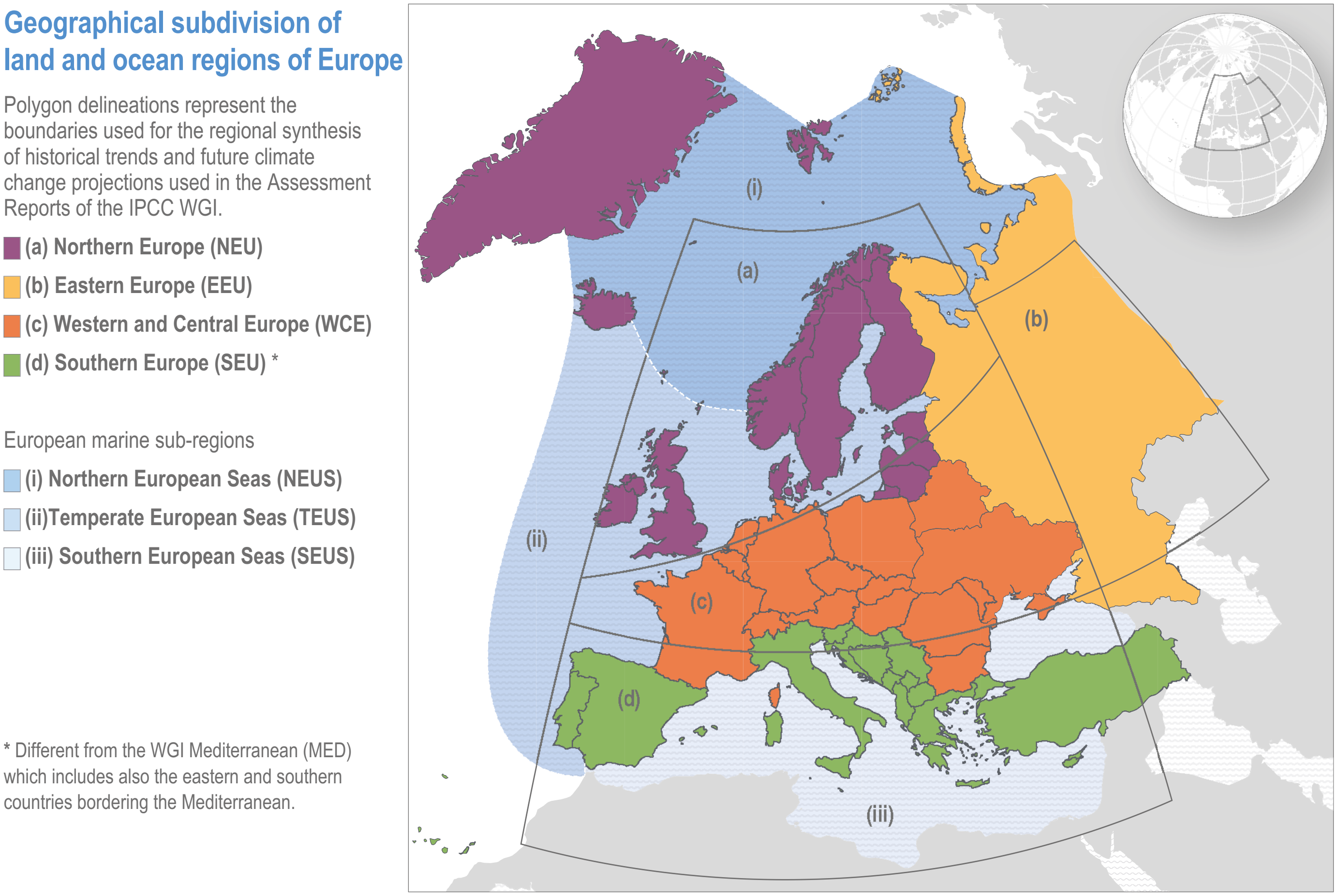


**Figure 13.1 | Geographical subdivision of land (a,b,c,d) and ocean (i,ii,iii) regions of Europe.** The overlay represents the WGI AR6 (IPCC, 2021) subdivisions for climate-change projections of land, while the colour coding indicates the European countries (or, in case of the Russian Federation, the European part of the country, EEU, used for this chapter). Note that in the WGI AR6 report, MED includes both Southern Europe and Northern Africa, while this chapter includes only the northern (European) part of the MED region. To distinguish between the two the region is called SEU here.

systematically assessed here, as it is extensively captured in Cross-Chapter Paper 6. Information relevant to Europe is also synthesised in the CCPs (Cross-Chapter Papers), including European biodiversity hotspots (Cross-Chapter Paper 1), coastal cities and settlements (Cross-Chapter Paper 2), Mediterranean regions (Cross-Chapter Paper 4) and mountains (Cross-Chapter Paper 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 the Black Sea (SEUS) (Figure 13.1).

### 13.1.2 Socioeconomic Boundary Conditions

The adaptive capacity, as measured by the GDP per capita, tends to be higher in northern and western parts of Europe (Figure 13.2a). In recent 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 SEU and WCE (Figure 13.2c). Current vulnerability to extreme weather and climatic events in European countries is low to moderate compared with the rest of the world (Figure 13.2d).

### 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 IPCC Special Report on 1.5°C (Hoegh-Guldberg et al., 2018), highlighted the impacts of warming and rainfall variations and their extremes on Europe, particularly SEU 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 characterised 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 past two decades, and permafrost in the European Alps and Scandinavia

Damages to people and assets, vulnerability and adaptive capacity across Europe

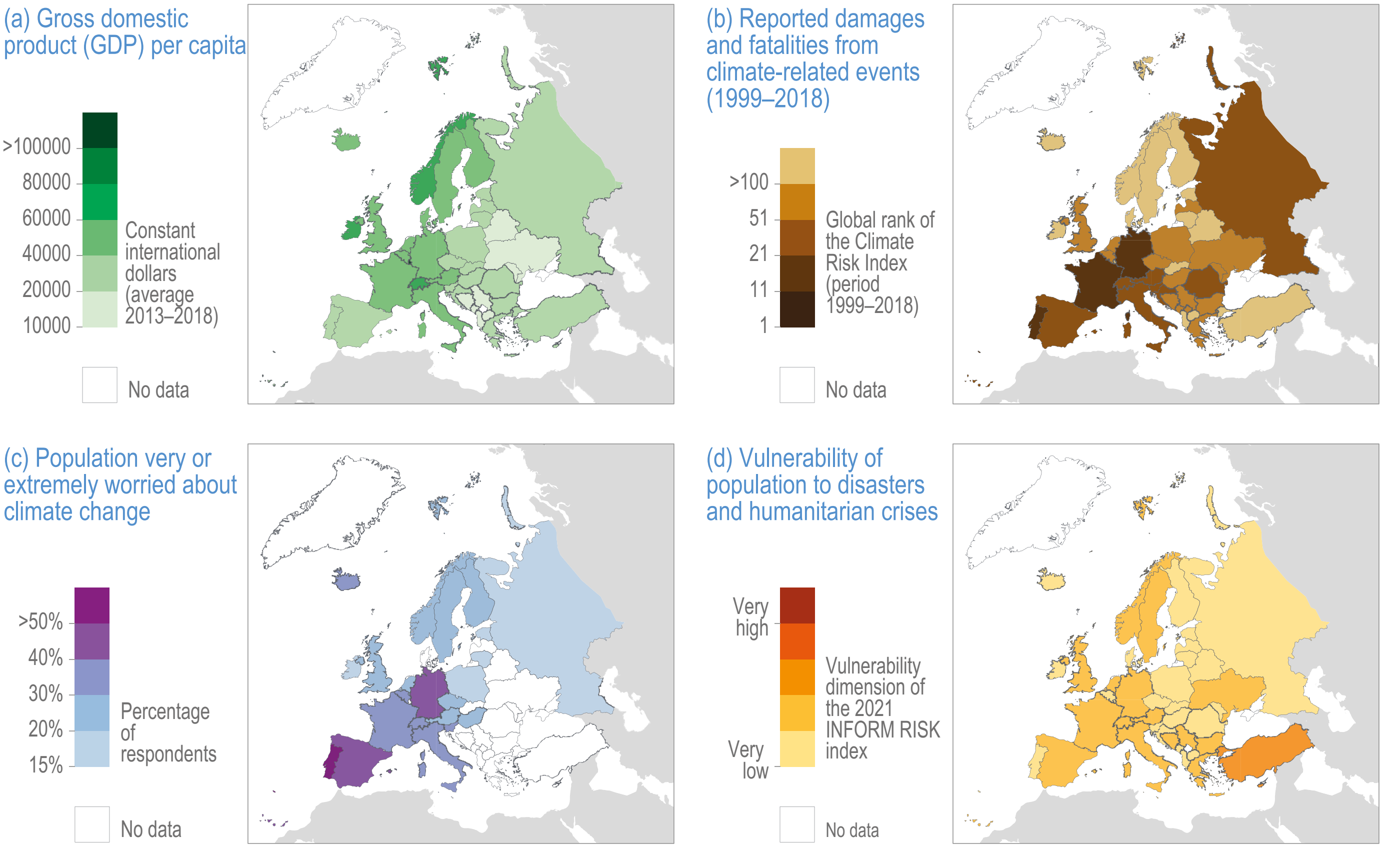


**Figure 13.2 | Indicators of reported damages to people and assets, vulnerability and adaptive capacity across European countries:**

**(a)** GDP per capita (average 2013–2018), in constant 2011 international dollars (World Bank, 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 and aid dependency) and vulnerable groups (DRMKC, 2020).

is decreasing (Hock et al., 2019). In Central Europe, Scandinavia and Caucasus, mountain glaciers were projected to lose 60–80% 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 SEU 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 with 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 Coninck et al., 2018).

### 13.1.4 European Climate: Main Conclusions of WGI AR6

Changes in several climatic-impact drivers have already emerged in all regions of Europe: increases in mean temperature and extreme heat, and decreases in 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 heatwaves 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 all of Europe, with largest winter warming in NEU and EEU and largest summer warming in MED (*high confidence*) (Gutiérrez et al., 2021; Ranasinghe et al., 2021). An increase in hot days and a decrease in cold days are *very likely* (Figure 13.4a,b). Projections suggest a substantial reduction in European ice glacier volumes and in 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).

The assessment of climate change in WGI AR6 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

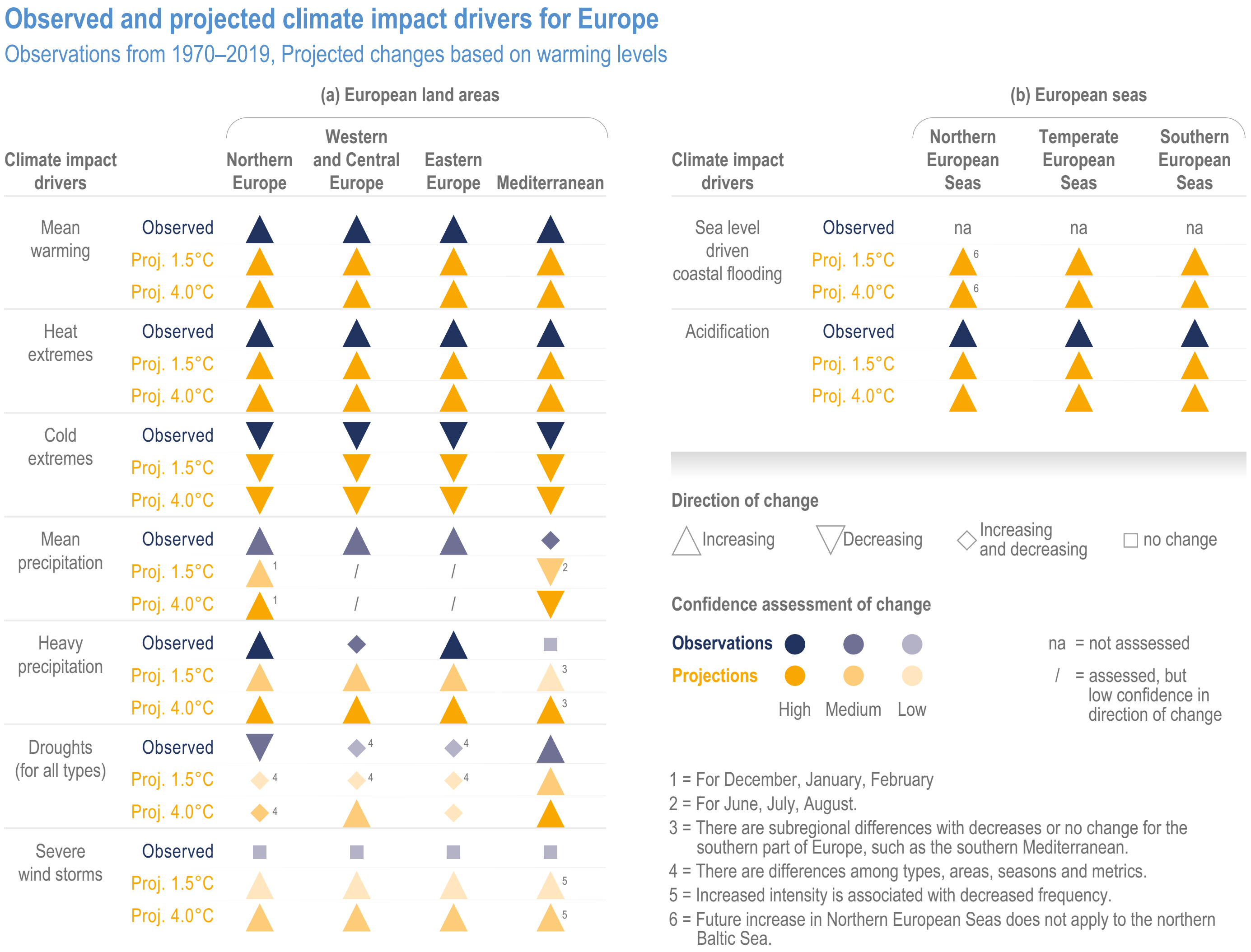
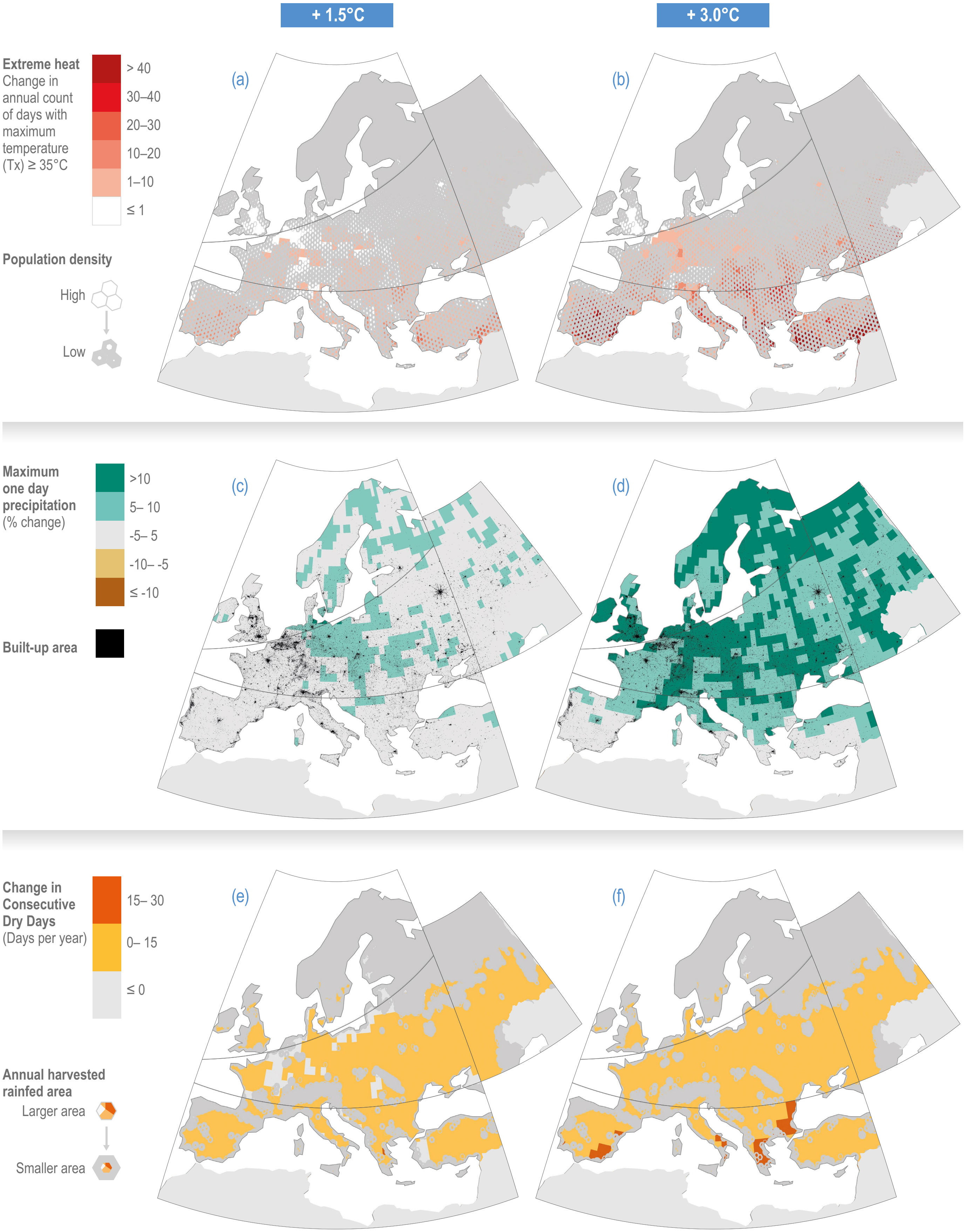


**Figure 13.3 | Observed and projected direction of change in climate-impact drivers at 1.5°C and 4°C GWL for European sub-regions and European seas.** (Assessment from Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021).

## Climate impacts drivers and socio-ecological vulnerabilities



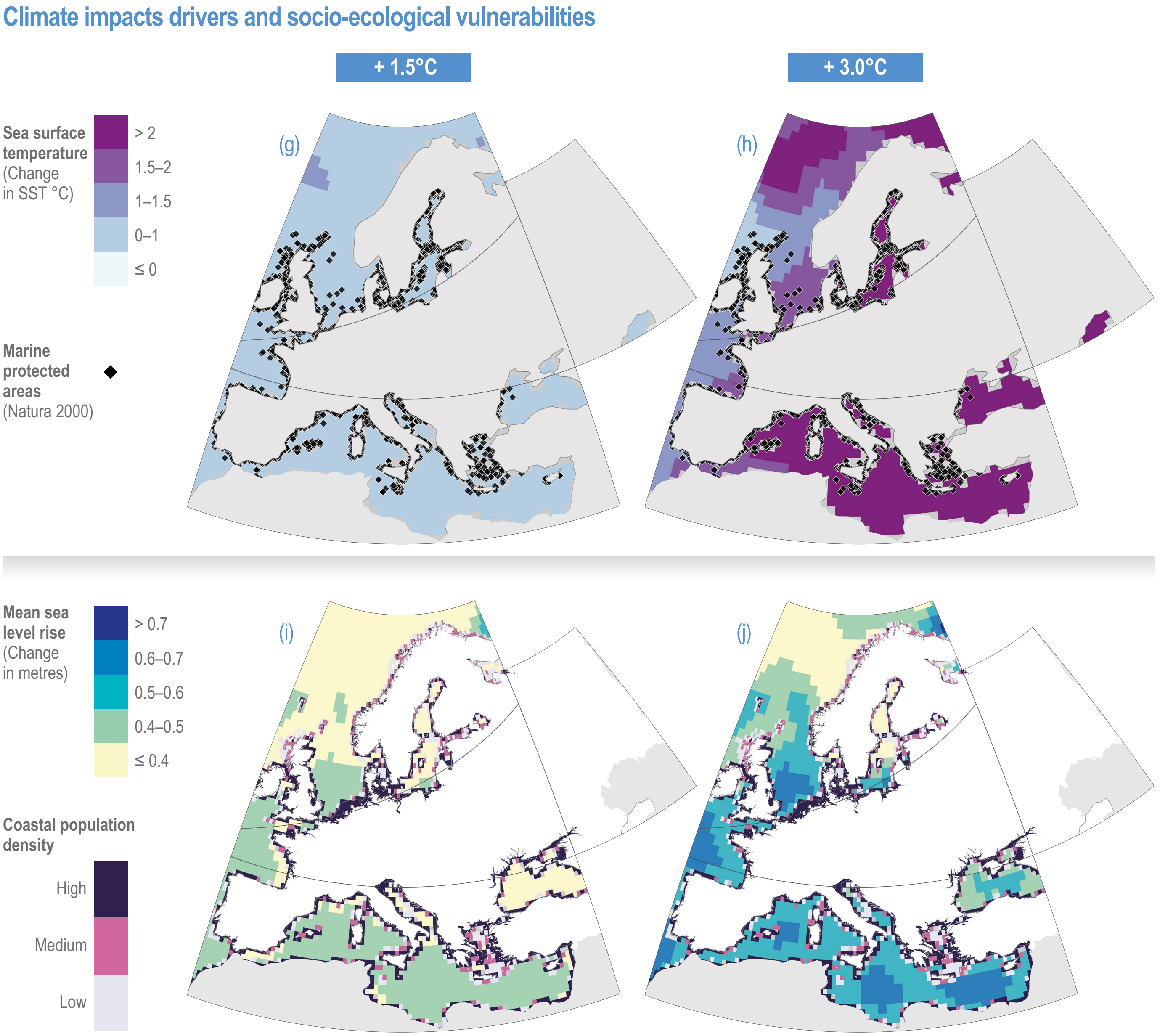


**Figure 13.4 | Changes in climate hazards for global warming levels of 1.5°C and 3°C based on the CMIP6 ensemble (Gutiérrez et al., 2021) with respect to the baseline period 1995–2014, combined with information on present exposure or vulnerability:**

**(a,b)** number of days with temperature maximum above 35°C (TX35) and population density (European Comission, 2019);

**(c,d)** daily precipitation maximum (R × 1 d) and built-up area (JRCdatacatalogue, 2021);

**(e,f)** consecutive dry days and annual harvested rain-fed area (Portmann et al., 2010);

**(g,h)** sea surface temperature and marine protected areas (EEA, 2021b); and

**(k,l)** sea level rise (SLR) and coastal population (Merkens et al., 2016). The SLR data consider the long-term period (2081–2100) and SSP1–2.6 for (i) and SSP3–7.0 for (j).

(*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 sub-regions (*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 and hydrological drought (Ranasinghe et al., 2021) with *low confidence* in the direction of change in NEU, WCE and 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 in storms across all of Europe (*medium confidence*) for >2°C GWL with a decrease in their frequency in the MED (Ranasinghe et al., 2021).

Sea surface warming between 0.25°C and 1°C has been observed in all regions over recent decades (*high confidence*) (Ranasinghe et al., 2021) and are projected to continue increasing (*high confidence*), particularly in the SEUS and at the NEUS (Figure 13.4g,h; Gutiérrez et al., 2021). Salinity has increased in the SEUS and decreased in NEUS and is projected to continue (*medium confidence*) (Fox-Kemper et al., 2021). European waters have been, and will continue, acidifying (*virtually certain*) (Eyring et al., 2021; Szopa 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°C GWL with the 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). This SLR will *very likely* continue to increase during the 21st century (Figure 13.4k,l) (*high confidence*), with regional deviations from global mean SLR (*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 Europeans 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 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 increase beyond 2040 (Vousdoukas et al., 2018a) reaching 10 million people under RCP8.5 by 2100, but it stays just below 10 million people 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 especially in response to increasing population under SSP5 (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 EUR today to 13–39 billion EUR by 2050 between 2°C and 2.5°C GWL and 93–960 billion EUR by 2100 between 2.5° and 4.4°C GWL, largely depending on socioeconomic 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 (Section 13.8.1.3; Cross-Chapter Paper 4; Marzeion and Levermann, 2014; Reimann et al., 2018b) as are coastal landfills and other key infrastructures 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, for example, 27–40% of Europe's sandy coast eroding today, without climate change being identified as the main driver so far (Pranzini et al., 2015; 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 could retreat by about 100 m in Europe at 4°C GWL; limiting warming to 3°C GWL could reduce this value by one-third (Vousdoukas et al., 2020).

### 13.2.1.2 Risks Related to Inland Water

#### *13.2.1.2.1 Riverine and pluvial flooding*

Precipitation has raised river flood hazards in WCE and the UK by 11% per decade from 1960 to 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 flood 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 three times higher at 1.5°C GWL, four times at 2°C GWL and six times at 3°C GWL (Alfieri et al., 2018; Dottori et al., 2020). At 2°C GWL, the 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 snowmelt-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 (Cross-Chapter Paper 4; Llasat et al., 2016; Rudd et al., 2020). The majority (56%) of flood events between 1860 and 2016 were flash floods (Paprotny et al., 2018a). These floods had considerable impacts including danger to human lives, for example, causing total economic damage of 1 billion USD in Copenhagen (Denmark) in 2011 (Wójcik et al., 2013), damage to private households of more than 70 million EUR in Münster (Germany) in 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 urbanisation, 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 the 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 as opposed to 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 SEU (Sections 13.5.1, 13.10.3).

Groundwater abstraction rates reach up to 100 million $m^3$ $yr^{-1}$ across WCE and SEU, and exceed 100 million $m^3$ $yr^{-1}$ 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). Declines in groundwater recharge of up to 30% further increase groundwater depletion (Aeschbach-Hertig and Gleeson, 2012) especially in SEU and semiarid 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 with 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 ).

## 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.

The elevation of the average city pedestrian level and of its inner historic area are, respectively, 105 and 55 cm 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 rose at about 2.5 mm $yr^{-1}$ 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 was used for the first time in October 2020 (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 flooding of the central monument area, additional measures have been proposed including inlets, expansion of salt marshes 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 EUR have been estimated for the next 50 years (Caporin and Fontini, 2016). Additionally, the ecosystem is vulnerable to warming (Solidoro et al., 2010) and SLR (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 $yr^{-1}$ for RMSL rises of 30 cm, to 2 months $yr^{-1}$ for 50 cm and 6 months $yr^{-1}$ for 75 cm (Figure Box 13.1.1b; Umgiesser, 2020; Lionello et al., 2021b), 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 SLR.

*Box 13.1 (continued)*

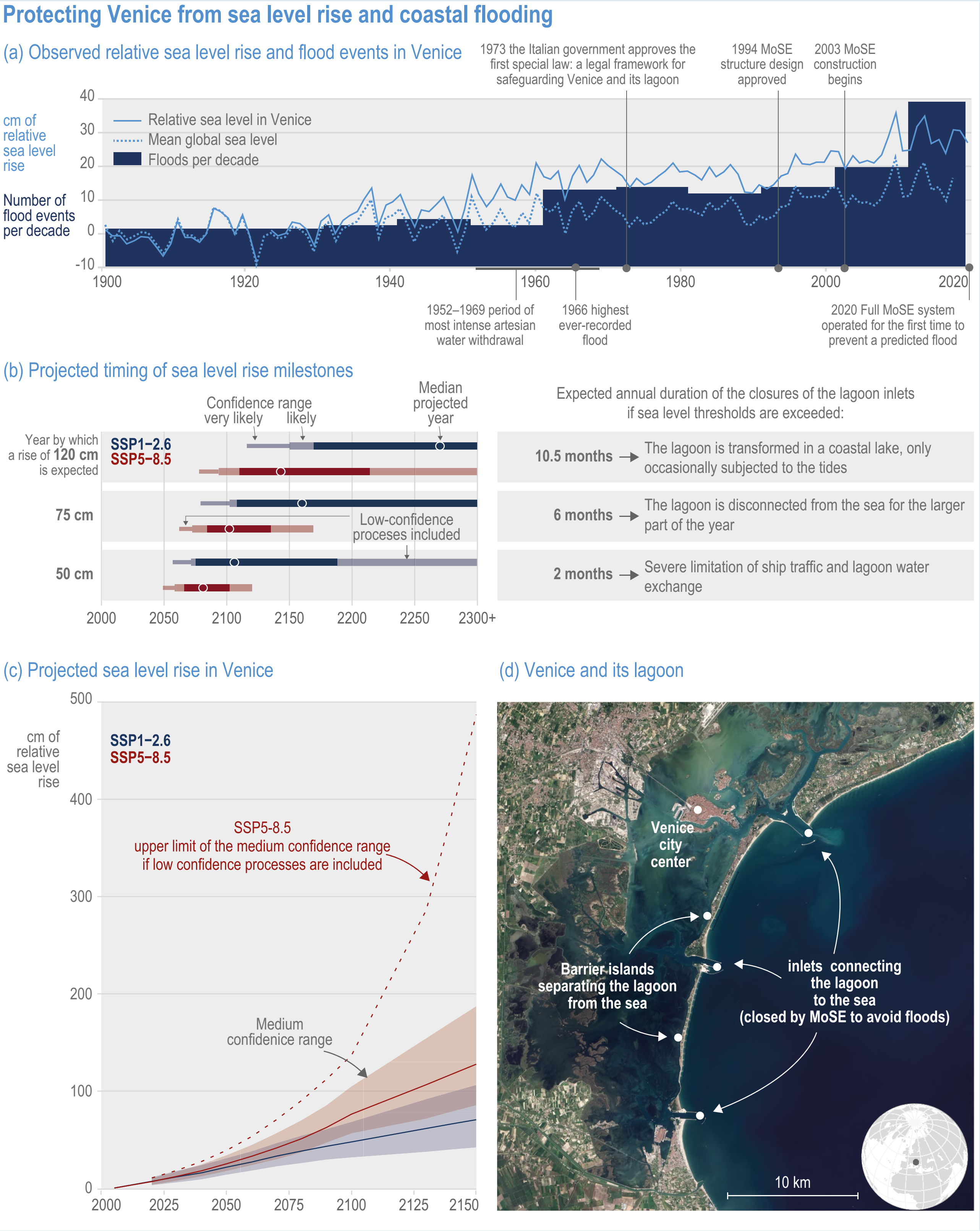


**Figure Box 13.1.1 | Venice sea level rise (SLR) and coastal flooding: (a)** evolution of relative and mean sea level in Venice and decadal frequency of floods above the safeguard level in the city centre (Frederikse et al., 2020; Lionello et al., 2021a; Lionello et al., 2021b; Zanchettin et al., 2021); **(b)** projected relative SLR at the Venetian coast (Fox-Kemper et al., 2021); "very likely" corresponds to 5–95th percentile range, "likely" to 17–83rd percentile range; **(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), the upper limit of the medium confidence range under SSP5–8.5 represents a low-likelihood, high-impact storyline, low confidence processes include ice sheet instability; **(d)** Landsat view of Venice and its lagoon with the three inlets connecting it to the Adriatic Sea.

#### 13.2.1.2.3 Water Temperature and Quality

Water temperatures in rivers and lakes have increased over the past century by ~1–3°C in major European rivers (CBS, 2014; EEA, 2017a; 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, resulting in more frequent closure of water inlets in the downstream part of the rivers in a period when water is most needed (*high agreement, low evidence*) (e.g., Haasnoot et al., 2020b).

## 13.2.2 Solution Space and Adaptation Options

In recent decades water management in Europe has increasingly shifted towards integrated and adaptive strategies, with the 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*) (Cross-Chapter Paper 2; 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 1-m 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 3 m), which may lead to unequal impacts over time (McEvoy et al., 2021).

### 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 the 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 with 1980–1989) (Jongman et al., 2015; Paprotny et al., 2018a).

#### 13.2.2.1.1 Coastal flood risk management

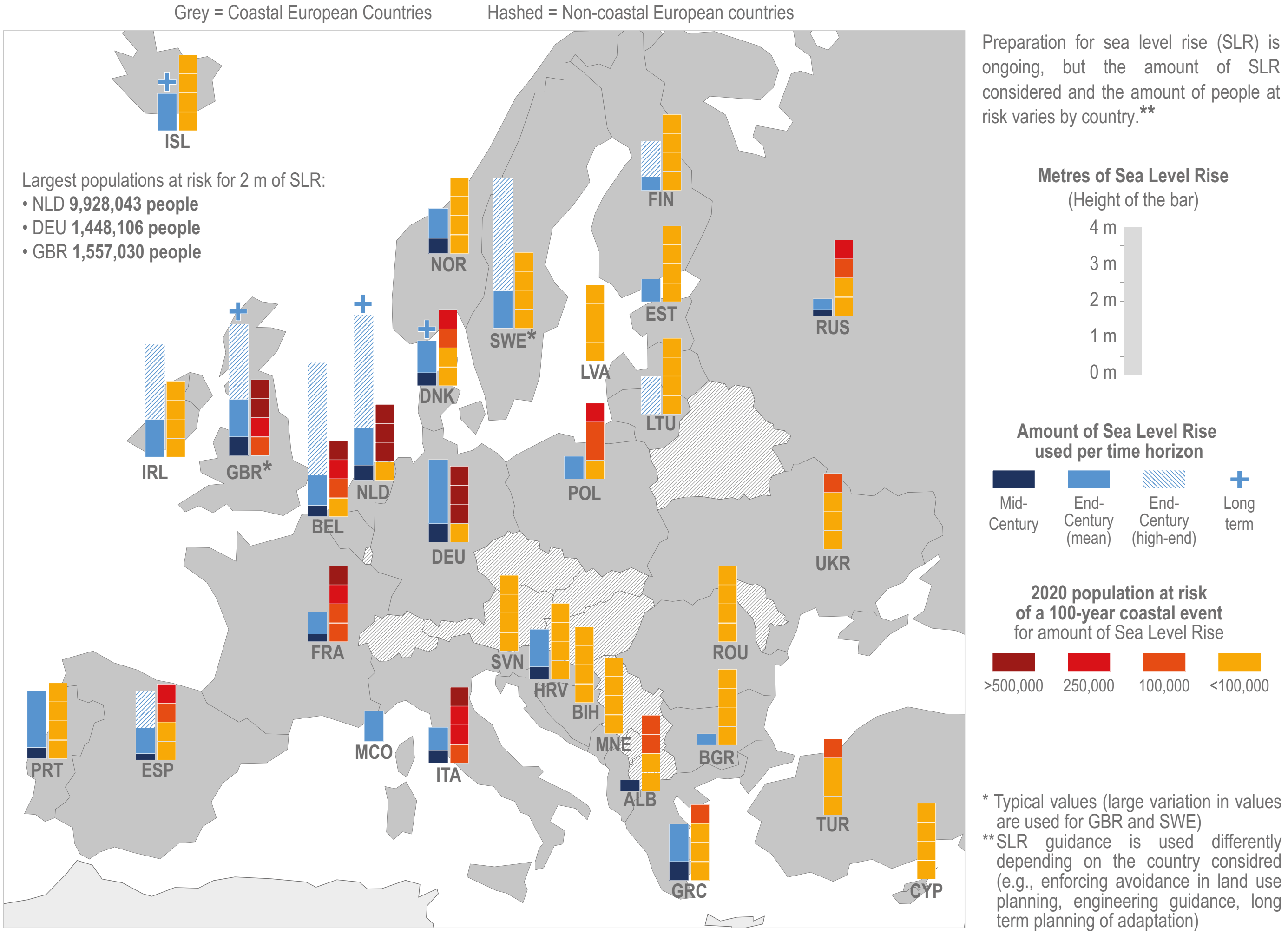
Further protection against coastal flooding is considered economically beneficial for densely populated areas (Lincke and Hinkel, 2018; Tiggeloven et al., 2020). At least 83% of flood damages due to coastal flooding could be avoided by elevating dykes along ~23–32% of Europe's coastline by 2100 (RCP4.5-SSP1, 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 Solutions (NbS) (e.g., wetlands) and sediment-based solutions (e.g., sand nourishment) 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 0.5 m large-scale losses of these habitats will impact their ecological importance, ecosystem function (Section 13.4; KR 1, Section 13.10.2) 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 urbanised 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 (Section 13.6.2; Cross-Chapter Paper 2; 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 100 m from the coast in unprotected areas. Setback zones are projected to reduce impacts considerably in urbanised regions (Lincke et al., 2020). Planned relocation is increasingly considered as a realistic adaptation option in cases of extreme SLR (Haasnoot et al., 2021a; Lincke and Hinkel, 2021; Mach and Siders, 2021), for example, UK Shoreline Management Plans (Nicholls et al., 2013; Buser, 2020). Retreat is rarely applied in Europe (*medium confidence*), though it can have greater benefit-to-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.,

## Risk and national adaptation planning to sea level rise in Europe

### (a) Amount of sea level rise used in national level planning per country and population at risk by amount of sea level rise per country

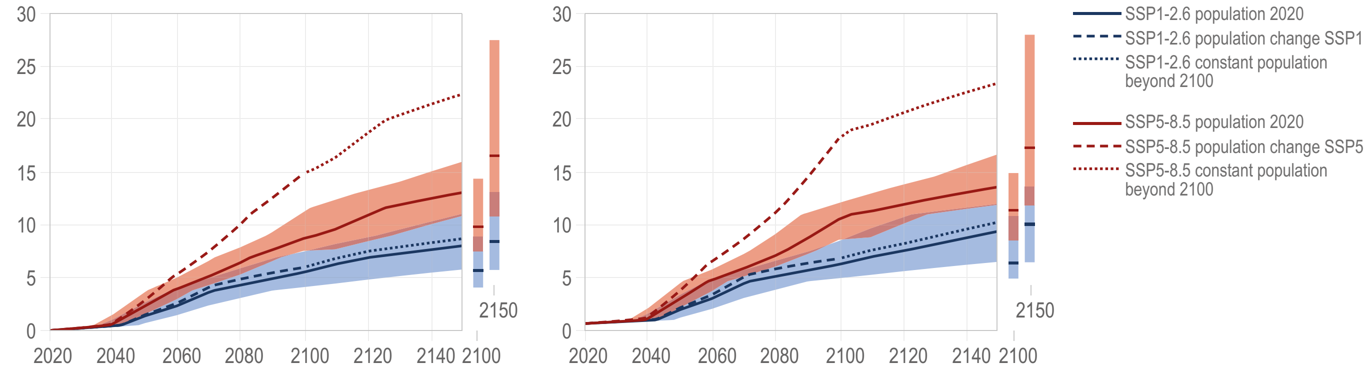


Largest populations at risk for 2 m of SLR:
- NLD **9,928,043 people**
- DEU **1,448,106 people**
- GBR **1,557,030 people**

Preparation for sea level rise (SLR) is ongoing, but the amount of SLR considered and the amount of people at risk varies by country.**

* Typical values (large variation in values are used for GBR and SWE)

**SLR guidance is used differently depending on the country considred (e.g., enforcing avoidance in land use planning, engineering guidance, long term planning of adaptation)



(b) Millions of people at risk of a 10-year flood event

(c) Millions of people at risk of a 100-year flood event

**Figure 13.5 | Sea level rise (SLR) vulnerability and national planning in Europe:**

**(a)** map of countries in Europe summarising the amount of SLR each country is planning for, at different time horizons (blue bars), and the 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 experience a 1-in-10-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5 assuming present protection and population levels, as well as population change according to, respectively, SSP1 and SSP5, based on Merkens (2016);

**(c)** projected population at risk to experience a 1-in-100-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5, assuming the present protection and population levels, as well as population change according to, respectively, SSP1 and SSP5, based on Merkens (2016) (based on Haasnoot et al., 2021b).

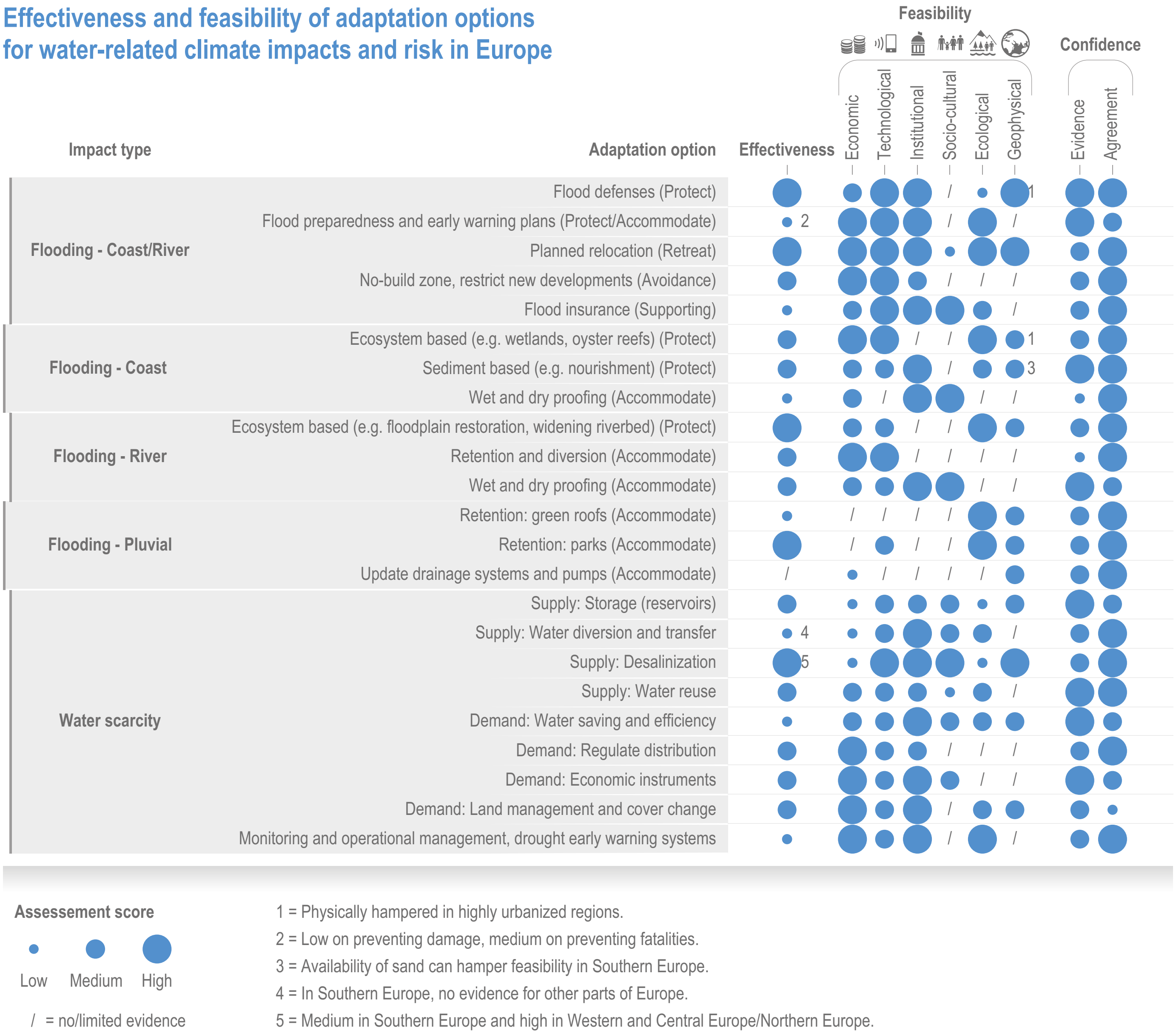


**Figure 13.6 | Effectiveness and feasibility of water-related adaptation options to achieve objectives under increasing climate hazards** (Section SM13.9; Table SM13.1)

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).

### *13.2.2.1.2 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 by ~45% as 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 level can reduce the risk of flooding, there is often insufficient investment (*medium confidence*) (Bamberg et al., 2017; Aerts et al., 2018). 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 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).

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 and 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), resulting in unavailable or unaffordable insurance for private customers (Section 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, leading to (re)-settlement in flood-prone areas (Fanta et al., 2019).

Limits to adaptation to extremely high SLR scenarios have been identified for coastal defences, such as the Venice MoSE barrier (see 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 has been poorly studied. Given the lead and long lifetime of large critical infrastructures, there is a growing need to look beyond 2100 to support the design of new infrastructures (Cross-Chapter Box SLR in Chapter 3).

#### 13.2.2.2 Water Resources Management

Planning adaptation to water scarcity has centred on increasing the availability and supply of freshwater 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). Wastewater 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, for example, 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 in 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 (Section 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 in 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, the 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 GWL, including the long term, is lacking. A quantification of the effectiveness of measures in reducing risk is limited in the scientific literature. The 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

### 13.3.1.1 Observed Impacts on Terrestrial and Freshwater Ecosystems

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 (Cross-Chapter Paper 1). Interacting with climate change are non-climatic hazards, such as habitat loss and fragmentation, overexploitation, 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,

Köppen-Geiger climate classification and biodiversity hotspots in Europe

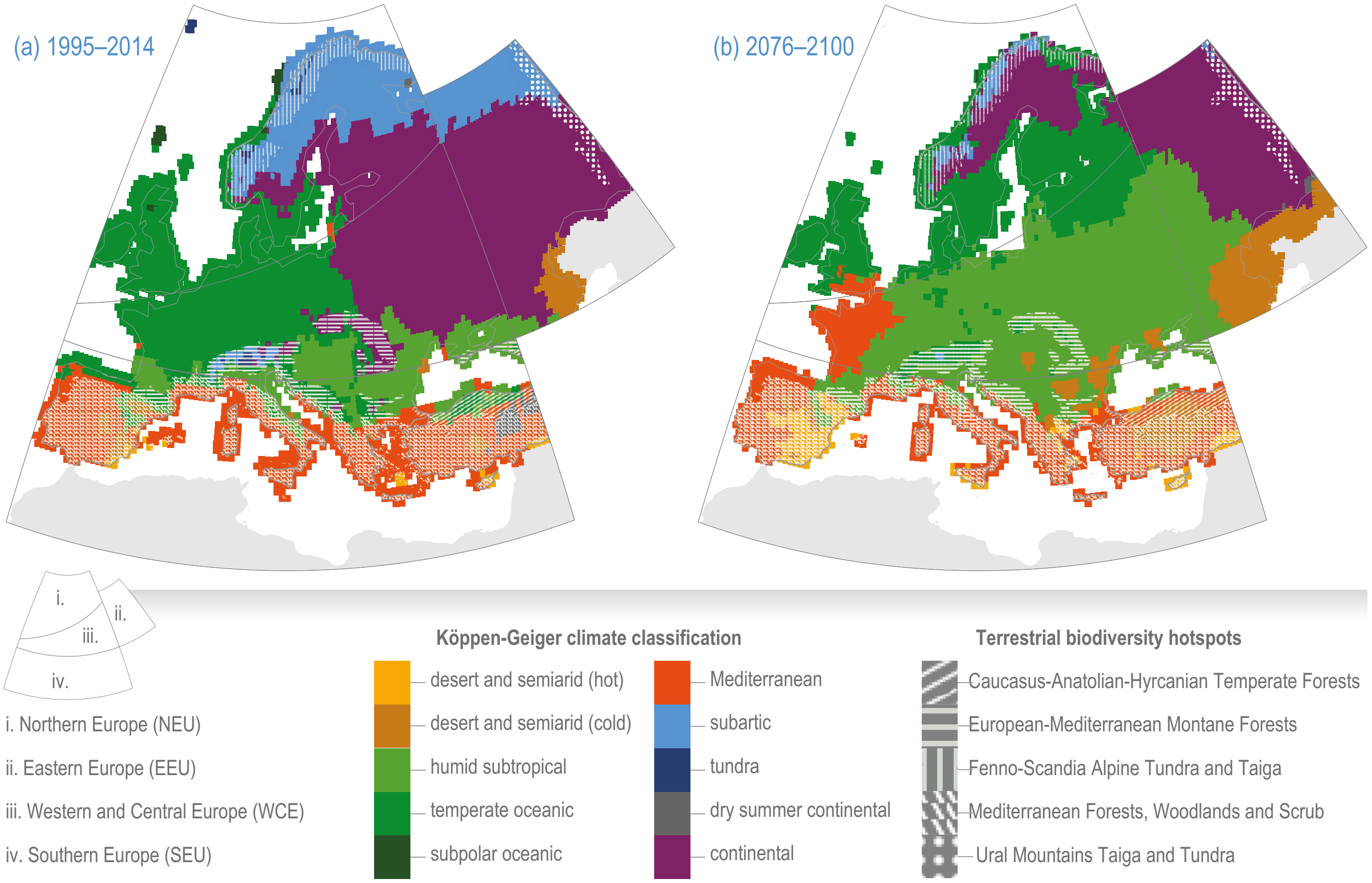


**Figure 13.7 | Köppen-Geiger climate classification and biodiversity hotspots in Europe.** Boundaries are of the

**(a)** Northern European (NEU),

**(b)** Western–Central European (WCE),

**(c)** Southern European (SEU) and

**(d)** Eastern European (EEU) regions for 1985–2014 (left) and 2076–2100 (right, A1FI scenario, ~4°C GWL), based on Rubel and Kottek (2010).

is changing biodiversity; however, overall biodiversity could remain stable because losses may be offset 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).

Range shifts are leading to northward and upwards expansions of warm-adapted taxa (*very high confidence*) (Figure 13.8; Chapter 2). These shifts have 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, autumn senescence and flight rhythms, have 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, for example, in earlier arrival dates for many birds and butterflies (Karlsson, 2014; Bobretsov et al., 2019; Lehikoinen et al., 2019). The largest increase in length of growing season 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

Risks for terrestrial ecosystems will increase with warming (*very high confidence*) with high impacts at >2.4°C GWL and very high impacts >3.5°C GWL (*medium confidence*) (Section 13.10.3.1). Land-use changes will increase extirpation and extinction risk (*very high confidence*) (Vermaat et al., 2017). 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 <1.5°C GWL would limit risks to biodiversity, while 4°C GWL and intensive land use could lead to a loss of suitable climate and habitat space for most species (*low confidence*) (Warren et al., 2018; Harrison et al., 2019).

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 (*medium evidence*) (Markovic et al., 2017). 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).

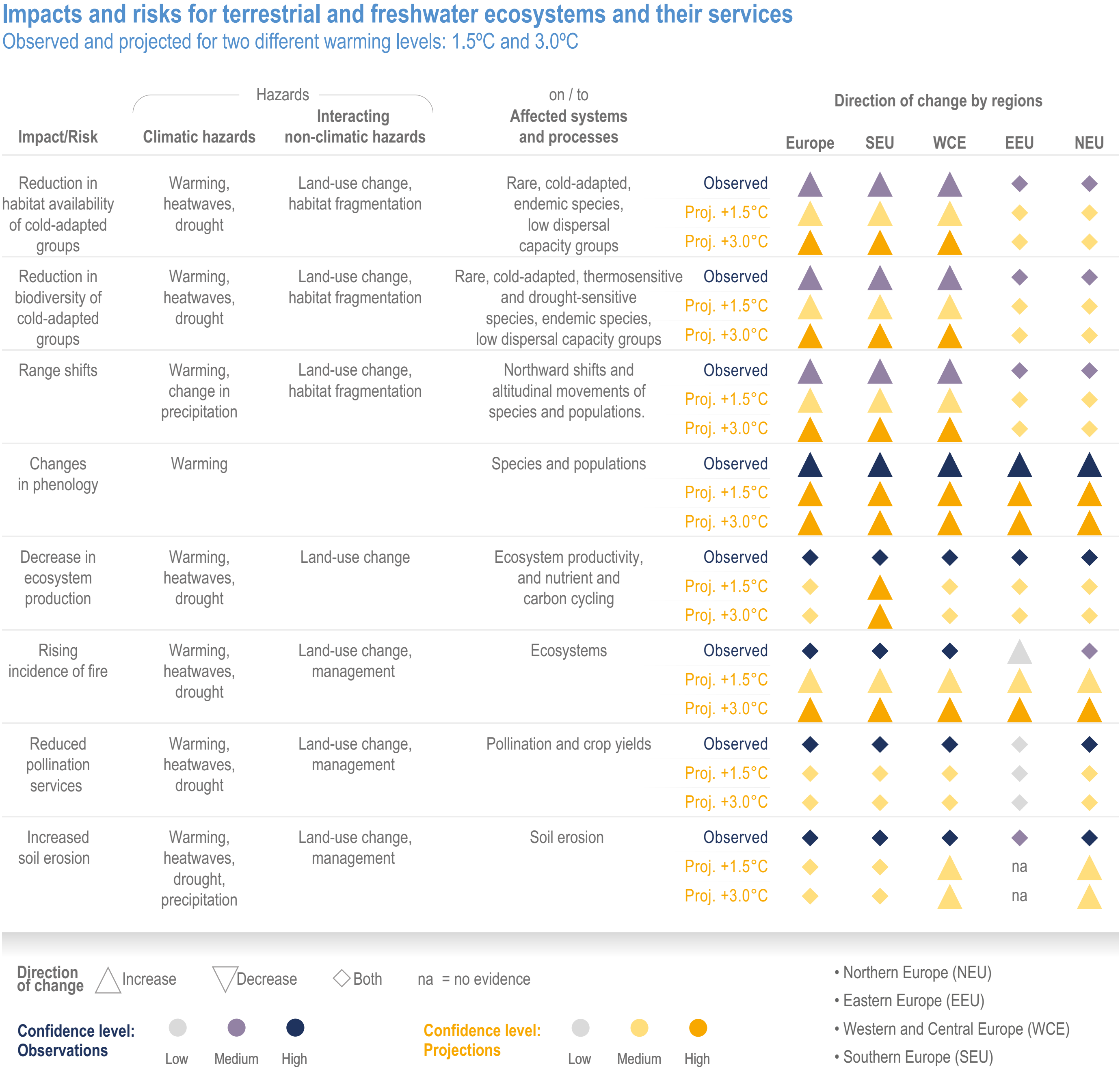
Population range shifts (Figures 13.7, 13.10) are projected to continue (*medium confidence* at 1.5° GWL, *high confidence* at 3.0°C GWL) (Figure 13.8). The largest losses of suitable climatic conditions are projected for plants and insects, with different taxon-specific regions of highest risk, while proportions of species projected to lose suitable climates are lower for other groups (*medium confidence*) (Figure Box 13.1.1; Table SM13.3; Warren et al., 2018). Temperatures >1.5°C GWL will lead to a progressive subtropicalisation in SEU, expanding into WCE at >3°C GWL, a northward shift in the temperate domain into NEU (*medium confidence*) (Feyen et al., 2020) 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 (Section 13.5.1.4). The longer growth season in NEU and WCE will support the establishment of invasive species (Cross-Chapter Paper 1). Temperatures <1.5°C GWL would limit expansion and novel appearances of pests, while >3.4°C GWL would make large parts of SEU and WCE suitable for pests, for example, 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 (*medium confidence*) (Delgado et al., 2020; Ettinger et al., 2020). 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 EU (San-Miguel-Ayanz et al., 2019), with 85% of the area located in SEU (Khabarov et al., 2016; de Rigo et al., 2017; Gomes Da 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 heatwaves (Boer et al., 2017), 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 have caused more than 90–95% of the fires, while natural ignition accounts for a substantial portion of burned areas in EEU (Wu et al., 2015; Filipchuk et al., 2018).

Except for Portugal, burned area in SEU has shown a slightly decreasing trend since 1980, with high interannual variability (Cross-Chapter Paper 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



Impacts and risks for terrestrial and freshwater ecosystems and their services

Observed and projected for two different warming levels: 1.5ºC and 3.0ºC

| | Hazards | | on / to | | Direction of change by regions | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Impact/Risk** | **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 | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +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 | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +3.0°C | ▲ | ▲ | ▲ | ◆ | ◆ |
| Range shifts | Warming, change in precipitation | Land-use change, habitat fragmentation | Northward shifts and altitudinal movements of species and populations. | Observed | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ▲ | ▲ | ▲ | ◆ | ◆ |
| | | | | Proj. +3.0°C | ▲ | ▲ | ▲ | ◆ | ◆ |
| Changes in phenology | Warming | | Species and populations | Observed | ▲ | ▲ | ▲ | ▲ | ▲ |
| | | | | Proj. +1.5°C | ▲ | ▲ | ▲ | ▲ | ▲ |
| | | | | Proj. +3.0°C | ▲ | ▲ | ▲ | ▲ | ▲ |
| Decrease in ecosystem production | Warming, heatwaves, drought | Land-use change | Ecosystem productivity, and nutrient and carbon cycling | Observed | ◆ | ◆ | ◆ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ◆ | ▲ | ◆ | ◆ | ◆ |
| | | | | Proj. +3.0°C | ◆ | ▲ | ◆ | ◆ | ◆ |
| Rising incidence of fire | Warming, heatwaves, drought | Land-use change, management | Ecosystems | Observed | ◆ | ◆ | ◆ | ▲ | ◆ |
| | | | | Proj. +1.5°C | ▲ | ▲ | ▲ | ▲ | ▲ |
| | | | | Proj. +3.0°C | ▲ | ▲ | ▲ | ▲ | ▲ |
| Reduced pollination services | Warming, heatwaves, drought | Land-use change, management | Pollination and crop yields | Observed | ◆ | ◆ | ◆ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ◆ | ◆ | ◆ | ◆ | ◆ |
| | | | | Proj. +3.0°C | ◆ | ◆ | ◆ | ◆ | ◆ |
| Increased soil erosion | Warming, heatwaves, drought, precipitation | Land-use change, management | Soil erosion | Observed | ◆ | ◆ | ◆ | ◆ | ◆ |
| | | | | Proj. +1.5°C | ◆ | ◆ | ▲ | na | ▲ |
| | | | | Proj. +3.0°C | ◆ | ◆ | ▲ | na | ▲ |

Direction of change △ Increase ▽ Decrease ◇ Both na = no evidence

Confidence level: Observations ● Low ● Medium ● High

Confidence level: Projections ● Low ● Medium ● High

- Northern Europe (NEU)
- Eastern Europe (EEU)
- Western and Central Europe (WCE)
- Southern Europe (SEU)

**Figure 13.8 | Summary of major impacts on, and risks for, terrestrial and freshwater ecosystems in Europe for 1.5°C and 3°C GWL** (Table SM13.2)

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 could 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 rise to 30% at 4.4°C GWL (Turco et al., 2018; Gomes Da 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).

### 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

Species projected to remain in suitable climate conditions in Europe

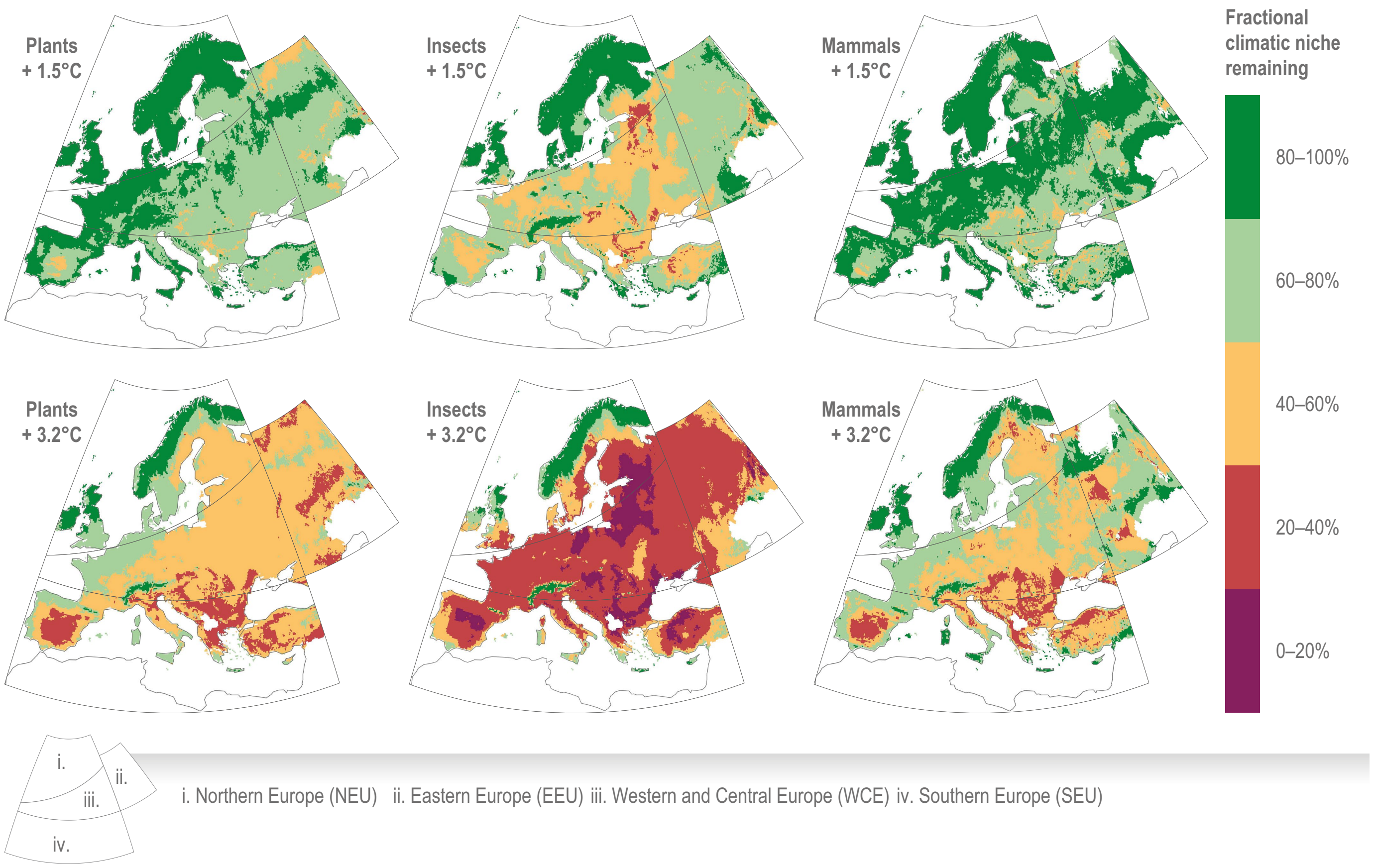


**Figure 13.9 | Species projected to remain within their suitable climate conditions at increasing levels of climate change.** Colour shading represents the proportion of species projected to remain within their suitable climates averaged over 21 CMIP5 climate models (Warren et al., 2018). Areas shaded 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 species without dispersal (Table SM13.3).

detected across European regions (*high confidence*) (Figure 13.8; 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 (Figure 13.8; Verhagen et al., 2018). If not managed through increased reforestation and/or 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 $CO_2$ fertilisation 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 change are occurring for many groups in Europe (*high confidence*) (Figure Box 13.1.1; Figure 13.8; Kerr et al., 2015; Soroye et al., 2020; Zattara and Aizen, 2020), with observed shifts to higher elevations in 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 that current impacts on pollination have not been fully realised (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). Geographical changes to the climatic niche of pollinators are similar to those of 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 microclimatic buffering (Vasiliev and Greenwood, 2021).

Soil erosion varies across Europe, with higher rates in parts of SEU and WCE, but lower rates in NEU (*high confidence*) (Figure 13.8; Petz et al.,

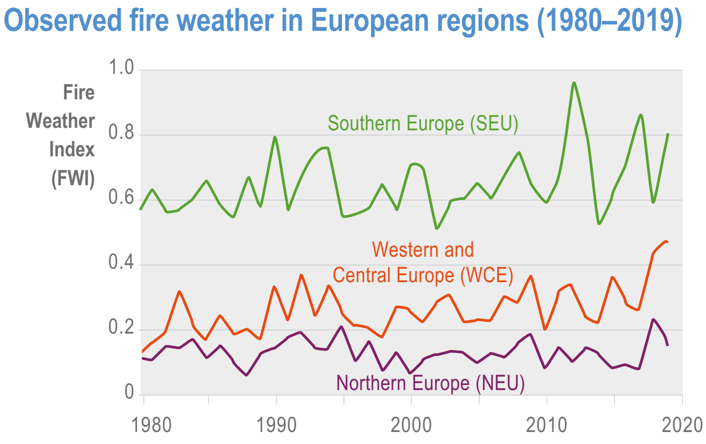


**Figure 13.10 | Geographical variability and dynamic changes in fire danger in Europe over recent decades.** Significant increases in fire hazard at the multi-decadal scale and unprecedented years of elevated fire hazard have occurred over the past decade in Southern and Western Central Europe (SEU, 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). The FWI trends were calculated with the ECMWF ERA-5 FWI reanalysis dataset (Copernicus, 2019; Copernicus, 2020a; Copernicus, 2020b).

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 snowmelt 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 erosion 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 also extirpation, have been documented in all European regions (*very high confidence*) (Figure 13.8). 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 at 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 (*high confidence*) (Hazarika et al., 2021). The combination of supporting the resilience of species, increasing functional diversity of habitats and assisting the migration of species at the limit of their adaptive capacity (Park and Talbot, 2018) is 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 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 programmes 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). The 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 combine fire-risk mitigation, prevention and preparation (Moreira et al., 2020), recovery through post-fire management (Lucas-Borja et al., 2021) and diverse fuel treatment (Mirra et al., 2017), including prescribed burning (Fernandes et al., 2013).

Ecosystem-based adaptations (EbA) and 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), while urban green infrastructure can reduce flooding (Section 13.2.2) and heat stress as well as provide recreation opportunities and health benefits (Section 13.6.2.3; see Box 13.3; Kabisch et al., 2016; Choi et al., 2021).

Appropriately implemented ecosystem-based mitigation, such as reforestation with climate-resilient native species (Section 13.3.1.4), peatland and wetland restoration, and agroecology (Section 13.5.2), can enhance carbon sequestration or storage (*medium confidence*) (Seddon et al., 2020). Salt marsh 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 (*medium confidence*) (Lee et al., 2019; Krause et al., 2020).

The solution space for responding to climate-change risks for terrestrial ecosystems 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, 2013), as well as several national and regional policies. Yet, in the northern parts of EEU and NEU (e.g., Greenland, Iceland, northwest 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) (Section 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 the 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

Despite growing evidence of climate-change impacts and risks, including attributed changes to terrestrial ecosystems (Section 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 (Section 13.3.1.3) suggests increasing risk of 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 (Section 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 are missing, due to the time lag in determining the effectiveness of an action and attributing risk reduction (Morecroft et al., 2019). For example, many landscape restoration actions have been discussed, but it is unclear which would bring the greatest benefits and which species should be used for the restoration (Ockendon et al., 2018). Furthermore, 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).

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 sub-regions (*high confidence*) (Figure 13.11; Chapter 3). Marine heatwaves have had severe ecological impacts in SEUS (*high confidence*) (Cross-Chapter Paper 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 have altered community compositions (Vasilakopoulos et al., 2017), resulting in the 'subtropicalisation' of TEUS and 'tropicalisation' of SEUS (Chapter

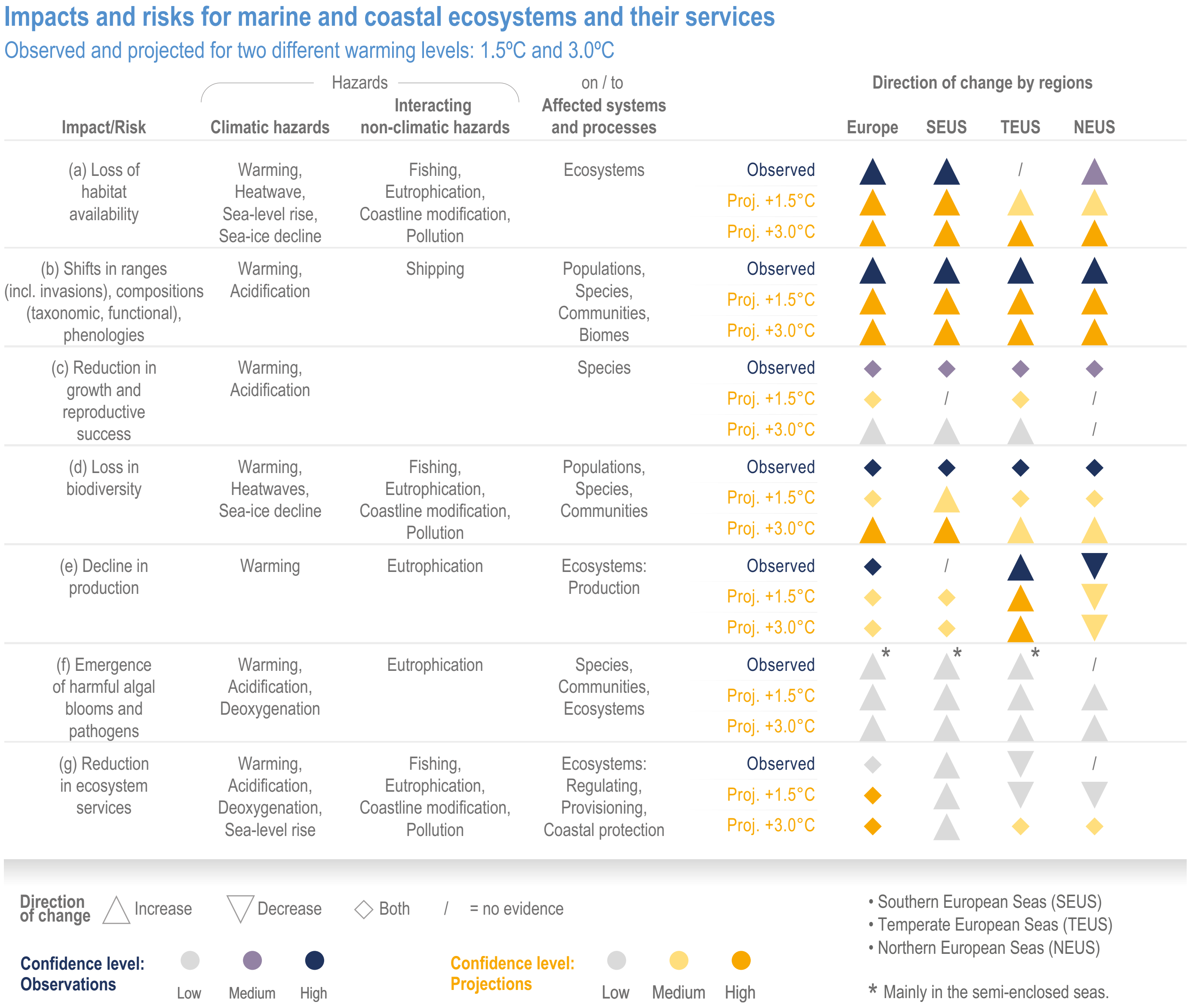


**Figure 13.11 | Major impacts and risks for marine and coastal ecosystems in Europe for observed and projected 1.5°C and 3.0°C GWL** (Table SM13.4)

3; Cross-Chapter Paper 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 (*medium confidence*) (Figure 13.11), 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 (*medium confidence*) (Figure 13.11) overall resulting in the redistribution of biodiversity in Europe (García Molinos et al., 2016), and biodiversity declines in some sub-regions (*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 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 (*high confidence*) (Free et al., 2019), while in NEUS sea ice decline has resulted in primary production increase by 40–60% (*high confidence*) (Figure 13.11; Arrigo and van Dijken, 2015; Borsheim, 2017; Lewis et al., 2020). Climate-related deoxygenation impacts are small in most European waters (*medium confidence*) (Figure 13.11), 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 have altered ecosystem functioning (*high confidence*), reduced potential fish yield and 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) along with 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 inter-regional variability, but *high confidence* in the decrease in regulating services and coastal protection because of the 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 (*medium confidence*) (Thomsen et al., 2017; Miller et al., 2018; Bindoff et al., 2019), 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 (*medium confidence*) (Clark et al., 2020). Warming at this level will threaten many species currently living in marine protected areas (MPAs) in TEUS and NEUS (Bruno et al., 2018). Increasing marine heatwaves (MWHs), 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 (*high confidence*) (Figure 13.11), 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 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), for example, 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 northeast 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 (*medium confidence*) (Figure 13.11). Coralline algae are projected to reduce skeletal performance at 3°C GWL, with negative consequences for habitat formation (*medium confidence*) (Ragazzola et al., 2016). Regionally (Brodie et al., 2014), differences in species-specific vulnerability will result in community shifts from calcifying macroalgae (*medium confidence*) (Ragazzola et al., 2013) to non-calcifying macroalgae (*high confidence*) (Gordillo et al., 2016). 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*) (Thomsen et al., 2013; Büscher et al., 2017). This suggests that acidification risks will be amplified by increased stratification and reduced primary production (*medium confidence*). The emergence of harmful algal blooms and pathogens at higher GWLs is unclear across all European seas (*low confidence*) (Figure 13.11).

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, for example, 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 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 6–10 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 EUR of ecosystem services in 2018, and 4.2–5.1% 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 operationalising and enforcing marine conservation; however, ICZM and MSP commonly do 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) (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 (MSFD) and European Water Framework Directive (EWFD) of the EU. 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 EbA or NbS, 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*), for example, from avoided expenditures for flood defence infrastructure and avoided loss of the built assets (Gedan et al., 2010).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). These MPAs provide protection from local stressors, such as commercial exploitation, and enhance the resilience of marine and coastal ecosystems, thus lessening 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, 2014). There is evidence that better international cooperation is required to increase the 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 km²). No-take areas account, in total, for less than 0.4% of the area of 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 partially protected MPAs is debated and dependent on local management (Zupan

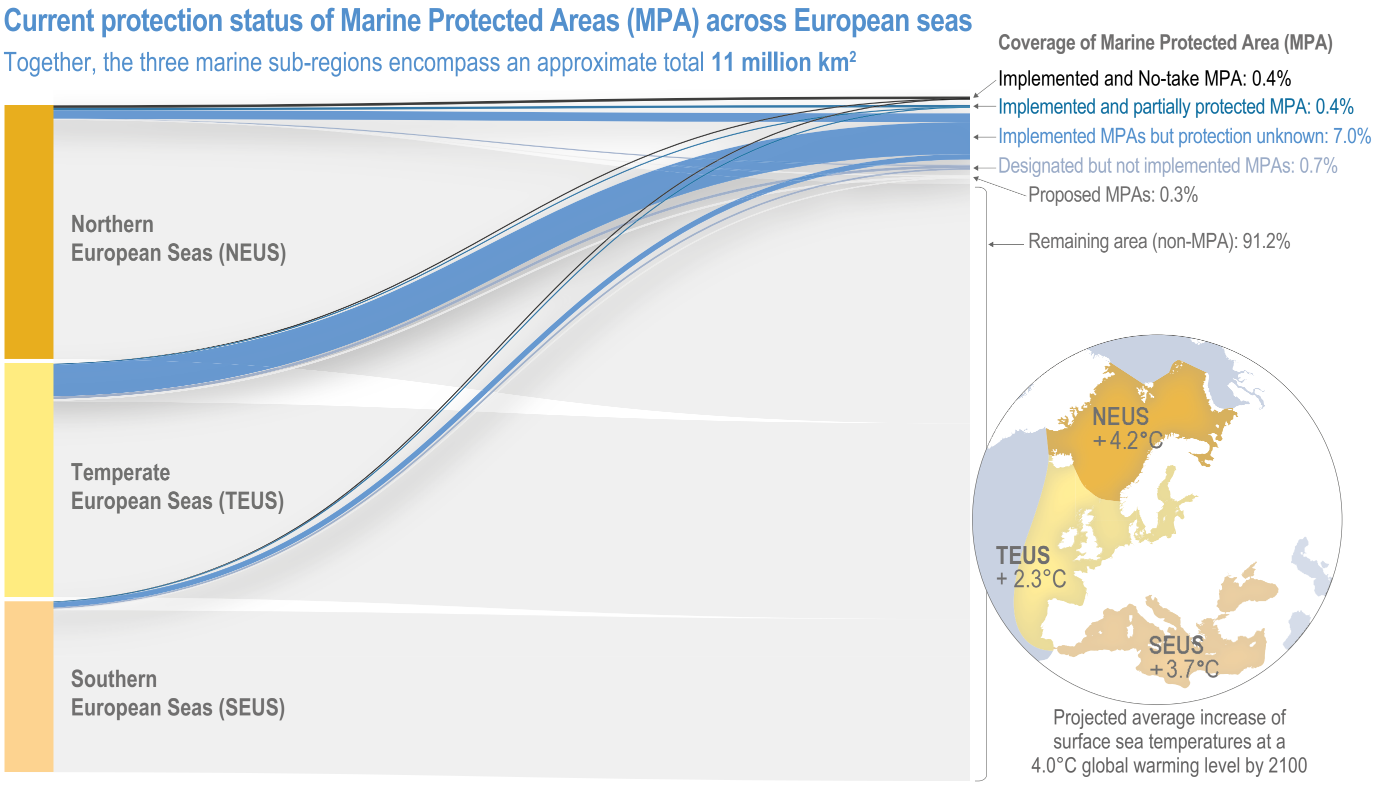


**Figure 13.12 | Marine protected areas (MPAs) in European seas.** Shown are proportions of designated and proposed MPAs in the total areas of northern (NEUS), temperate (TEUS) and southern (SEUS) European seas, as well as the shares of no-take, partial, unimplemented and unknown protection levels of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

et al., 2018b). Marine protected areas 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, while 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).

Conservation approaches (e.g., 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 SLR (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 landward and upwards is provided, enhancing their ability to capture and store carbon (Lecocq et al., 2022; Rogers et al., 2019). 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 reforestation 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 (Clarke et al., 2022). The introduction of novel hard-substrate intertidal habitats has, and will continue to have, profound ecological ramifications for marine systems, including hydrodynamic changes, stepping stones for non-native species, noise and vibration, and changes in the food web (*high confidence*) (Lindeboom et al., 2011; De Mesel et al., 2015; Gill et al., 2018; Dannheim et al., 2019).

### 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 MPA networks (Dubois et al., 2016; Sahyoun et al., 2016) and facilitate assisted migration. Such MPAs cover a wide range of protection status with *limited evidence* regarding 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 EEU. The detection and attribution of ongoing or emerging environmental and biological changes are 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 in 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 globalised food system with a third of the commodities produced and consumed in Europe traded internationally (FAOSTAT, 2019).

Observed climate change has led to a northward movement of agro-climatic zones in Europe and earlier onset of the growing season (*high confidence*) (Ceglar et al., 2019). Warming and precipitation changes since 1990 explain continent-wide reductions in yield of wheat and barley, as well as 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 SEU 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 (Sections 13.2.1, 13.3.1, 13.10.2) have increased costs and cause economic losses in forest productivity (Schuldt et al., 2020), 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 (*high confidence*) (Ivanov et al., 2016; Loboda et al., 2017), with the severity of impacts from extreme heat and drought tripling over the past 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 and 2018 (Ben-Ari et al., 2018; van der Velde et al., 2018; Zscheischler et al., 2018; Toreti et al., 2019b) that were exceptional compared with 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 (*high confidence*) (Garcia-Mozo et al., 2015). Delayed harvest, due to both wet conditions and earlier harvests in Central Europe in response to warming, has 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 parameterisation 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 (*high confidence*) (Hannah et al., 2013; Litskas et al., 2019), 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 per decade, fastest in EEU (Ceglar et al., 2019). Negative impacts of warming and drought are counterbalanced by $CO_2$ fertilisation 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 (*high confidence*) (Figure 13.5; Trnka et al., 2014; Webber et al., 2016; Szewczyk et al., 2018). The largest impacts of warming are projected for maize in SEU (*high confidence*) (Deryng et al., 2014; Knox et al., 2016) with yield losses across Europe of 10–25% at 1.5°C–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 NEU, but not SEU for 4°C GWL (*medium confidence*) (Siebert et al., 2017; Ceglar et al., 2019). Irrigation can reduces projected heat and drought stress, for example, for wheat and maize (Ruiz-Ramos et al., 2018; Feyen et al., 2020), but use is limited by water availability (KR3, Section 13.10.2). The advantages of a longer growing season in NEU and EEU are outbalanced by the increased risk of early spring and summer heatwaves (Ceglar et al., 2019).

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

Net yield losses will reduce economic output from agriculture in the EU, reaching a reduction of 7% for the EU and the 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 decrease profitability and cause abandonment of farmland in SEU (*limited evidence, low confidence*) (Holman et al., 2017).

### 13.5.1.2 Livestock Production

Heat and humidity affect livestock, such as dairy cows and goats, directly exposed in open barns and outdoors (Gauly et al., 2013; Bernabucci et al., 2014; Silanikove and Koluman, 2015), and cold-adapted husbandry (*high confidence*) (see Box 13.2; Section 13.8.3). 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 alters the prevalence, distribution and load of pathogens and their vectors (*high confidence*) (Section 2.4.2.7.3; Morgan et al., 2013; Charlier et al., 2016). Projected impacts on poultry and pigs are low due to temperature control in large parts of Europe, but are 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 (*high confidence*) (Section 13.8.3; Herzog and Seidl, 2018). 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 (*high confidence*) (Silanikove and Koluman, 2015).

### 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 25% of seafood production in Europe (FAOSTAT, 2019).

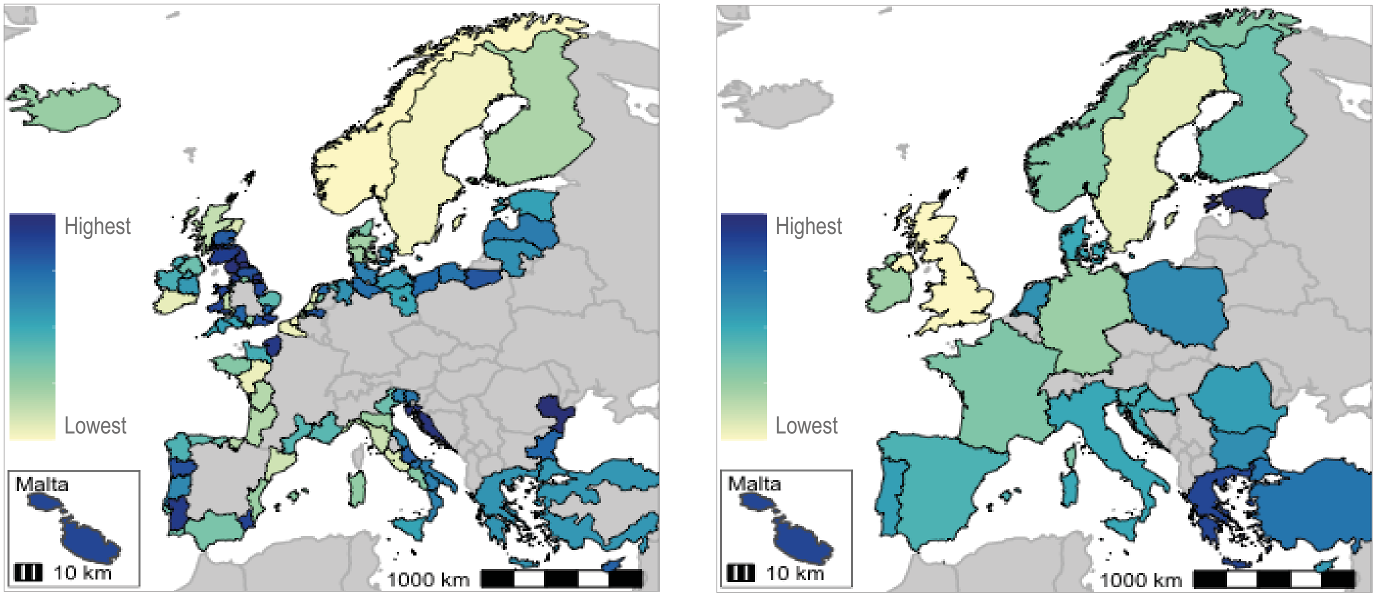
Climate change has impacted European marine food production (*high confidence*); however, extraction is still the major impact on commercially important fish stocks in Europe (Mullon et al., 2016), with 69% of stocks overfished and 51% outside safe biological limits (Froese et al., 2018). The North Sea, the Iberian Coastal Sea and the 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 recent decades (Free et al., 2019). Warming has caused ongoing northward movement and range expansion of Northeast Atlantic fish stocks (Section 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) have become 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 the 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 the

Future vulnerability and risks for aquatic food production

(a) Risk to fisheries in European coastal regions

(b) Vulnerability of national European aquaculture sectors



(c) Difference (%) in projected population sizes of major fisheries species between 1.5°C and 4°C global warming

(d) Difference (%) in projected population sizes of major aquaculture species between 1.5°C and 4°C global warming

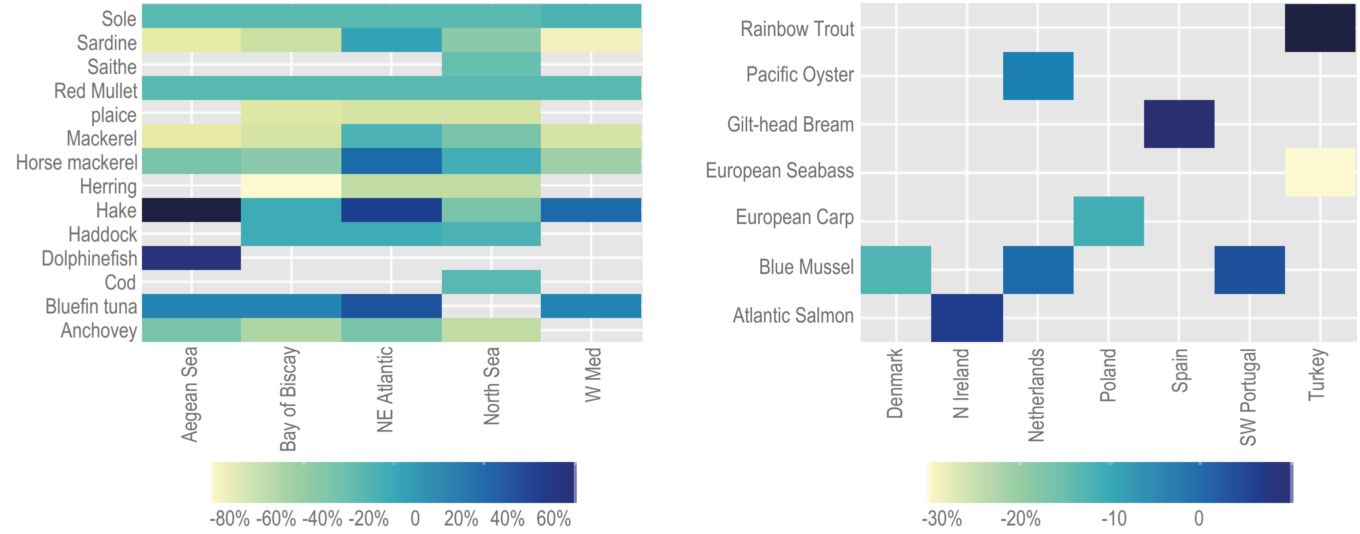


**Figure 13.13 | Future vulnerability and risks for aquatic food production:**

**(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 GWL (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

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).

Future vulnerabilities, risks and opportunities are projected to strongly vary regionally and between major fisheries and aquaculture species (Figure 13.13 c,d; Peck et al., 2020). 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 (*medium confidence*) (Figure 13.13; Peck et al., 2020; Payne et al., 2021). In response to 4°C GWL, higher trophic-level biomass is projected to increase in the SEUS mainly due to increases in 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 (Swat 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 (*high confidence*) (Section 13.3.1; Moreno et al., 2018; Morin et al., 2018; Senf et al., 2018; Orlova-Bienkowskaja et al., 2020). Species-specific responses of trees to drier summers (Vitali et al., 2018) shape regional variability in European forest productivity in response to water and nutrient availability, heatwave and evaporative demand (Reyer et al., 2014; Kellomäki et al., 2018). While warming and extended growing seasons have positive impacts on forest 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 (*high confidence*) (Primicia et al., 2015; Marqués et al., 2018; Ruiz-Pérez and Vico, 2020). 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 tree mortality (Buras et al., 2020) with carryovers into 2019 (Schuldt et al., 2020), as well as bark beetle outbreaks (Netherer et al., 2019) resulting in felling and cutting of more than 1 million ha of spruce forest and disrupting timber markets (Mauser, 2021).

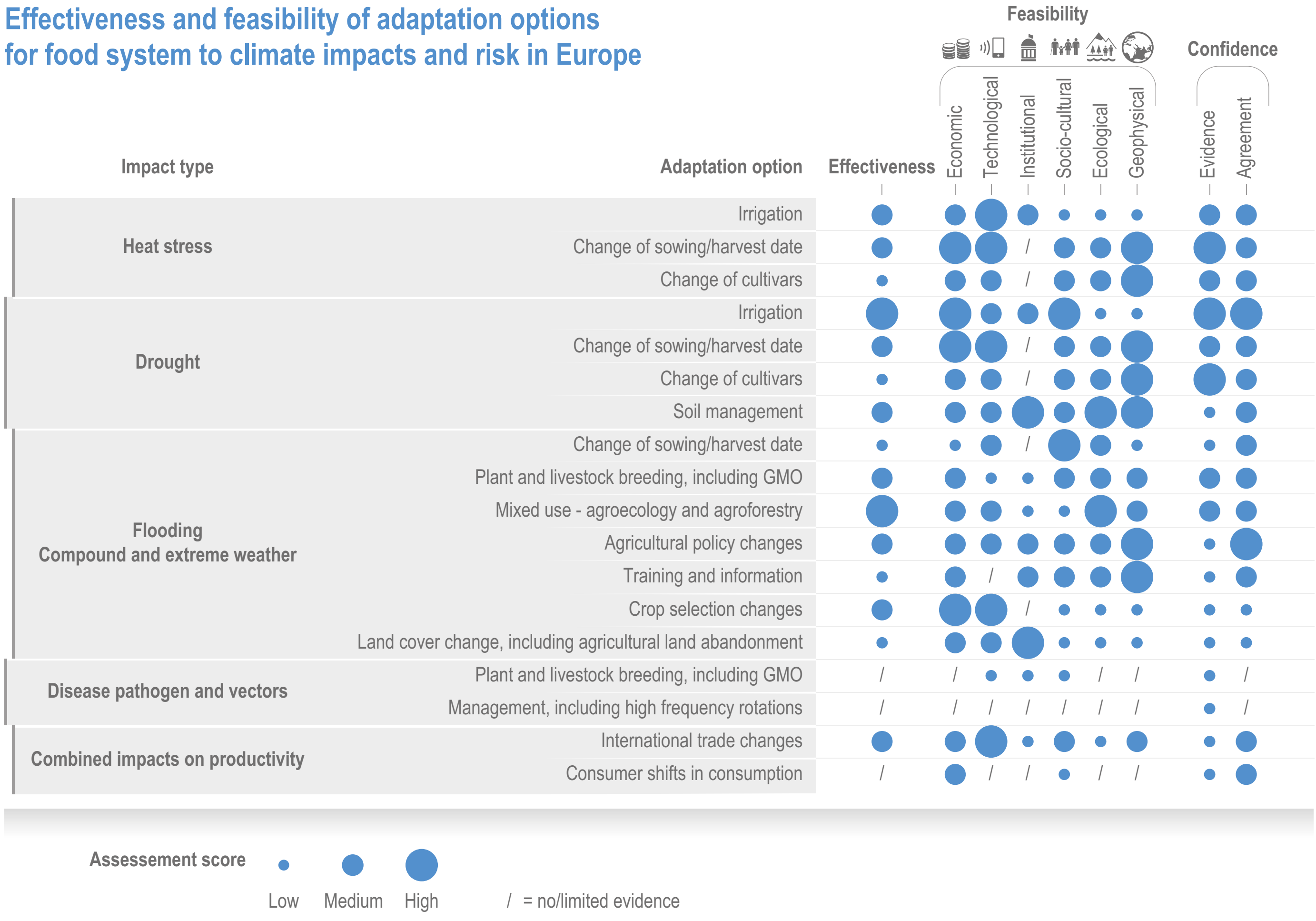


**Figure 13.14 | Effectiveness and feasibility of the main adaptation options for food systems in Europe** (Section SM13.9, Table SM13.5)

In response to 3°C GWL, forest productivity is projected to increase in NEU and altitudes, show mixed trends in WCE and decrease in SEU (*medium confidence*) (Reyer et al., 2014). 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 (Section 13.3.1), resulting in forest productivity declines or cancelling out productivity gains from $CO_2$ (*high confidence*) (Seidl et al., 2014; Reyer et al., 2017). In response to 1.7°C GLW, managed forest and unmanaged woodland areas are projected to decrease only minimally, while at GWL >2.5°C losses are increasing for managed forest and unmanaged woodland (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 (Sections 13.5.2.1–13.5.2.3) and market-based changes to consumer demand and trade (Section 13.5.2.4). The assessment of effectiveness and feasibility of options in the food system is summarised in Figure 13.14.

#### 13.5.2.1 Crops and Livestock

Farm management adaptation options to climate change include changing sowing and harvest dates, changes in cultivars and irrigation, and selecting alternative crops (Figures 13.14, 13.15; Donatelli et al., 2015). Irrigation is effective at reducing yield loss from heat stress and drought, for example, for wheat and maize (Figures 13.14, 13.15), but it 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 as much as 80 to 11% (Feyen et al., 2020). Extensive droughts during the past two decades have caused many irrigated systems in SEU 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, Section 13.10) and is limited by costs and institutional coordination (Iglesias and Garrote, 2015). Agricultural water management adaptation practices include irrigation, reallocating water to other crops, improving use efficiency and soil water conservation practices (Iglesias and Garrote, 2015). In-season forecasts of climate impacts on yield were successfully used for European wheat during the 2018 drought (van der Velde et al., 2018).

Changes to cultivars and sowing dates can reduce yield losses (Figure 13.15) but are insufficient to fully ameliorate losses projected >3°C 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 are limited in mountain pastures (*high confidence*) (Deléglise et al., 2019). Response options to insufficient amounts 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 maximise the use of grazed pasture are considered more environmentally sustainable but are not fully supported by policy and markets (*medium confidence*) (Hennessy et al., 2020). 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 the risk of introducing or spreading pests (European Comission, 2016).

Agroecological 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 agroecological 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 programmes and policy support (*high confidence*) (Hernández-Morcillo et al., 2018).

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 socioeconomic factors play a more important role in short-term farm-level investment decisions than climate-change impacts (*high confidence*) (Juhola et al., 2016; Hamidov et al., 2018).

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

Projected yield changes with climate change, altered crop management and associated water demand

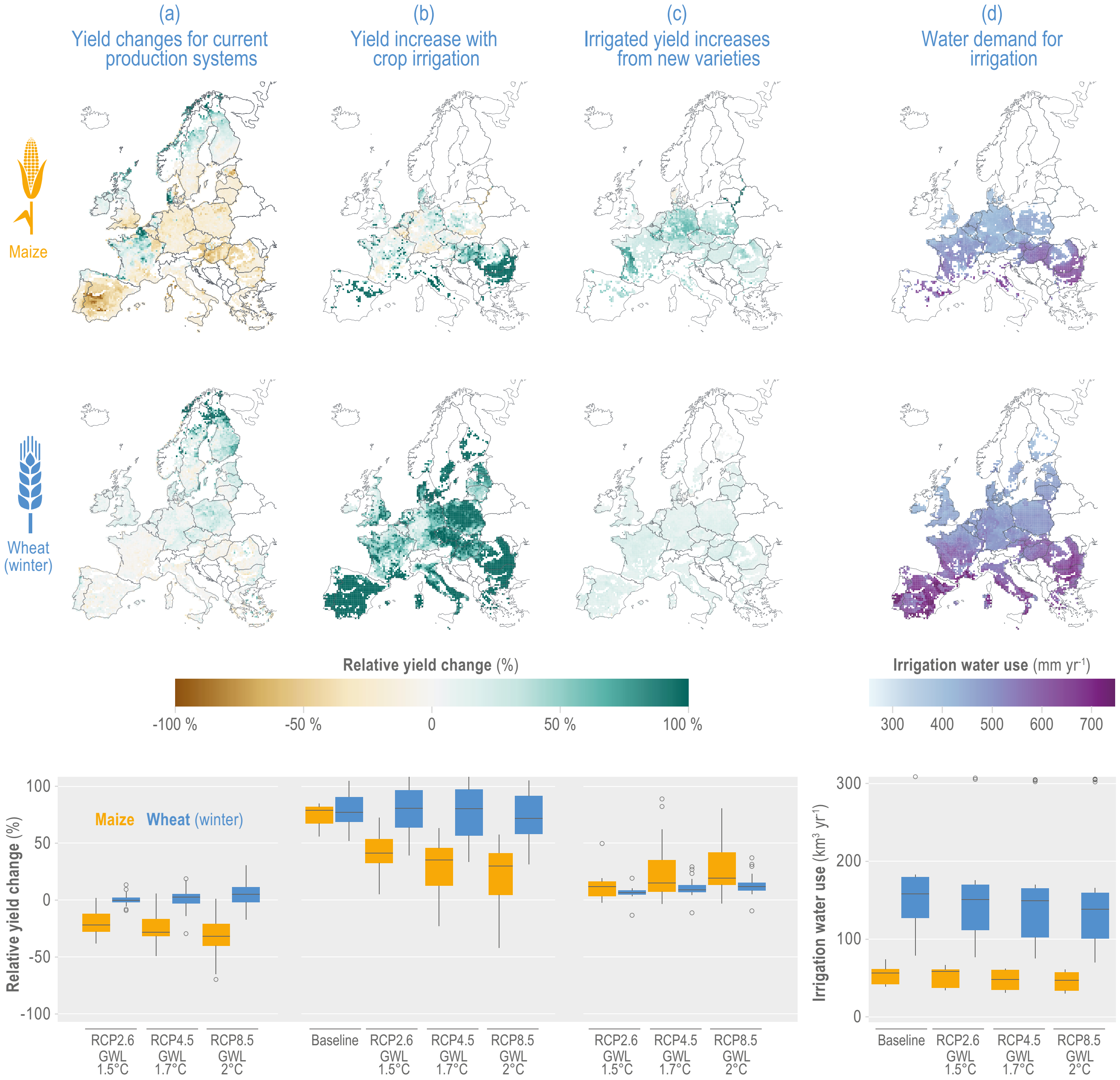


**Figure 13.15 | Projected yield changes with climate change for 1.5°C (RCP2.6), 1.7°C (RCP4.5) and 2°C GWL (RCP8.5).** Altered crop management and associated water demand shows:

**(a)** relative yield changes under climate change and elevated $CO_2$ for current production systems (i.e., rain-fed and irrigated simulations weighted by current the share of rain-fed and irrigated areas);

**(b)** yield increase if current predominantly rain-fed areas are fully irrigated;

**(c)** additional yield increases for irrigated production systems if new varieties are 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 rain-fed areas (Webber et al., 2018). Relative yield changes to a period centred on 2055 relative to a baseline period centred on 1995. Box plots are Europe's aggregate results considering current production areas (a) or current rain-fed areas (b,c), showing uncertainty across crop models and general circulation models. The maps are for the crop model median for RCP4.5 (1.7°C GWL) with GFDL-CM3.

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 (Alliance Environnement, 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, 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 EU's Common Fisheries Policy (CFP) rebuilding fish stocks to 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 MSFD 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 Northeast 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). Sociopolitical 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 (*high confidence*) (Schelhaas et al., 2015; Zubizarreta-Gerendiain et al., 2017; Pukkala, 2018). Greater diversity of tree species reduces vulnerability to pests and pathogens (Felton et al., 2016), and increases resistance to natural disturbances (*high confidence*) (Jactel et al., 2017; Pukkala, 2018; Pardos et al., 2021). Depending on forest successional history (Sheil and Bongers, 2020), tree composition change can increase carbon sequestration (*high confidence*) (Liang et al., 2016), biodiversity and water quality (Felton et al., 2016). Conservation areas can also help climate-change adaptation by keeping the forest cover intact, creating favourable microclimates and protecting biodiversity (*low confidence*) (Jantke et al., 2016).

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 (Section 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 globalised 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 (*high confidence*) (Alexander et al., 2019; Willett et al., 2019). Although mitigation potentials of dietary changes have received increasing attention, evidence is lacking on potential for adaptation through changes in European food consumption and trade, despite these socioeconomic factors being a strong driver for change (*medium confidence*) (Harrison et al., 2019; Kebede, 2021). 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 (Section 13.7) (Venghaus and Hake, 2018).

### 13.5.3 Knowledge Gaps

Aggregated projections of impacts, especially of combined hazards, are still rare despite many physiological papers on species-specific responses to warming in all food sectors (*high confidence*). This is specifically true for scenarios that consider land-use change and population growth, although Agri SSPs are currently being developed (Mitter et al., 2019). Effectiveness of adaptation options is predominantly qualitatively mentioned but not assessed, and the effectiveness of combinations of measures is rarely assessed (*high confidence*) (Ewert et al., 2015; Holman et al., 2018; Müller et al., 2020). 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 EU-28 and have gaps within the eastern part of WCE and EEU, despite dramatic changes in land use over 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 (*high confidence*) (Challinor et al., 2016; Webber et al., 2016).

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 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 Infrastructures

Urban areas in Europe house 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 1 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 the 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, for example, in France, Germany, Switzerland and the 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, 2017a). Projected climate risks for energy supply are summarised in Figure 13.16.

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).

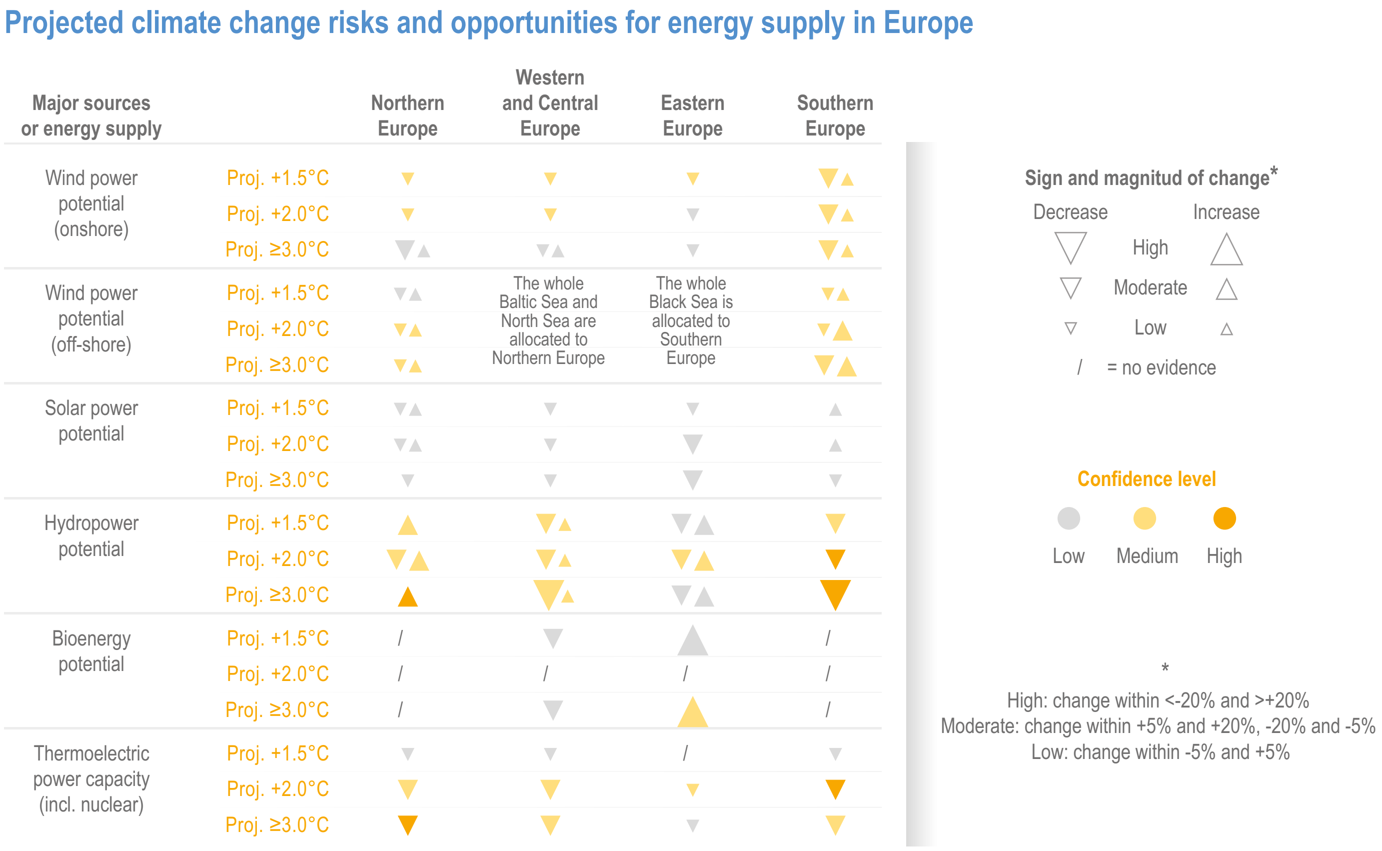
There is *low evidence* and *limited agreement* on projections of solar power potential due to differences in the integration of aerosols and the estimated cloud cover between climate models (Bartok et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020). Studies on climate risks for bioenergy are also limited.

Energy demand is projected to display regional differences in response to 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 al., 2017; Spinoni et al., 2018; Coppola et al., 2021). Under the present population numbers, total energy demand would decrease in almost all of 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 2°C 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 the 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 2°C GWL, while



Projected climate change risks and opportunities for energy supply in Europe

**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 SM13.5–13.13)**

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 3°C 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 2°C GWL could significantly reduce road maintenance costs in NEU (Lorentzen, 2020), but limit off-road overland transport in northwest Russia (Gädeke et al., 2021). Beyond 3°C GWL, more frequent hourly precipitation extremes are projected over WCE and NEU in summer (e.g., a twofold and tenfold increase, respectively, for events exceeding the present-day 99.99th percentile in Germany and the UK) but more widely across Europe in autumn and winter (an increase higher than tenfold for 99.99th percentile events in SEU 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 2°C GWL, threatening road networks (Schlogl and Matulla, 2018; Rianna et al., 2020).

The 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 EUR 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 carriage cooling (Jenkins et al., 2014a).

The number of airports vulnerable to inundation from SLR 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 2°C GWL and beyond in airports of France, the 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 with 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 reduces the productivity of labour particularly in construction, agriculture and manufacturing (Section 13.7.1; García-León et al., 2021; Schleypen et al., 2021). Direct losses from floods in Europe are highest for manufacturing, utilities and transportation; indirect losses arise, for example, 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 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 has 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 and 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 Martinez 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 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 SLR amplifying coastal erosion and inundation risks, although less in NEU (Section 13.2; Ebert et al., 2016; Toimil et al., 2018; Lopez-Doriga et al., 2019; Ranasinghe et al., 2021).

#### 13.6.1.5 Built Environment, Settlements and Communities

The 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).

About 32% of 571 European cities in the GISCO Urban Audit 2014 dataset show a medium to high or relatively high vulnerability against heatwaves, droughts 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.

##### *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 SLR 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, 2020b). Apart from climate change, urbanisation 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 EU cities live within potential river floodplains. In many of these places (e.g., 50% of UK cities), a significant increase in 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, 2020b).

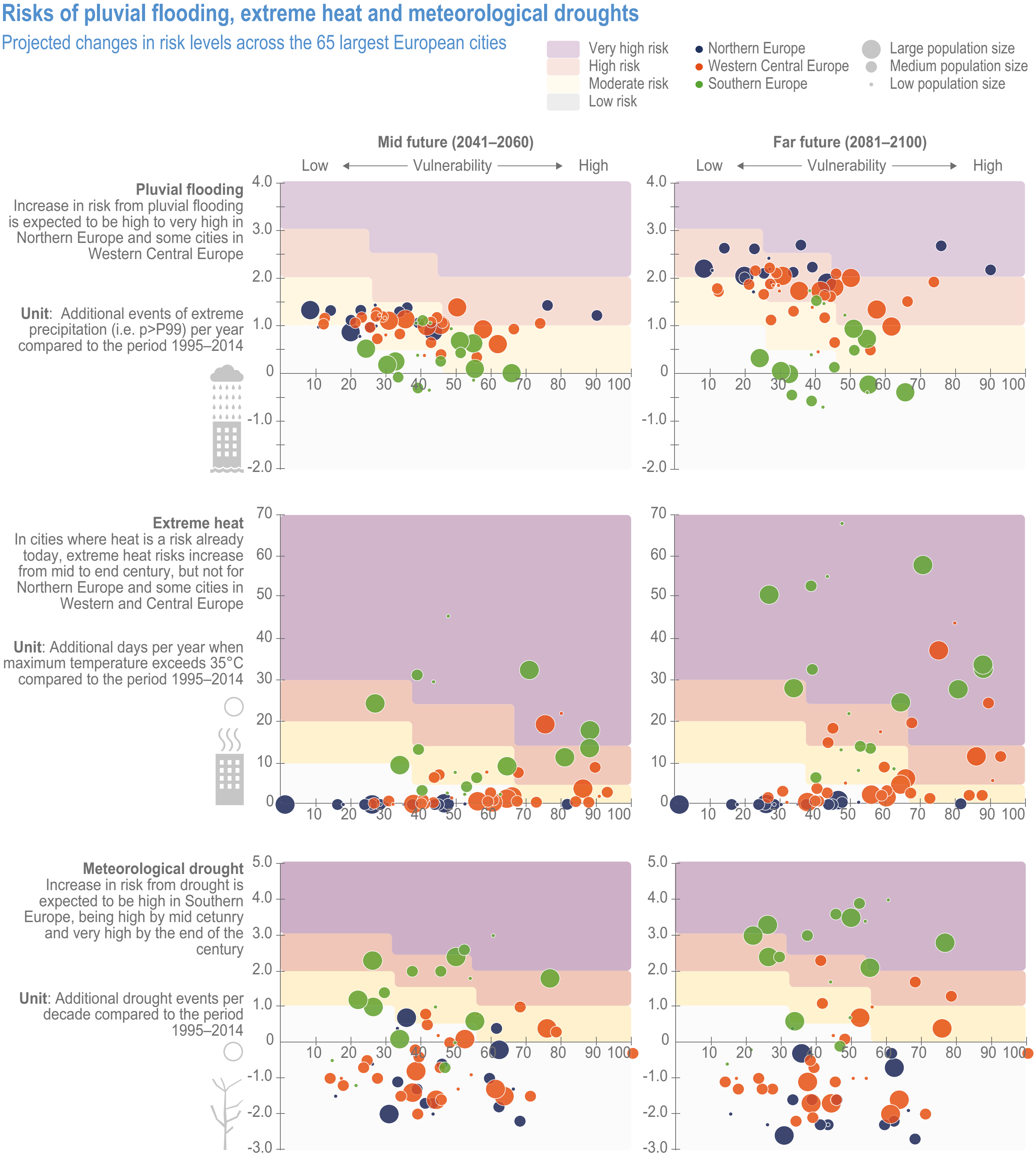


**Figure 13.17 | Projected changes in pluvial flooding, extreme heat and meteorological drought risks for the 65 largest cities in EU-28 plus Norway and Switzerland for 2.5°C and 4.4°C GWL compared with the baseline (1995–2014) (Tapia et al., 2017).** Exposure is expressed in terms of current population.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

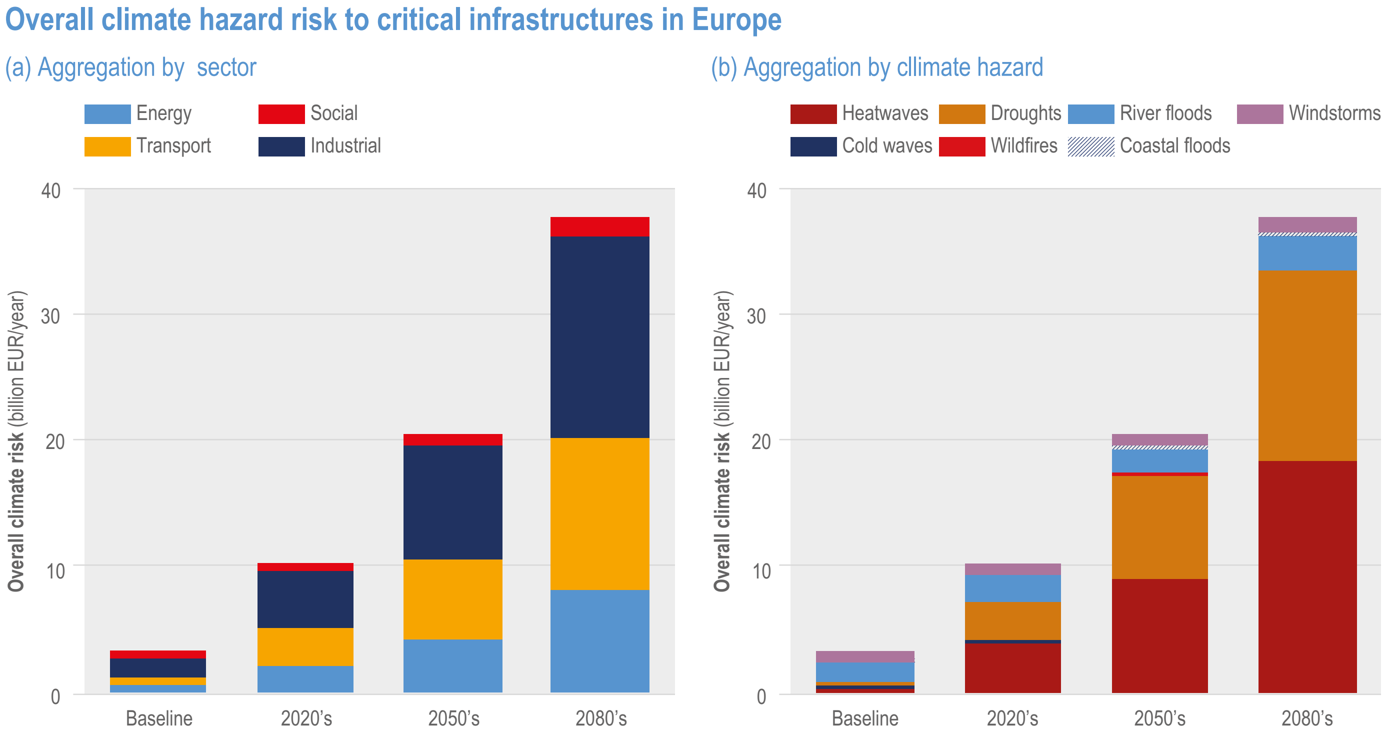


**Figure 13.18 | Climate risks to critical infrastructures, aggregated at European (EU+) level under the SRES A1B scenario (Forzieri et al., 2018).** Baseline: 1981–2010; 2020s: 2011–2040; 2050s: 2041–2070; 2080s: 2071–2100

### *13.6.1.5.2 Risks from heatwaves, cold waves and drought*

Heatwave days and number of long heatwaves increased in most capitals from 1998–2015 compared with 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 (see also Section 13.7.1; Di Napoli et al., 2018; EEA, 2020b).

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 2°C GWL and SSP3, half of 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, 2020b). 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 SEU at 3°C 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 91–244% after 2065 compared with 1961–1990 depending on GWL (Cellura et al., 2018). Increases of 31–73% by 2050 and 165–323% by 2100 compared with 1996–2005 were estimated for buildings in NEU (Dodoo and Gustavsson, 2016) with risks modified by adaptation (Section 13.6.2; Viguié et al., 2020). Cold waves beyond 3°C GWL will not represent an effective threat for European cities at the end of the century, and only a marginal hazard under 2°C GWL (Smid et al., 2019).

At 2°C 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 (see Section 13.2 on drought risks) 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 2°C 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 with 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 (Section 13.3.1.3). High fuel load combined with proximity of the built environment to wildland highly increases fire risks (EEA, 2020b).

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 EUR during

**Table 13.1 |** Present status of planned and implemented adaptation in European cities, energy sector, tourism sector, transport and industry (Table SM13.17)

| | General commitments / Adaptation Plans | Implemented adaptation actions |
|---|---|---|
| Cities | – An increasing number of cities acknowledge the critical role of adaptation in building resilience to climate change.<br>– 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 less than 300 reported adaptation goals and funds. Extreme heat, drought and forest fire were the most often reported hazards.<br>– Most urban adaptation plans include ecosystem-based measures, but often with limited baseline information and convincing implementation actions.<br>– Adaptation to risks from climate extremes (mostly flooding) is often addressed through municipal emergency plans. | – Large cities (e.g., Helsinki, Copenhagen, Rotterdam, Barcelona, Madrid, London, Moscow) are in the process of implementing adaptation actions.<br>– Current climate policies implemented at city-scale are primarily addressing mitigation and, to a lesser extent adaptation. Though many cities have implemented measures potentially supporting adaptation, they are not labelled as such.<br>– Nature-based Solutions and ecosystem-based adaptation are increasingly used to address urban heat and flooding risks that are enhanced by surface sealing and limited infiltration.<br>– Strategic and emergency measures have been applied for drought management in some cities (e.g., London, Istanbul). |
| Energy | – In 2020, 29 countries had an adaptation plan for the energy sector. Some of them included specific adaptation actions (mostly preparatory) in their national or energy-specific risk assessments. | – In 2020, 11 countries had implemented adaptation actions in the energy sector. |
| | | – Measures undertaken by some distribution system operators and energy companies, focus on adaptation of transmission lines, water cooling, actions to avoid flooding (e.g. dams) and secure fuel supply. |
| Tourism | – Consideration of tourism in national adaptation strategies is limited, and national tourism strategies rarely mention adaptation.<br>– In some countries there is legally binding consideration of climate change when constructing new tourism units (e.g., the 2016 French Mountain Act).<br>– Many tourism operators focus on near-term coping strategies and do not consider longer term adaptation. | – Snow making is widely applied in the Alps and Pyrenees ski resorts; e.g. from 18% of ski slopes in Germany to 67% in Austria. Some resorts already offer nocturnal skiing (e.g., Spain) and other snow-based activities.<br>– There is already some transformation to year-round mountain resorts (e.g., in 70% of Spanish ski resorts). |
| | | – Some diversification of tourism products is offered in Mediterranean coastal destinations.<br>– Water saving measures, primarily for cost reduction, have been implemented, e.g. in hotels. |
| Transport | – At the national level, 10 countries have started coordination activities or identified adaptation measures. Some countries are mainstreaming adaptation within transport planning and decision-making (e.g., the 'Low-water Rhine' action plan, in Germany).<br>– Some action is undertaken in the public and private sector, e.g., revised manuals/guidelines/ protocols that consider climate change impacts and extreme events (e.g., Deutsche Bahn, Norwegian Public Roads Administration).<br>– An integrated, transmodal approach to transport adaptation is lacking. | – Most adaptation actions are preparatory; 5 countries have implemented specific actions. Planned and implemented actions mostly focus on infrastructure and much less on services, although the latter are increasing (e.g., operational forecasts for water levels in rivers).<br>– Transport modes often compete for public funds and political priorities often influence adaptation for specific modes. |
| | | – Some public and private actors are moving faster: new railway drainage standards (Network Rail/ UK), adverse weather event predictions (Spanish rail service operator), measures against coastal flooding (Copenhagen Metro), measures for sea level rise (Rotterdam port, France). |
| Industry and business | – Some businesses are following recommendations of the High-Level Expert Group on Sustainable Finance, endorsed by the European Commission, and implementing the guidelines provided by the Task Force on Climate-Related Financial Disclosure in 2019. | – Fifty large European publicly listed companies disclosed their climate risks in 2020, yet only a small percentage provided specifics on sectoral risks, as well as how risks differ over time and according to different climate scenarios.<br>– Large national and multinational companies, and companies regulated by mitigation policy are the first movers in corporate adaptation, while small and medium-sized enterprises often lack the knowledge and resources to address risks and adaptation options.<br>– Climate service providers, insurance companies and central banks have developed different tools for climate risk assessment, such as, stress testing, scenario analysis, value at risk. |

| | | | | | |
|---|---|---|---|---|---|
| 🟧 | Well-established adaptation | 🟨 | Advancing adaptation | ⬜ | Low adaptation |

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 has led to accelerated degradation of permafrost, negatively affecting the stability of infrastructures (Stoffel et al., 2014; Beniston et al., 2018; Duvillard et al., 2019). In the Caucasus, glacial mudflows due to permafrost degradation and modern tectonic processes pose a significant danger to the infrastructure (Vaskov, 2016). In the past 30 years, the permafrost temperature in the European part of the Russian Arctic has increased by 0.5–2°C, resulting in damage to buildings, roads and pipelines, and to significant expenditure for stabilising 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). The increasing number of cycles of freezing and thawing, observed in EEU, has led to accelerated ageing of building envelopes (Section 13.8.1.4; Frolov et al., 2014). Permafrost degradation due to higher temperatures could increase the potential of debris flow detachment in Alpine locations (Section 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 put 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 an escalating sevenfold increase by 2080s (Figure 13.18) compared with the baseline (Forzieri et al., 2018), highlighting the need for adaptation.

### 13.6.2.1 Current Status of Adaptation

There is new evidence on increasing adaptation planning in cities, settlements and key infrastructures, but less on implemented adaptation (Table 13.1; see Box 13.3; Figure 13.36), adaptation by private actors and by cities against SLR (Chapter 16; Cross-Chapter Paper 2).

Although urban adaptation is underway, many small, economically weak (i.e., with low GDP per 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 (Chapter 17; Bertoldi et al., 2020).

Only 29% of local adaptation plans are mainstreamed in cities, which could reduce the effectiveness of implementing adaptation (Section 13.11.1.2; Reckien et al., 2019). 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.

Both NbS and 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 has 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 with the conventional system (EEA, 2020b). 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 the uncertainties of climate projections and climatic extremes (Fowler et al., 2021) and to translate scientific input into practical guidance for adaptation (Section 13.11.1.3; Dale, 2021).

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

There are gaps in knowledge on the social, environmental and geophysical dimensions of feasibility for many options, and a holistic assessment of different options is largely lacking. This latter issue 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, and Incremental and Transformative Adaptation

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

Adaptation options for many sectors will not be sufficient to remove residual risks, for example, regarding (a) 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); (b) snowmaking beyond 3°C GWL (Scott et al., 2019; Steiger and Scott, 2020; Steiger et al., 2020); (c) hydropower (Gaudard et al., 2013; Ranzani et al., 2018); (d) electricity transmission and demand (Bollinger and Dijkema, 2016; EEA, 2019a; Palkowski et al., 2019); (e) urban subways (Jenkins et al., 2014a); and (f) 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 (Sections 13.2.2, 13.2.3; Pranzini et al., 2015).

Examples of transformative adaptation in urban areas have been 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). Active involvement of local stakeholders, public administration

## Adaptation options for cities, settlements and key infrastructure

**Energy**

**Thermoelectric power**
- Cooling towers/Dry cooling/ Seawater cooling
- Replace by better plants
- Institutional measures
- Shift production to coasts
- Use 'non-traditional' water
- Inter-basin transfer ▲▼

**Hydropower**
- Warning systems
- Adjust management
- Recalibrate spillways
- Monitor/ forecast snowpack, river flows
- Increase plant capacity

**Transmission-Distribution**
- Improve electricity interconnections
- Switch to RES with low water use ●●

**Transport**
- Cooling ●●
- Improve/renew existing infrastructure
- Climate services
- Improve maintenance
- Revise guidelines & standards ●●

**Economic activities and leisure**

**Winter Tourism**
- Protection & conservation
- Management options
- Alternative/complementary activities
- Snowmaking ●●
- Expansion
- Shift to other destinations

**Summer, coastal & other tourism**
- Hard defenses
- Inland shift of activities
- Extend activities
- Water supply & demand measures
- 'Soft' measures ●●

**Business-Finance-Insurance**
- Individual & corporate adaptation
- Extend financial regulations for risk monitoring
- Public reinsurance - Extension of risk monitoring

**Water and wastewater**

**Urban water**
- Expand drainage system
- Expand water supply
- Update flood defenses ▲▼

**Urban wastewater**
- Expand sewer system

**Urban areas**

**Buildings**
- Flood-proof buildings
- Use resistant materials
- Interventions at the buildings' shell ●●
- Increase flood & heat risk standards ●●
- Passive & active cooling ●●

**City/town**
- Climate services
- Emergency plans, evacuation, early warning
- Facilitate recovery
- Update flood defenses
- Green, blue and grey infrastructure
- NbS to manage water runoff
- Water roads and pavements
- Move to nearby regions during heatwaves
- Planned relocation

●● Potential synergies and trade-offs with mitigation

**Figure 13.19 | Adaptation options in cities, settlements and key infrastructures in Europe** (Table SM13.7)

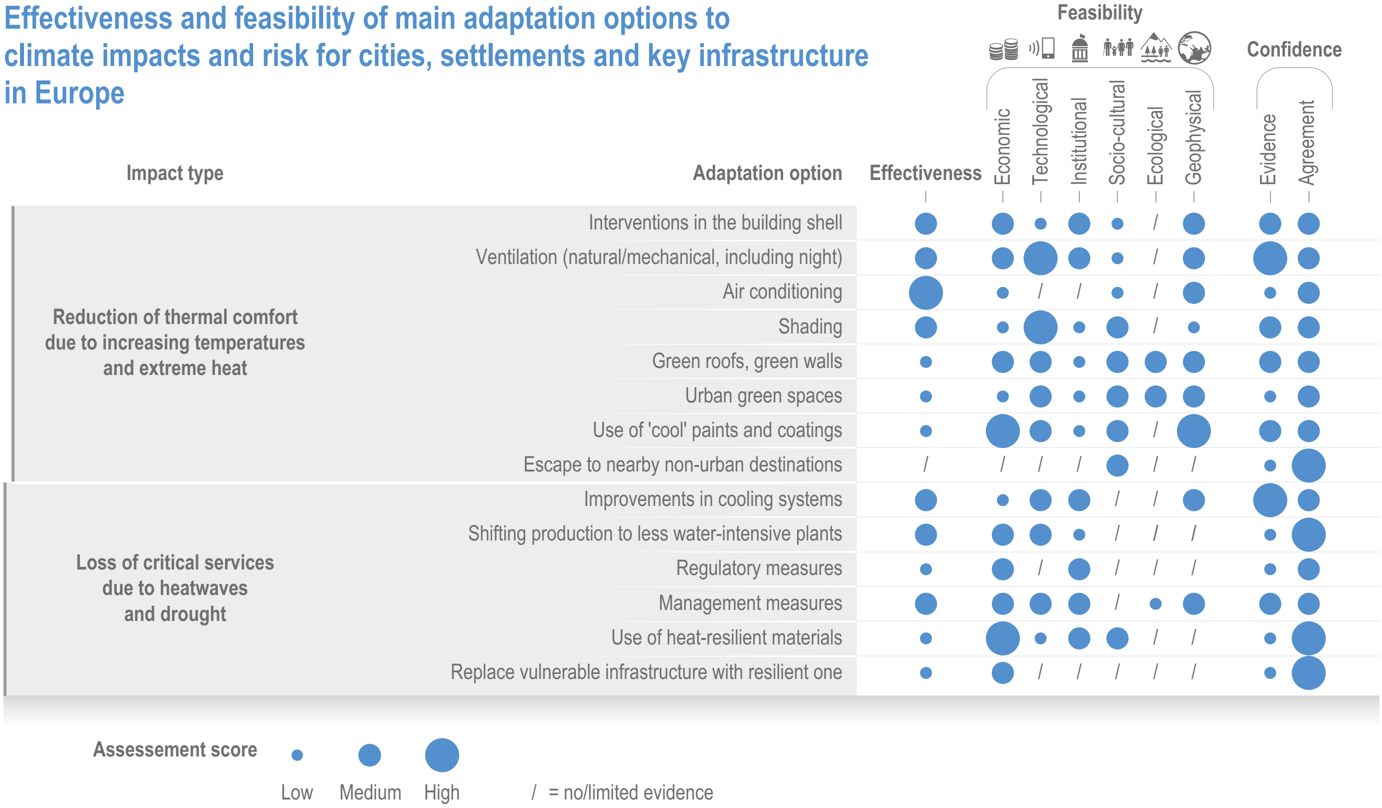


**Figure 13.20 | Effectiveness and feasibility of the main adaptation options for cities, settlements and key infrastructures in Europe** (Section SM13.9; Table SM13.8)

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 organisational 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 utilised 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, as well as collaboration between city departments, government levels, businesses and other stakeholders (Holscher et al., 2019). In most other cities, however, adaptation planners 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 sectors in managing climate risks varies across Europe (Wiering et al., 2017; Alkhani, 2020). For example, in flood management (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 infrastructures, 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 decarbonisation of electricity supply, greenhouse gas emissions will increase due to the increased use of air conditioning installations in cities. This trade-off

**Indicative adaptation limits in cities, settlements and key infrastructure in Europe**

| Economic activities and leisure | Supply of energy & water | City/town | Household/Building |
|---|---|---|---|
| **Technical limits**<br>Limited resources for implementing adaptation<br>Technological limits | **Technical limits**<br>Technical/ management measures not possible due to plant characteristics | **Technical limits**<br>Limited efficacy of measures under high/ rapidly changing climate hazards | **Technical limits**<br>Physical characteristics of building stock |
| **Socio-economic limits**<br>High investments needed<br>Small size of enterprises | **Socio-economic limits**<br>High installation costs for large-scale adaptation<br>Too risky investments when in highly vulnerable locations | **Socio-economic limits**<br>High investments to upgrade municipal facilities<br>High installation cost for new infrastructure | **Socio-economic limits**<br>Low probability hazards prohibit adaptation payoff<br>Poverty<br>Comfort and safety |
| **Environmental & regulatory limits**<br>Limited water resources<br>Shift to other locations is prohibited<br>Limited areas for expansion | **Environmental & regulatory limits**<br>Limited water resources<br>Competitive water uses | **Environmental & regulatory limits**<br>Space constraints for expanding green infrastructure | **Environmental & regulatory limits**<br>Legislation on buildings and appliances |

**Figure 13.21 | Indicative adaptation limits in cities, settlements and key infrastructures in Europe** (Table SM13.16)

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 socioeconomic 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 studied, studies on risks for cities and key infrastructures from hailstorms and lightning are missing.

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

There is limited knowledge on interactions created by synchronous adaptation in ski tourism supply and demand, and models do not yet include 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.

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, Well-Being 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 heatwaves 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); also, 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; Szopa et al., 2021). An ageing 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).

A GWL of 1.5°C could result in 30,000 annual deaths due to extreme heat, with up to threefold 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 (Figure 13.22; Rohat et al., 2019; Ebi et al., 2021). Heat stress risks will be lower under SSP1 than the 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 and 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).

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

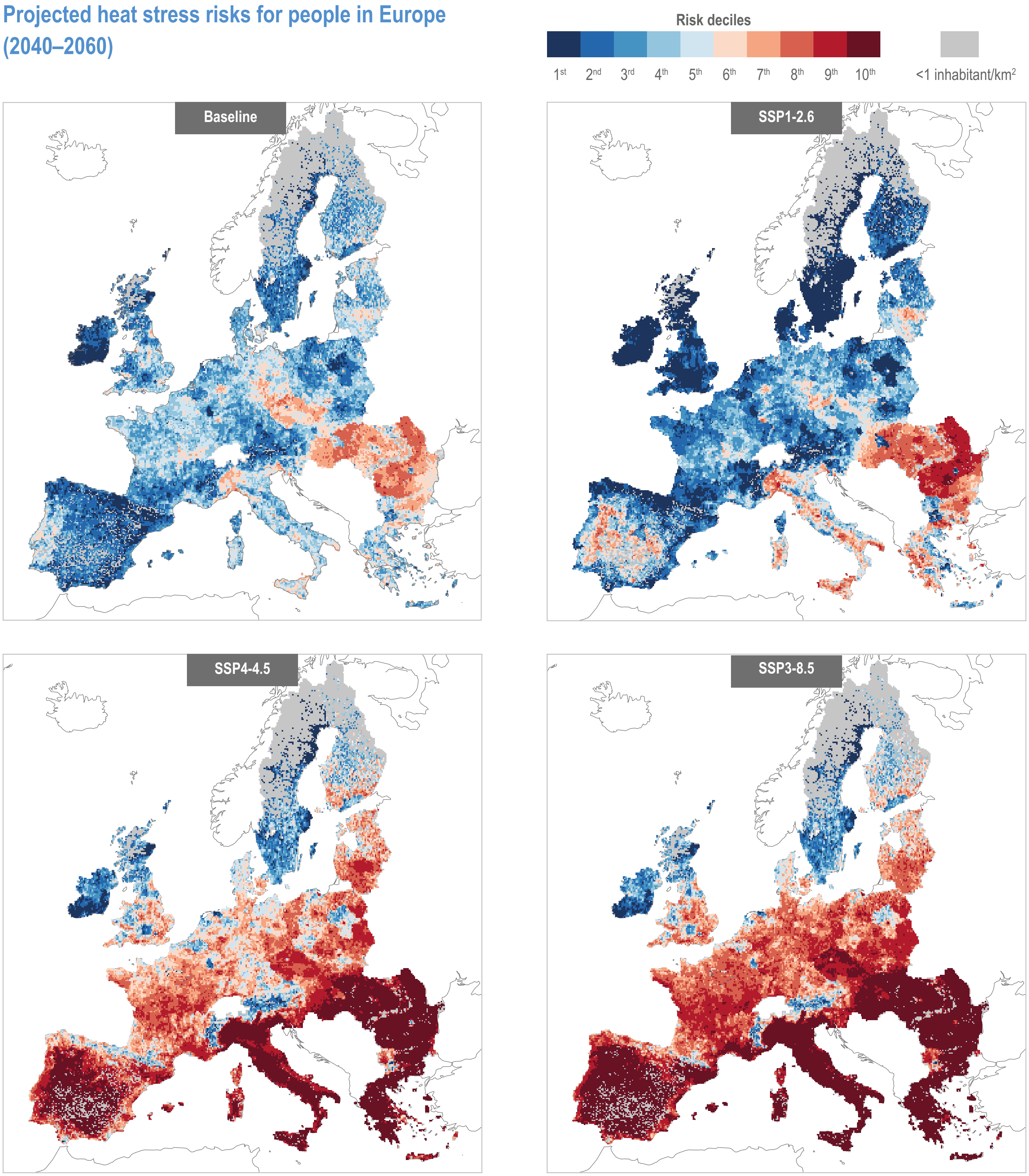
Although there is *very high confidence* that risk consequences will inevitably be more pervasive and widespread in a warmer Europe, evidence of higher heat tolerance is also emerging across most European regions (Todd and Valleron, 2015; Åström et al., 2016; Follos et al., 2020). Future projections of mortality rates in Europe under the assumption of complete acclimatisation 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).

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 (Section 13.2.2), wildfires (Section 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% greater at 3.5°C compared with 1.5°C GWL (Thiery et al., 2021).

#### 13.7.1.2 Air Quality

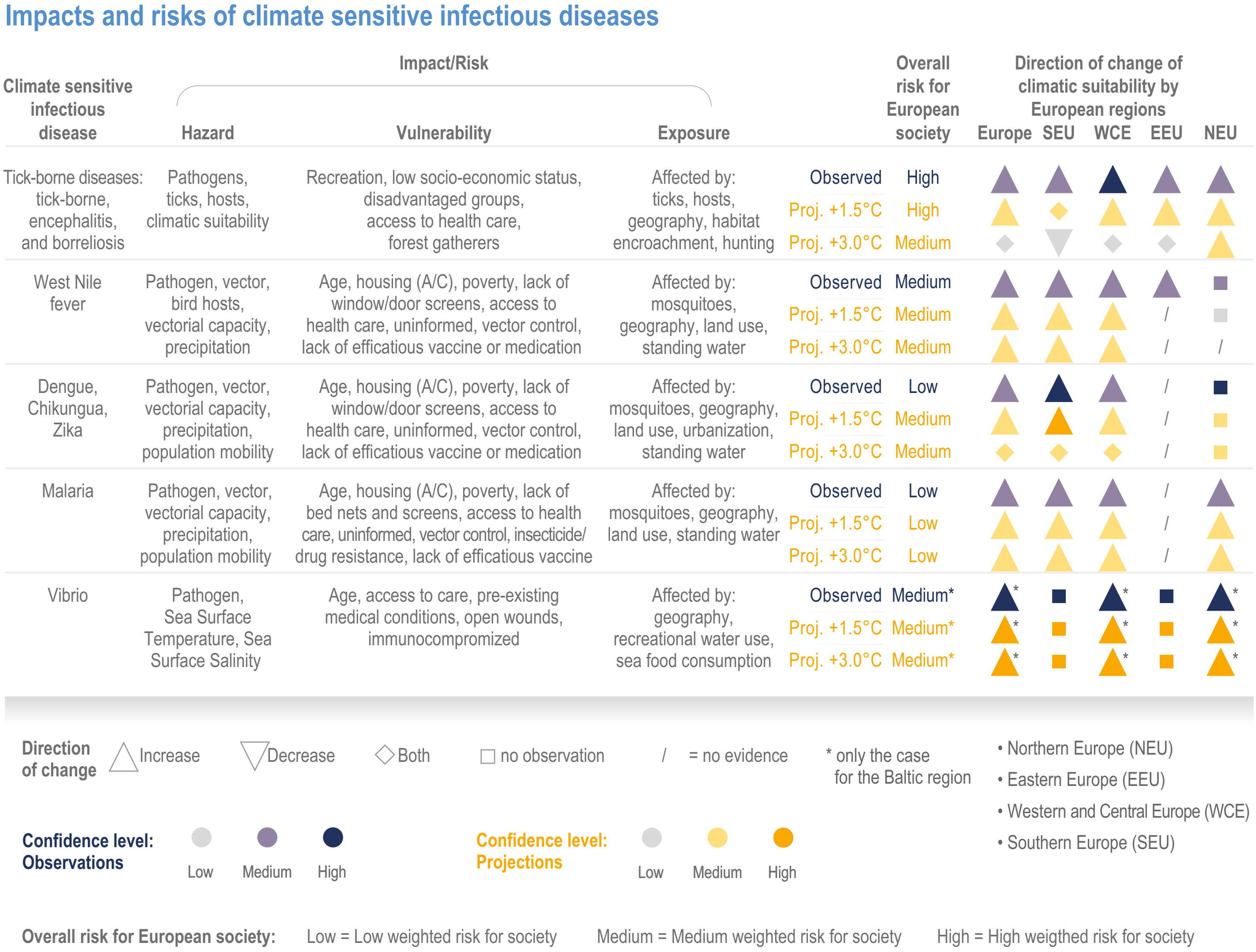
Air pollution is already one of the biggest public health concerns in Europe: in 2016, roughly 412,000 people died prematurely due to long-term exposure to ambient PM2.5, 71,000 due to $NO_2$ and more than 15,000 premature mortalities occurred due to near-surface ozone (EEA, 2019b; Lelieveld et al., 2019). The impacts of air pollution are determined by air-quality policies, changes to temperature, humidity and precipitation (Szopa et al., 2021). Climate change could increase air pollution health effects, with the size of the effect differing across European regions and pollutants (*medium confidence*) (Jacob and Winner, 2009; Orru et al., 2017; Tarin-Carrasco et al., 2021). 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 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 WCE and SEU and to decrease up to 9% in NEU (under RCP4.5) (*medium confidence*) (Orru et al., 2019). A 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 the coming decades (*medium agreement, low evidence*). The ageing population in Europe will augment the air-quality mortality burden 3–13% by 2050 (Geels et al., 2015; Orru et al., 2019). Besides ambient air quality, projected increases in flood risk and heavy rainfall could decrease indoor air quality (Section 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).



Projected heat stress risks for people in Europe (2040–2060)

**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.** The SSPs are extended for Europe (EU28+). Heat stress risk is calculated by geometrical aggregation of the hazard (heatwave 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 by Rohat et al. (2019).



## Impacts and risks of climate sensitive infectious diseases

| | Impact/Risk | | | | Overall risk for European society | Direction of change of climatic suitability by European regions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Climate sensitive infectious disease | Hazard | Vulnerability | Exposure | | | Europe | SEU | WCE | EEU | NEU |
| Tick-borne diseases: tick-borne, encephalitis, and borreliosis | Pathogens, ticks, hosts, climatic suitability | Recreation, low socio-economic status, disadvantaged groups, access to health care, forest gatherers | Affected by: ticks, hosts, geography, habitat encroachment, hunting | Observed | High | ▲ | ▲ | ▲ | ▲ | ▲ |
| | | | | Proj. +1.5°C | High | ▲ | ◆ | ▲ | ▲ | ▲ |
| | | | | Proj. +3.0°C | Medium | ◆ | ▼ | ◆ | ◆ | ▲ |
| West Nile fever | Pathogen, vector, bird hosts, vectorial capacity, precipitation | Age, housing (A/C), poverty, lack of window/door screens, access to health care, uninformed, vector control, lack of efficacious vaccine or medication | Affected by: mosquitoes, geography, land use, standing water | Observed | Medium | ▲ | ▲ | ▲ | ▲ | ■ |
| | | | | Proj. +1.5°C | Medium | ▲ | ▲ | ▲ | / | ■ |
| | | | | Proj. +3.0°C | Medium | ▲ | ▲ | ▲ | / | / |
| Dengue, Chikungua, Zika | Pathogen, vector, vectorial capacity, precipitation, population mobility | Age, housing (A/C), poverty, lack of window/door screens, access to health care, uninformed, vector control, lack of efficacious vaccine or medication | Affected by: mosquitoes, geography, land use, urbanization, standing water | Observed | Low | ▲ | ▲ | ▲ | / | ■ |
| | | | | Proj. +1.5°C | Medium | ▲ | ▲ | ▲ | / | ■ |
| | | | | Proj. +3.0°C | Medium | ◆ | ◆ | ◆ | / | ■ |
| Malaria | Pathogen, vector, vectorial capacity, precipitation, population mobility | Age, housing (A/C), poverty, lack of bed nets and screens, access to health care, uninformed, vector control, insecticide/drug resistance, lack of efficacious vaccine | Affected by: mosquitoes, geography, land use, standing water | Observed | Low | ▲ | ▲ | ▲ | / | ▲ |
| | | | | Proj. +1.5°C | Low | ▲ | ▲ | ▲ | / | ▲ |
| | | | | Proj. +3.0°C | Low | ▲ | ▲ | ▲ | / | ▲ |
| 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* | ▲* | ■ | ▲* | ■ | ▲* |
| | | | | Proj. +1.5°C | Medium* | ▲* | ■ | ▲* | ■ | ▲* |
| | | | | Proj. +3.0°C | Medium* | ▲* | ■ | ▲* | ■ | ▲* |

**Direction of change** △ Increase ▽ Decrease ◇ Both ☐ no observation / = no evidence * only the case for the Baltic region

- Northern Europe (NEU)
- Eastern Europe (EEU)
- Western and Central Europe (WCE)
- Southern Europe (SEU)

**Confidence level: Observations** ● Low ● Medium ● High

**Confidence level: Projections** ● Low ● Medium ● High

**Overall risk for European society:** Low = Low weighted risk for society Medium = Medium weighted risk for society High = High weigthed risk for society

**Figure 13.23 | Assessment of climate-sensitive infectious diseases.** The assessment considers the main drivers of hazard (climate-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 in climatic suitability (i.e., temperature, precipitation, relative humidity, extreme weather events) of observed changes and at 1.5°C and 3°C GWL, and the overall infectious disease risks across Europe (Chapters 7.3, 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).

### 13.7.1.3 Climate-Sensitive Infectious Diseases

Figure 13.23 summarises 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 (*medium confidence*) (Daniel et al., 2003; Heinz et al., 2015). 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 the West Nile virus in 2018, with elevated spring temperature abnormalities (Haussig et al., 2018; Marini et al., 2020). Projections for Europe show the West Nile virus risk to expand: by 2025, the risk is projected to increase in SEU and southern 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 as well as 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 various 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 that of 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).

#### 13.7.1.4. Allergies and Pollen

The main drivers of allergies are predominantly non-climatic (e.g., increased urbanisation, adoption of westernised lifestyles, social and genetic factors), but climate change strongly contributes to the spread of some allergenic plants, thus exacerbating existing allergies and causing new ones in people 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 (*Ambrosia asteraceae*) 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, sensitisation 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 birch-season flowering has been shifted and extended up to 2 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 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 (Section 13.6.1.3; Gosling et al., 2018; Szewczyk et al., 2018; Dellink et al., 2019; Orlov et al., 2019). The heatwaves of August 2003, July 2010 and July 2015 were 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 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 with 1981–2010, ranging from 2–3.5% in SEU to 0.5–1.5% in WCE, and below 0.5% in NEU and EEU (Section 13.10.3; Roson and Sartori, 2016; Takakura et al., 2017; Szewczyk et al., 2018; Dellink et al., 2019; García-León et al., 2021).

#### 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 with other regions (Fanzo et al., 2018; IFPRI, 2018). Projected changes in crop and livestock production (Section 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 groups in Europe most affected (IFPRI, 2018). Spikes in food prices due to changing growing conditions in Europe (Section 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 (Section 13.9.1; EASAC, 2019; Loopstra, 2020). Reduced access to healthy and varied food could contribute to being overweight or obese, which is a growing health concern across Europe (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 Well-Being

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

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), the UK (Carter et al., 2018) and 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 among 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, monitoring 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 (*high confidence*) (Confalonieri et al., 2015; Casanueva et al., 2019; Linares et al., 2020). Stricter enforcement of existing health regulations and policies can have a positive effect in reducing risks (Berry et al., 2018).

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 sociopolitical structure and culture, and other adaptation options in place (*high agreement, medium evidence*). Successful examples include the implementation of heatwave plans (Schifano et al., 2012; van Loenhout and Guha-Sapir, 2016; de'Donato et al., 2018), improvements in health services and infrastructure of homes (Section 13.10.2.1; Vandentorren et al., 2006). A study of nine European cities, for example, showed lower numbers of heat-related deaths in SEU and attributed this to the implementation of heat prevention plans, a greater level of individual and household adaptation, and growing awareness about exposure to heat (de'Donato et al., 2015). Long-term national prevention programmes in NEU have been shown to reduce temperature-related suicide (Helama et al., 2013). The 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 (*medium confidence*) (Chapter 7; Lesnikowski et al., 2019).

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 microclimates, reducing the impact of heatwaves, improving air quality and improving mental health by increasing access to fresh air and green (restorative) environments (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), 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 as well as 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 UHI 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

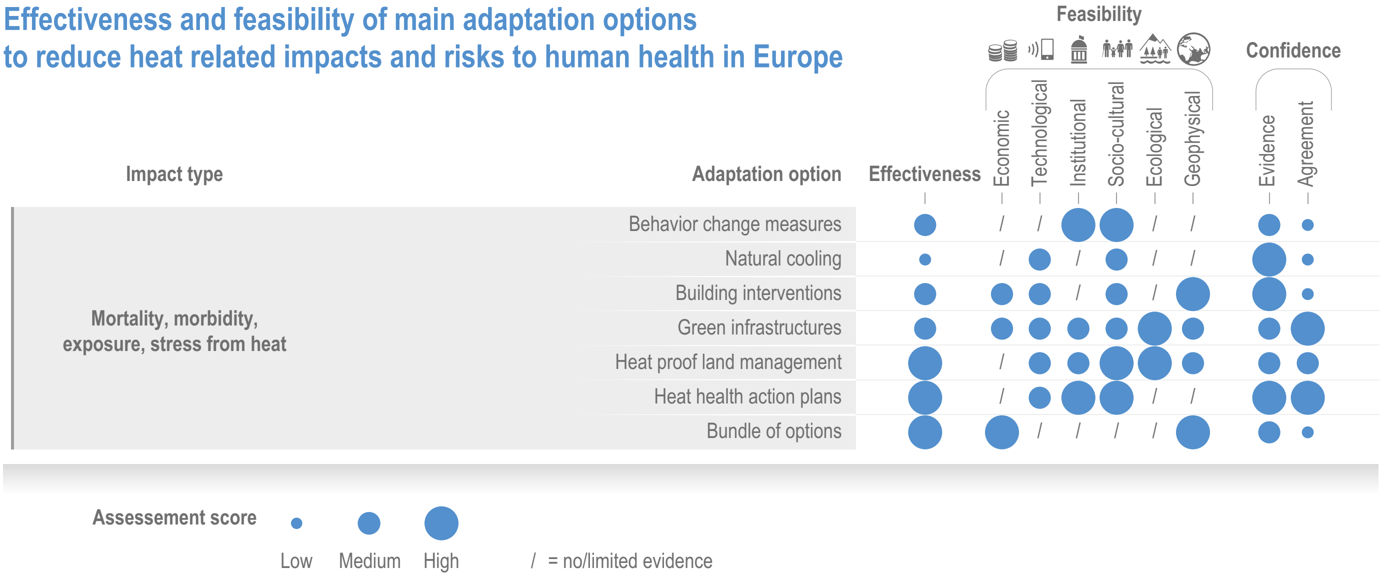


**Figure 13.24 | Effectiveness and feasibility of the main adaptation options to reduce heat-related impacts and health risks in Europe** (Section SM13.9, Table SM 13.19)

progress, limited mainstreaming of climate change has been 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 programmes 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 risks are predominantly discussed in the context of excess mortality and morbidity due to heat extremes (Hanna and Tait, 2015; Martinez et al., 2019). Future heatwaves are expected to stretch existing adaptation interventions well beyond levels observed in response to the observed events of 2003 and 2010 (Section 13.10.2.1; Hanna and Tait, 2015).

### 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 well-being, (mal)nutrition and food quality and climate-sensitive infectious diseases, where other socioeconomic determinants play an important role. The connection between climate change and health risks under different socioeconomic 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 (Section 13.2.1) and heatwaves (Section 13.7.1.1). There are very few studies assessing the barriers and enablers of health adaptations, nor systematic assessment of the effectiveness of (the 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

This section addresses the social consequences of climate change for Europe by looking into the 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 marginalised groups are affected more strongly by flooding, heat and drought, as well as health risks due to spreading diseases, than other social groups (*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, for example, during heatwaves 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 marginalised groups in Europe (Ezbakhe et al., 2019; Anthonj et al., 2020); this effect could be intensified by increasing water scarcity in certain 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 a 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 SEU and EEU (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 thus far has been the major share of energy costs (*medium confidence*) (Sanchez-Guevara et al., 2019; Randazzo et al., 2020).

**Table 13.2 |** Examples of losses and damages to vulnerable livelihoods in Europe, differentiated by category according to 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 distressTeiltabellen zusammengezogen. Bitte prüfen. |
| 🌱 | Biodiversity and ecosystems | | |

| Climate hazard | Change in exposure and vulnerability | Observed impact and/or projected risk |
|---|---|---|
| Loss of livelihood, culture, health and well-being of the Sámi and the Nenets<br>👥 🏘 🏛 🌱 🤝 🚩 😔 | | |
| 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), food security (for cold-dependent species), culture, health (impact on safety; psychological impacts from stress to reindeer and indigenous way of life), and cultural and linguistic well-being; 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, northwest Russia and Scotland<br>👥 🏘 🌱 🤝 😔 | | |
| Warmer water temperatures in high-Arctic freshwater habitats (Section 13.3.1) increase productivity in oligotrophic systems and eventually lead to loss of oxygen in water; warming temperatures and changes to ice cover and cryosphere lead to access issues to freshwater fisheries. | Introduced Pacific pink salmon has expanded in range since the 1970s, affecting endemic species through competition and reducing their abundance. Increased nutrient loading of rivers and rapid expansion of algae increase the risks for cold-dependent fish. | Shifts in freshwater aquatic habitats and loss of endemic cold-dependent fish, such as Arctic char and Arctic salmon, cause disruptions to local food supply, and local extinctions threaten livelihood safety and cultural well-being. |
| Warmer winters leading to loss of income from ice fishing and cultural heritage in Finland<br>👥 🏘 🏛 🌱 🤝 🚩 😔 | | |
| 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 resulting in loss of Indigenous knowledge and food insecurity in Greenland<br>👥 🏛 🌱 🤝 😔 | | |
| Warmer ocean waters are moving further north (so-called atlantification of Greenland waters); higher temperatures are melting 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 is occurring, as is loss of access to seals and walruses, as well as food insecurity. |
| Reduced yields on managed alpine grasslands decreasing the self-sufficiency of pastoral livestock farming in the Austrian, French and Swiss Alps<br>🏘 🌱 🤝 🚩 | | |
| Increase in heat, precipitation variability and agricultural as well as hydrological drought; less snow on the ground, increase in glacier melt, landslide 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, and 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 leading to loss of identity, culture and self-reliance in the Italian Alps (Alto Adige) | | |
| Glacier volume loss from increasing temperatures | Vulnerability 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 resulting in a reduction of provisioning (water) and regulating services (protection against floods) in the Western and Eastern Alps, Iberian Mountains and Dinaric Mountains | | |
| Increase in drought, particularly under high-end GWL | Forest management strategies, including that of natural forests, which can enhance or reduce vulnerability | Critical importance of alpine natural forests and meadows for regulating services; negative impacts of climate change found mainly at low elevations and for specific species (e.g., Norway spruce); decrease in soil moisture due to abandonment of pastoralism resulting in reduced water provision for downstream water users |
| Increase in sea temperature leading 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 does not match the skill sets, education or desires of small-scale fishers; national quota system leading to prices too high to buy or lease quotas and an 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. |

### 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 evidence* and *low agreement* 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 (Section 13.1) and adaptive capacity across European regions may increase pressure for internal migration (Williges et al., 2017; Forzieri et al., 2018). For instance, projected SLR (Section 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 are particularly vulnerable to climate change (Table 13.2): indigenous communities in the European polar region because of their dependence

## 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 recognised 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 past 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*) (see Figure Box 13.2.1; Mallory and Boyce, 2018). High snow depth and rain-on-snow events impede reindeer access to ground lichen in winter and delay spring green-up during the 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).

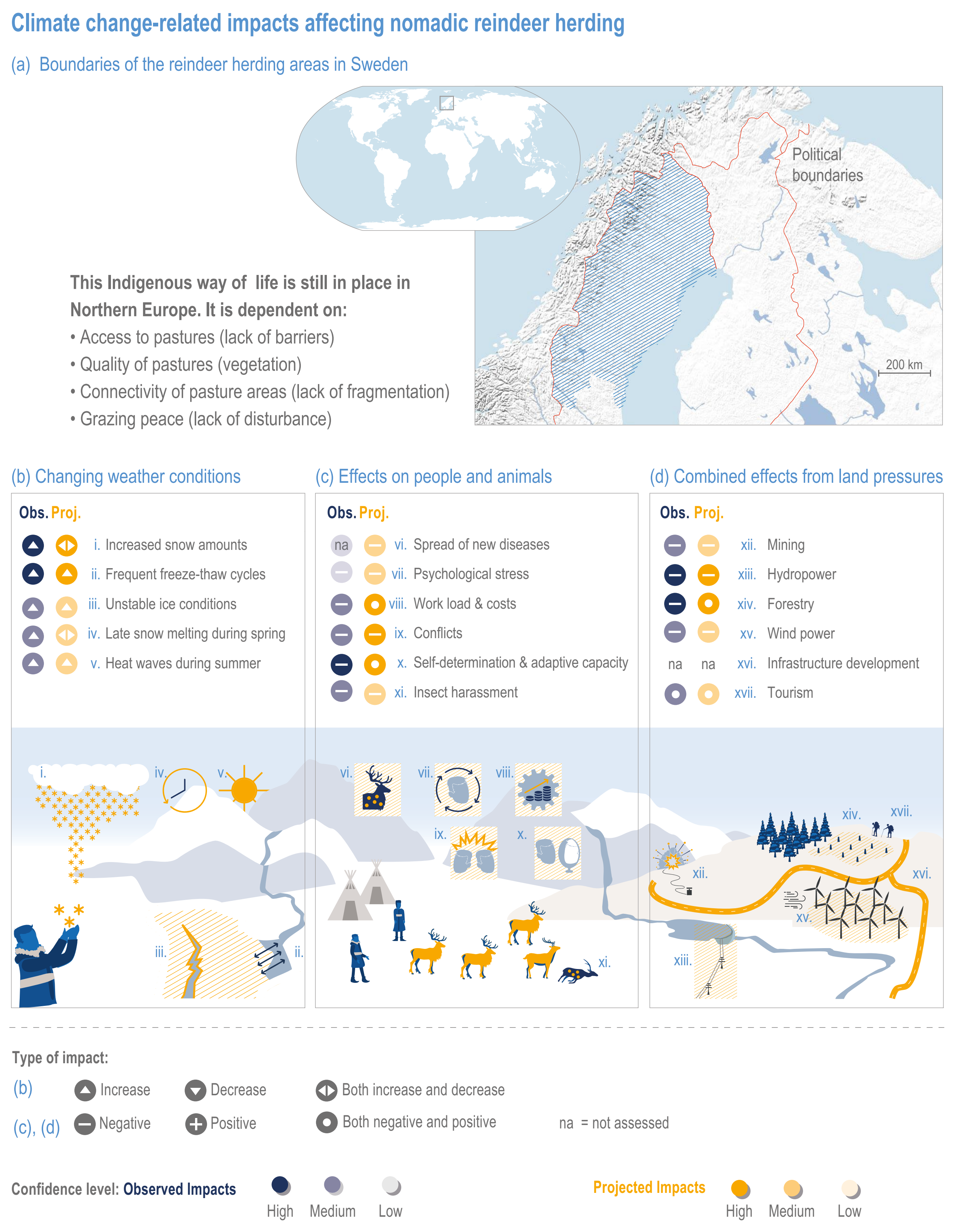
Reindeer herders already autonomously adapt to changing conditions through flexible use of pastures and supplementary feeding (*high confidence*), reducing and thereby hiding some of the negative impacts of climate change (Uboni et al., 2016). However, adaptive herding practices have themselves added significant burden through increased workload, costs and stress (*high confidence*) (Furberg et al., 2011; Löf, 2013; Rosqvist et al., 2021). Supplementary feeding increases the risk of 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 recognised 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 incidences (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).

*Box 13.2 (continued)*



## Climate change-related impacts affecting nomadic reindeer herding

(a) Boundaries of the reindeer herding areas in Sweden

**This Indigenous way of life is still in place in Northern Europe. It is dependent on:**

- Access to pastures (lack of barriers)
- Quality of pastures (vegetation)
- Connectivity of pasture areas (lack of fragmentation)
- Grazing peace (lack of disturbance)

(b) Changing weather conditions

| **Obs.** | **Proj.** | |
|---|---|---|
| ▲ | ◀▶ | i. Increased snow amounts |
| ▲ | ▲ | ii. Frequent freeze-thaw cycles |
| ▲ | ▲ | iii. Unstable ice conditions |
| ▲ | ◀▶ | iv. Late snow melting during spring |
| ▲ | ▲ | v. Heat waves during summer |

(c) Effects on people and animals

| **Obs.** | **Proj.** | |
|---|---|---|
| na | ⊖ | vi. Spread of new diseases |
| ⊖ | ⊖ | vii. Psychological stress |
| ⊖ | ⊙ | viii. Work load & costs |
| ⊖ | ⊖ | ix. Conflicts |
| ⊖ | ⊙ | x. Self-determination & adaptive capacity |
| ⊖ | ⊖ | xi. Insect harassment |

(d) Combined effects from land pressures

| **Obs.** | **Proj.** | |
|---|---|---|
| ⊖ | ⊖ | xii. Mining |
| ⊖ | ⊖ | xiii. Hydropower |
| ⊖ | ⊙ | xiv. Forestry |
| ⊖ | ⊖ | xv. Wind power |
| na | na | xvi. Infrastructure development |
| ⊙ | ⊙ | xvii. Tourism |

Type of impact:

(b) ▲ Increase ▼ Decrease ◀▶ Both increase and decrease

(c), (d) ⊖ Negative ⊕ Positive ⊙ Both negative and positive na = not assessed

Confidence level: **Observed Impacts** ● High ● Medium ○ Low

Projected Impacts ● High ● Medium ○ Low

**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)**

on cryosphere ecosystems (*high confidence*) (Cross-Chapter Paper 6; 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 (see Box 13.2; Figure 13.13; Feodoroff, 2021) and growing costs, for example, as a result of the need for artificial feeding of reindeer.

#### 13.8.1.4 Cultural and Natural Heritage

Climate change poses a serious threat to the 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 as along the North Sea and Mediterranean, are under water-related threats (see Box 13.1; Cross-Chapter Paper 4; Reimann et al., 2018b; Walsh, 2018; Harkin et al., 2020).

Disappearing cultural heritage can reduce incomes due to loss of tourism (Hall et al., 2016), as exemplified by glacier retreat, for example, in the Swiss Alps and Greenland (CCP5.3.2.4; Bjorst and Ren, 2015; Bosson et al., 2019). 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, for instance, when practices of disaster recovery focus on high-visibility areas and not on low-income neighbourhoods or marginalised communities (D'Alisa and Kallis, 2016). Risk communication and management reliant on new information technologies can exclude the elderly and populations with lower educational attainment (Kešetović et al., 2017).

Unlike migration within the EU, 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).

IKLK, embedded, for example, in fishers, farmers and navigators, can be a vehicle for detecting, monitoring and observing impacts (Section 13.11.1.3; Arctic Council, 2013; Brattland and Mustonen, 2018; Madine et al., 2018; Meredith et al., 2019). 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 the absence of overarching policy guidance (Phillips, 2015; Fernandes et al., 2017; Sesana et al., 2018; Daly et al., 2020; 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 (Section 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 socioeconomic and political change. For European cultural heritage, there is also a lack of tailored knowledge and understanding of the impacts and how to translate them into adaptation measures.

## 13.9 Inter-regional Impacts, Risks and Adaptation

This section addresses inter-regional risks between Europe and other parts of the world. Global risk pathways affecting sectors and supply chains relevant for European economies and societies involve (a) ecosystems, (b) people (e.g., through migration), (c) financial flows and (d) trade; and these pathways ultimately impact security, health, well-being and food supply (Cross-Chapter Box INTEREG in Chapter 16; Yokohata et al., 2019).

### 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 globalisation, the impacts of climate change outside the European region are *likely* to have implications for countries

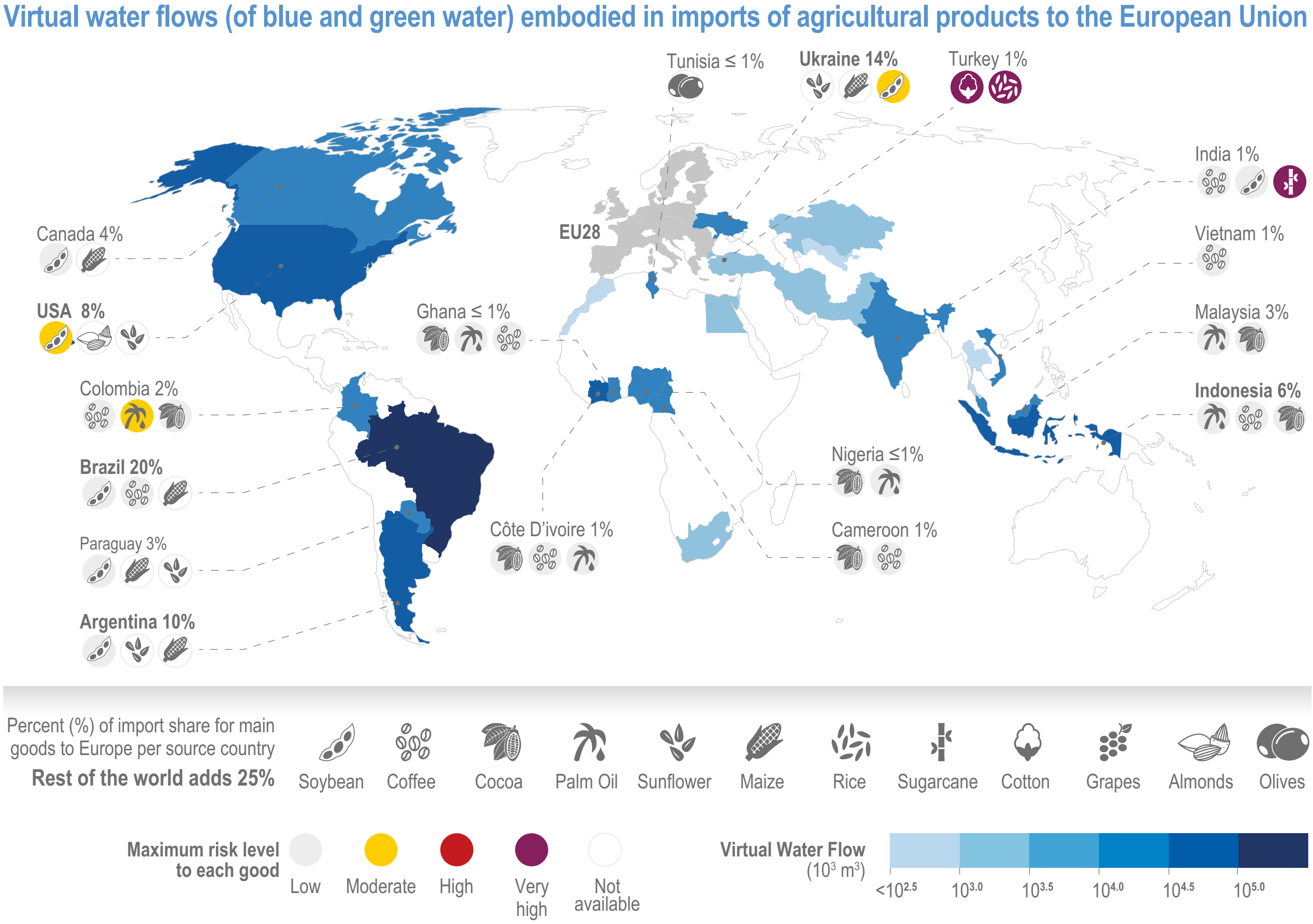


**Figure 13.25 | Trans-European climate risks in trade: virtual water flows embodied in agricultural imports to Europe in 2018 and the vulnerability to climate change of the most important crops in the originating countries** (Dolganova et al., 2019; Ercin et al., 2019)

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 inter-regional 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 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 (Section 13.7.1), and SLR affecting ports and cities along coastlines (Section 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).

### 13.9.2 Inter-regional 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 (Section 13.5.1; Berry et al., 2017; van der Velde et al., 2018) 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 (Figure 13.26; Mandel et al., 2021). 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 SLR (Section 13.6.1.2; Williams and Joshi, 2013;

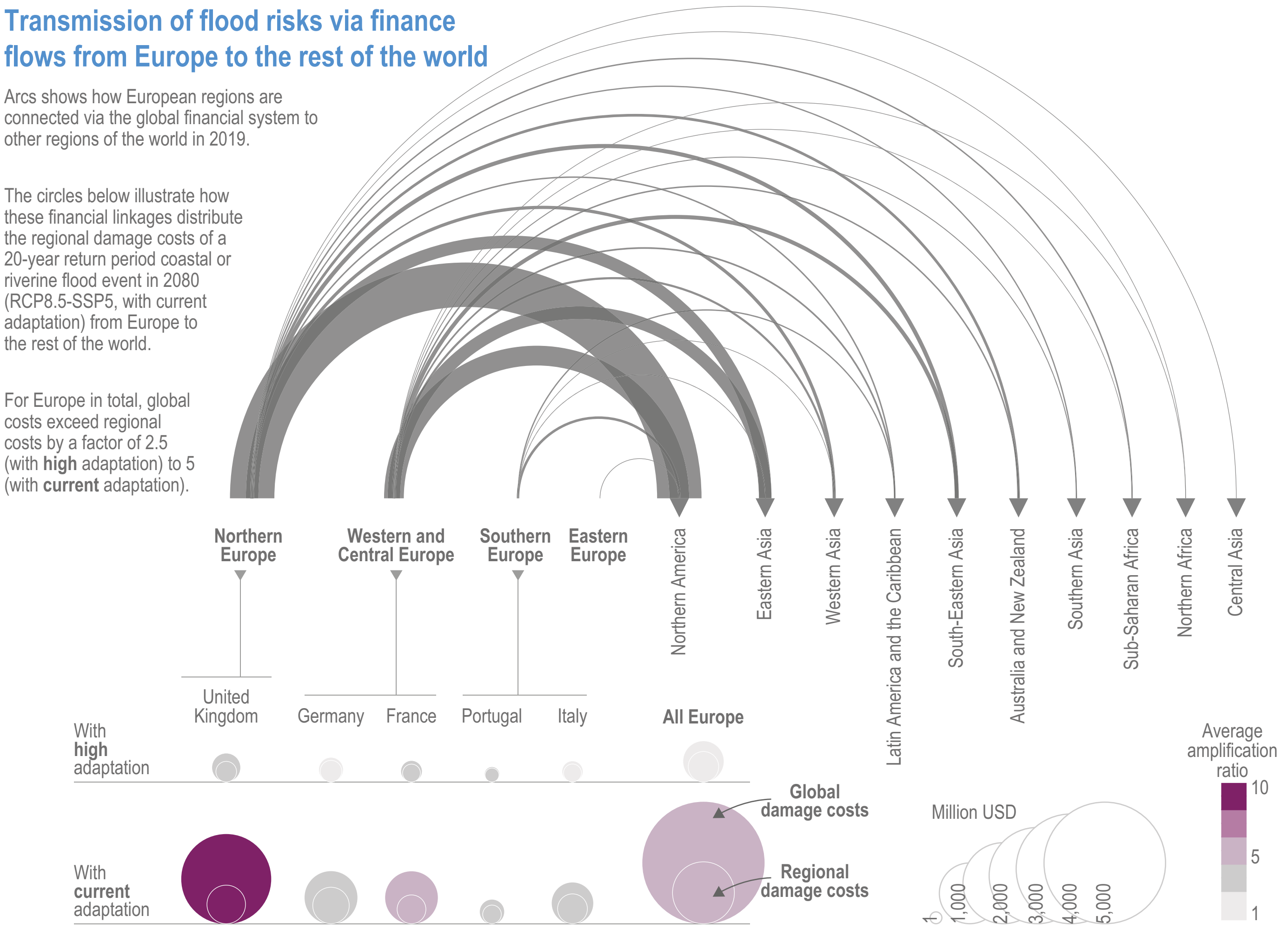


**Figure 13.26 | The transmission of coastal and riverine flood risks via finance flows from Europe to the rest of the world.** (From Mandel et al., 2021).

Irvine et al., 2016; Williams, 2016; Becker et al., 2018; Camus et al., 2019; Verschuur et al., 2020).

### 13.9.3 European Territories Outside Europe

European territories outside Europe are critically exposed to climate risks such as increased forest fires (e.g., in Russian Siberia) (Chapter 10; Sitnov et al., 2017), climate-change-induced biodiversity losses and SLR (e.g., in British, Spanish, Portuguese, French and Dutch overseas regions and territories) (Chapters 12, 15; Ferdinand, 2018; Sieber et al., 2018). 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 (Section 13.7; Schaffner and Mathis, 2014). Some MPAs (Section 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 inter-regional risks at the place of origin or destination, for example, by (a) 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), (b) providing international adaptation finance (Dzebo and Stripple, 2015; BMUB, 2017), (c) developing insurance mechanisms suitable for adaptation or (d) providing European climate services to support global adaptation (Cross-Chapter Box INTEREG in Chapter 16; Linnerooth-Bayer and Mechler, 2015; Brasseur and Gallardo, 2016; Street, 2016; Cavelier et al., 2017). 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 inter-regional climate risks into national adaptation strategies and plans, and mainstreaming them into EU policies (e.g., Common Agricultural Policy, trade agreements) (Benzie and Persson, 2019; Benzie et al., 2019; Groundstroem and Juhola, 2019; Adams et al., 2020). There is *high confidence* that the exposure of European countries to inter-regional risks can be reduced by international governance (Cross-Chapter Paper 4; Dzebo and Stripple, 2015; Cramer et al., 2018; Persson and Dzebo, 2019), for example, 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, relocation of species towards higher latitudes and altitudes (*high confidence*), and impacts of heat on human health and productivity (*high confidence*) (Figure 13.27; 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

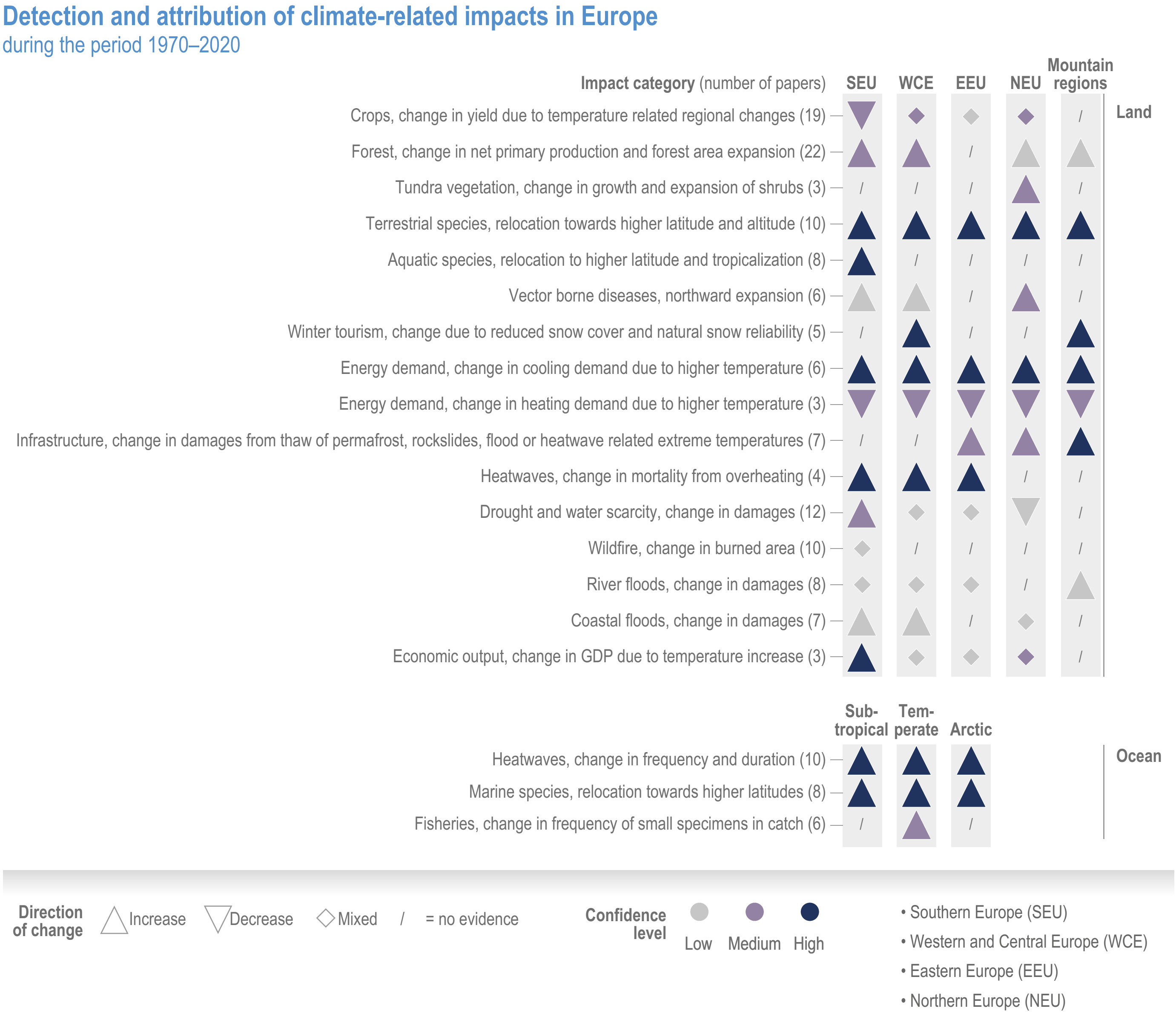
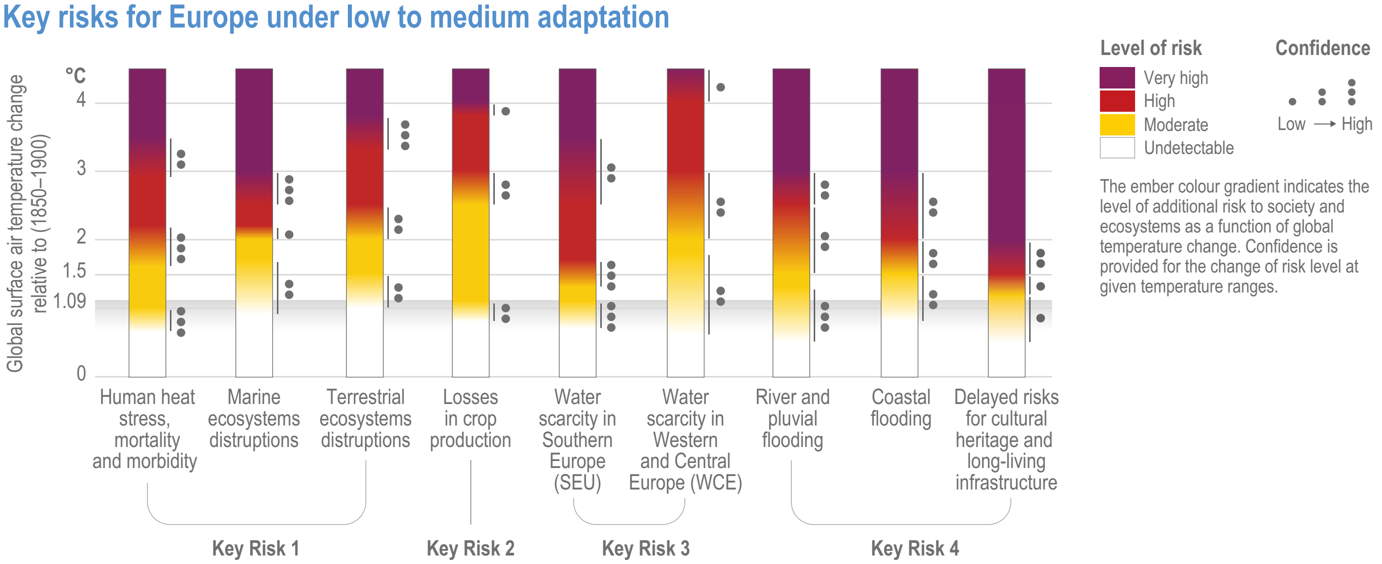
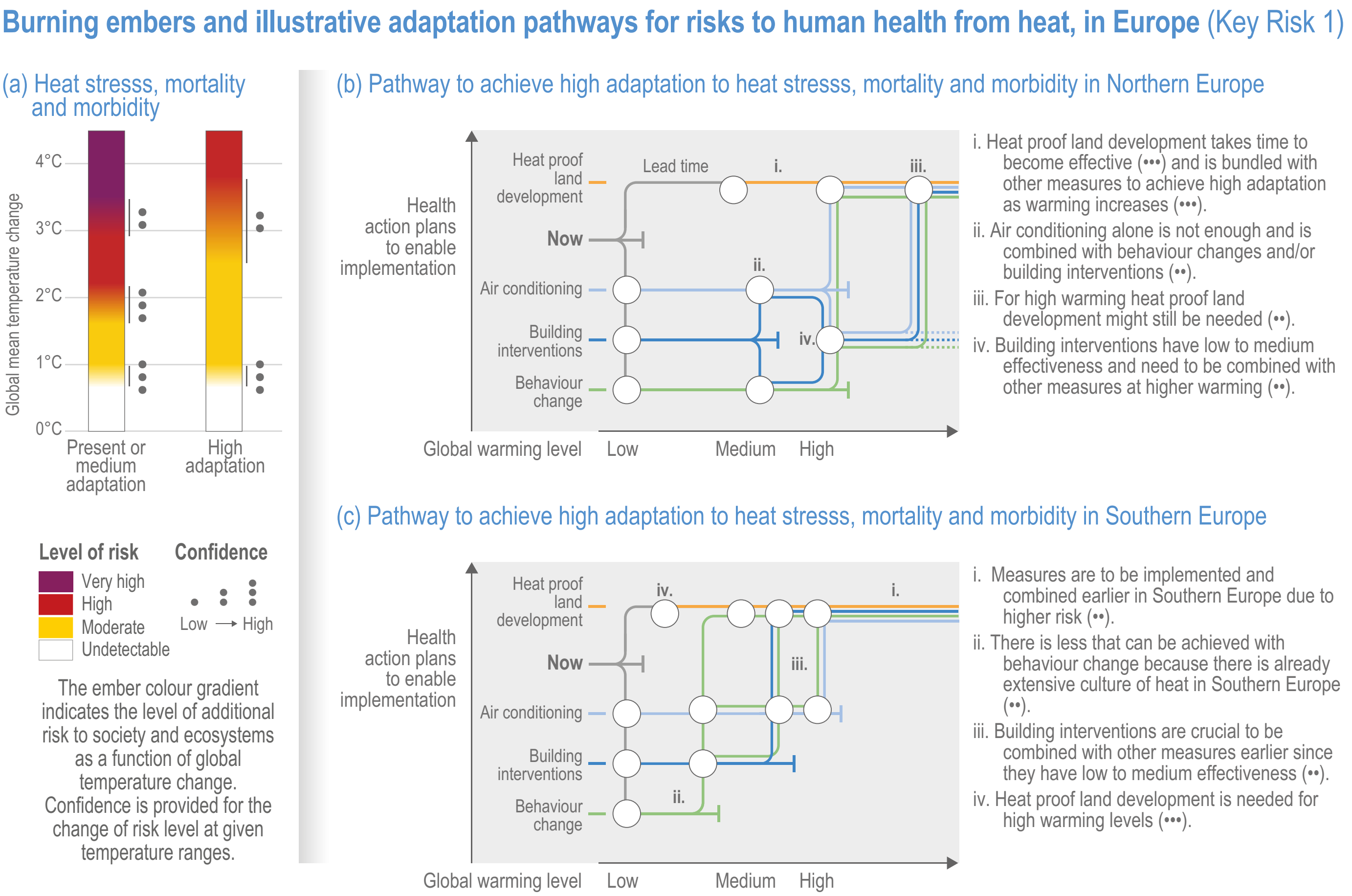


**Figure 13.27 | Detected changes and attribution (D&A) of climate-related impacts on land (top) and in the ocean (bottom) are shown.** Assessment is based on peer-reviewed literature in this chapter that reported observed evidence with at least 90% significance (usually with 95% significance or more) (Table SM13.22).



The ember colour gradient indicates the level of additional risk to society and ecosystems as a function of global temperature change. Confidence is provided for the change of risk level at given temperature ranges.

**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 Figures 13.29–13.34 alongside burning embers with high adaptation.)



The ember colour gradient indicates the level of additional risk to society and ecosystems as a function of global temperature change. Confidence is provided for the change of risk level at given temperature ranges.

i. Heat proof land development takes time to become effective (•••) and is bundled with other measures to achieve high adaptation as warming increases (•••).

ii. Air conditioning alone is not enough and is combined with behaviour changes and/or building interventions (••).

iii. For high warming heat proof land development might still be needed (••).

iv. Building interventions have low to medium effectiveness and need to be combined with other measures at higher warming (••).

i. Measures are to be implemented and combined earlier in Southern Europe due to higher risk (••).

ii. There is less that can be achieved with behaviour change because there is already extensive culture of heat in Southern Europe (••).

iii. Building interventions are crucial to be combined with other measures earlier since they have low to medium effectiveness (••).

iv. Heat proof land development is needed for high warming levels (•••).

**Figure 13.29 | Burning embers and illustrative adaptation pathways for risks to human health from heat (Key Risk 1)**

**(a)** Burning ember diagrams for the risk to human health from heat are shown. The low to medium adaptation scenario corresponds to present, SSP2 and SSP4 socioeconomic 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 imply that the measure has reached a tipping point (Tables SM13.24, SM13.25).

change have induced cascading impacts and other impact interactions (Smale et al., 2019; Vogel et al., 2019). In recent decades (2000–2015), economic losses intensified in SEU (*high confidence*) and were detected for parts of WCE and NEU (*medium confidence*). (The methodology for detection and attribution is presented in Section 16.2.)

## 13.10.2 Key Risks Assessment for Europe

Key risks (KRs) are defined as a subset of climate risks that can potentially become, or are already, severe (Section 16.5). The selection process included a review of KRs already identified in AR5 Chapter 23 (Kovats et al., 2014) and a review of the large body 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 characteristics of KRs, 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; 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 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, 13.5–13.7).

### 13.10.2.1 KR1: Risks of Human Mortality and Heat Stress, and of Ecosystem Disruptions Due to Heat Extremes and Increases in Average Temperatures

Key risk 1 has 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 socioeconomic pathways, with consequences being more severe under SSP3, SSP4 and SSP5 scenarios than SSP1 (*very high confidence*) (Figure 13.22; Sections 13.6.1.5.2, 13.7.1.1; Hunt et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019; Casanueva et al., 2020). The 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 (*high confidence*) (Sections 13.3.1.2, 13.4.1.2). More intense heatwaves on land and in the ocean, particularly in Mediterranean Europe (Section 13.4; Cross-Chapter Paper 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 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* (Section 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 a two- to threefold increase (compared with 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 (*high confidence* on the direction of change and temperature transition, but *medium confidence* on the magnitude) (Ranasinghe et al., 2021).

The burning embers on risk for terrestrial and marine ecosystems, and some of their services, are shown in Figure 13.28 (second and third ember from the 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 northward and upwards, and desynchronisation of species interactions, especially at the range limits, with cascading and cumulative impacts through ecosystems and food webs (*high confidence*) (Sections 13.3, 13.4; Figures 13.8, 13.12). 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 (*high confidence* on the direction of change, but *medium confidence* on the local and regional magnitude) (Raybaud et al., 2017). The transition is happening at slightly higher warming in terrestrial systems due to a 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; Sections 13.6.2, 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, 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 (e.g., heat-proof land management) (Chapter 16) and remain effective at higher warming levels (*medium confidence*) (Díaz et al., 2019). These transformations have long lead times, thereby 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, 3; Sections 13.3, 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 (*high confidence*) (Sections 13.3, 13.4; Ramírez et al., 2018). A major governance tool to reduce climatic and non-climatic impacts is the establishment of networks of protected areas (Sections 13.3.2, 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).

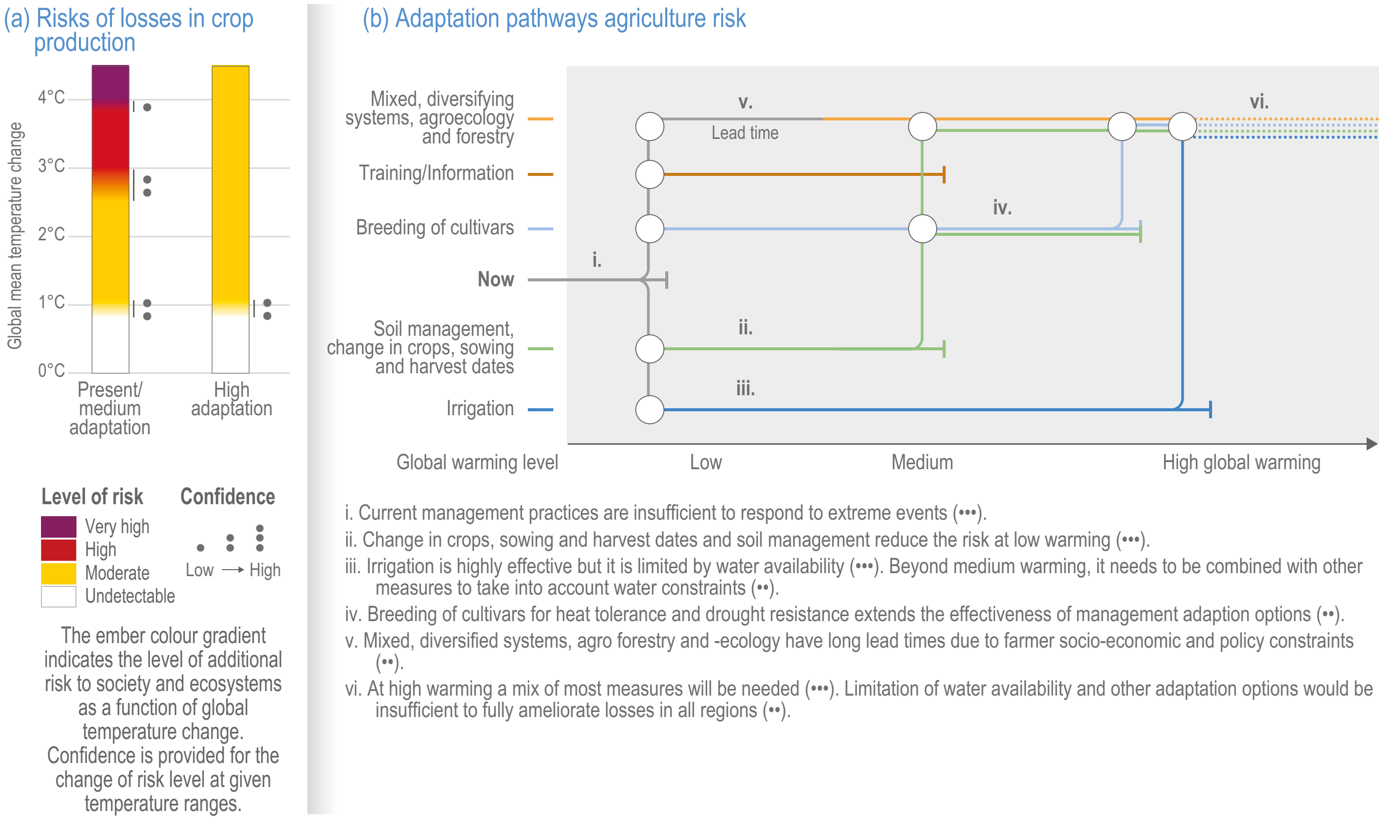
Very high risks are expected beyond 3°C GWL due to the magnitude and increased likelihood of serious consequences, as well as to the limited ability of humans and ecosystems to cope with these impacts. There is *high confidence* that even under high adaptation scenarios for human systems or autonomous 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 SLR will strongly impact coastal ecosystems (*high confidence*), minimising their contribution to shoreline protection (Section 13.10.2.4).

#### 13.10.2.2 KR2: Risk of Losses in Crop Production, Due to Compound Heat and Dry Conditions, and Extreme Weather

Key risk 2 encompasses agriculture productivity (Figure 13.30a). It is mainly driven by the increase in the likelihood of compound heat and dry conditions and extreme weather, 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 northwest 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 past 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 shifts in 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., 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 (*medium confidence*) (Castellanos-Frias et al., 2016; Nielsen et al., 2017; Brás et al., 2019). Combined with socioeconomic 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 crop 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; Figures 13.14, 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 (*high confidence*) (Section 13.5.1). 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 in risk from north to south and higher risk for late-season crops such as maize (*high confidence*). Under these conditions, land abandonment is projected (*low confidence*) (Holman et al., 2017).

**Burning embers and illustrative adaptation pathways for losses in crop production in Europe** (Key Risk 2)



The ember colour gradient indicates the level of additional risk to society and ecosystems as a function of global temperature change. Confidence is provided for the change of risk level at given temperature ranges.

i. Current management practices are insufficient to respond to extreme events (•••).

ii. Change in crops, sowing and harvest dates and soil management reduce the risk at low warming (•••).

iii. Irrigation is highly effective but it is limited by water availability (•••). Beyond medium warming, it needs to be combined with other measures to take into account water constraints (••).

iv. Breeding of cultivars for heat tolerance and drought resistance extends the effectiveness of management adaption options (••).

v. Mixed, diversified systems, agro forestry and -ecology have long lead times due to farmer socio-economic and policy constraints (••).

vi. At high warming a mix of most measures will be needed (•••). Limitation of water availability and other adaptation options would be insufficient to fully ameliorate losses in all regions (••).

**Figure 13.30 | Burning embers and illustrative adaptation pathways for losses in crop production (Key Risk 2)**

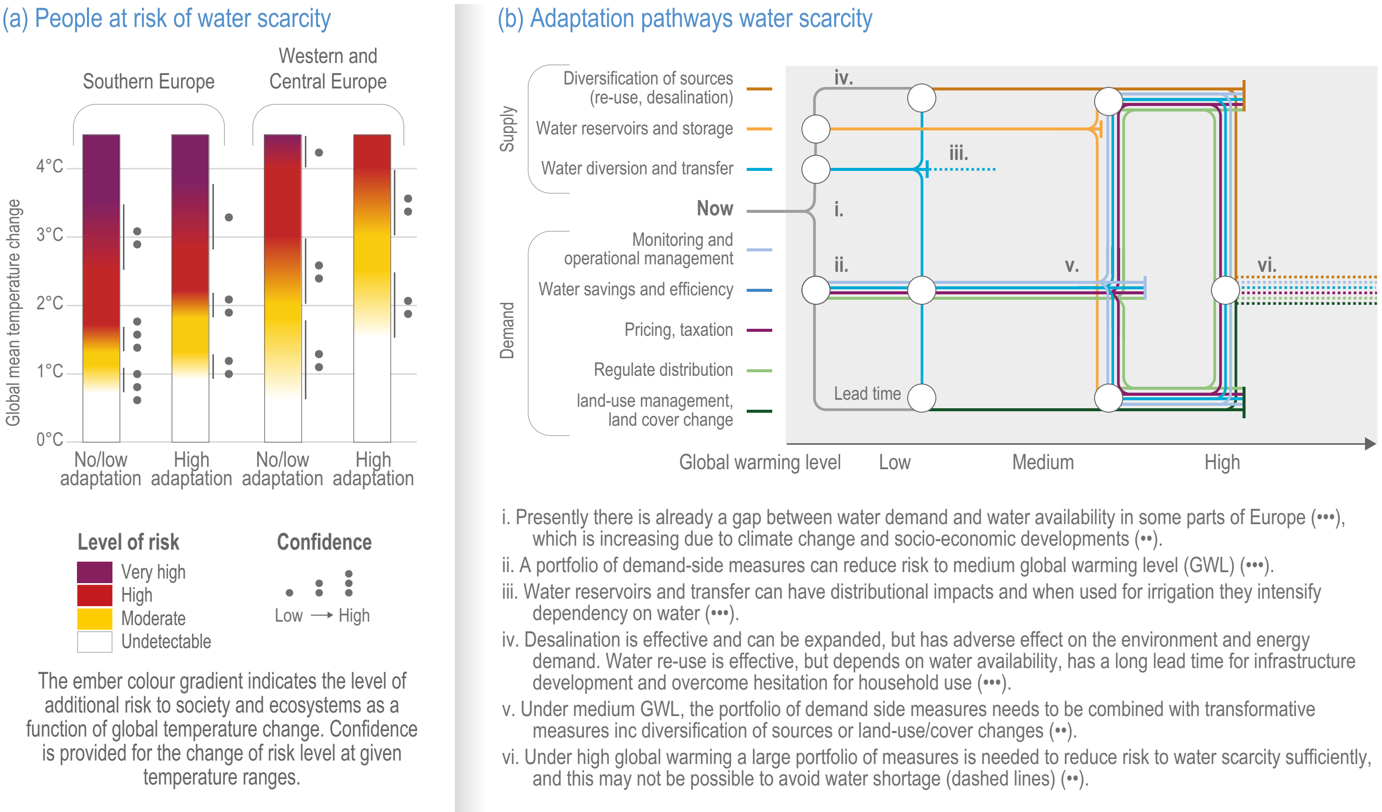
**(a)** Burning ember diagrams for losses in crop production with present or medium adaptation conditions, and with high adaptation, are shown.

**(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 imply that the measure has 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 they increase 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 EEU (Seneviratne, 2021, for hydrological drought and 4°C GWL; Kattsov and Porfiriev, 2020). Evidence from the detected changes and attribution assessment suggests that the risk is already moderate in SEU (e.g., 48 million people exposed to moderate water scarcity between 1981 and 2010) (*high confidence*) (Section 13.10.1; Figure 13.31a).

Risk of water scarcity has a high potential to lead to cascading impacts well beyond the water sector. These materialize in a number of highly interconnected sectors 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 be associated with more persistent droughts (Section 13.1.3), and at 2°C GWL to show a 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°C and 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).



**Burning embers and illustrative adaptation pathways for risk of water scarcity to people in Europe** (Key Risk 3)

(a) People at risk of water scarcity

(b) Adaptation pathways water scarcity

The ember colour gradient indicates the level of additional risk to society and ecosystems as a function of global temperature change. Confidence is provided for the change of risk level at given temperature ranges.

i. Presently there is already a gap between water demand and water availability in some parts of Europe (•••), which is increasing due to climate change and socio-economic developments (••).
ii. A portfolio of demand-side measures can reduce risk to medium global warming level (GWL) (•••).
iii. Water reservoirs and transfer can have distributional impacts and when used for irrigation they intensify dependency on water (•••).
iv. Desalination is effective and can be expanded, but has adverse effect on the environment and energy demand. Water re-use is effective, but depends on water availability, has a long lead time for infrastructure development and overcome hesitation for household use (•••).
v. Under medium GWL, the portfolio of demand side measures needs to be combined with transformative measures inc diversification of sources or land-use/cover changes (••).
vi. Under high global warming a large portfolio of measures is needed to reduce risk to water scarcity sufficiently, and this may not be possible to avoid water shortage (dashed lines) (••).

**Figure 13.31 | Burning embers and illustrative adaptation pathways for risk of water scarcity to people (Key Risk 3)**

**(a)** Burning ember diagrams for the risk of water scarcity with no or low adaptation, and with high adaptation for SEU and WCE, are shown.

**(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 imply that the measure has reached a tipping point (Table SM13.29).

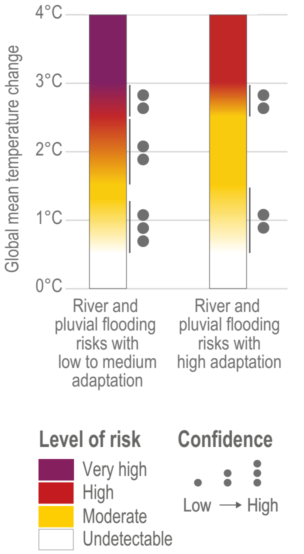
To reduce risk to water scarcity, adaptation measures, at both the supply and the demand side, have been suggested (Section 13.2.2; Figures 13.6, 13.31b; Garnier and Holman, 2019; Hagenlocher et al., 2019). Several measures are already in place showing high technical and institutional feasibility (Sections 13.2.2.2, 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 rain-fed supplies are not sufficient (Section 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 (including storage), water transfer, water recycling and reuse, and desalination will 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 (including 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.

### 13.10.2.4 KR4: Risks to People, Economies and Infrastructures Due to Coastal and Inland Flooding

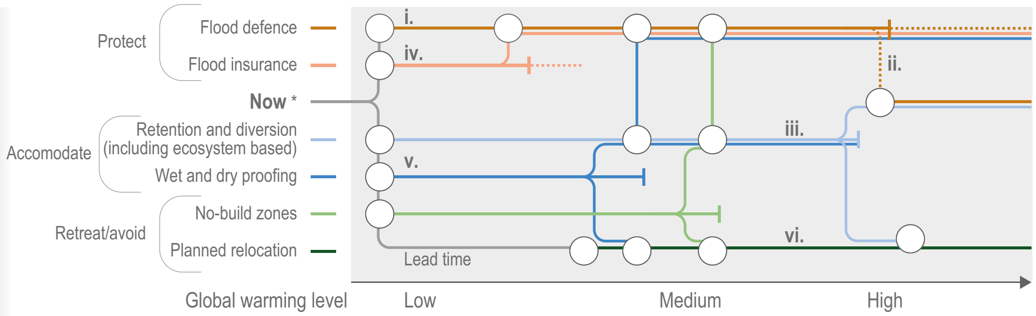
Damages and losses from coastal and river floods are projected to increase substantially in Europe over the 21st century (*high confidence*) (Section 13.2.1; SM13.10). Coastal areas have already started to be affected by SLR (see Box 13.1; Section 13.10.1) and human exposure to coastal hazards is projected 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 an increase in expected annual damage by a factor of at least 20 for 1.5°C–2.1°C GWL (i.e., high risks) and by two to three orders of magnitude between 2°C and 3°C GWL in EU-28 (i.e., very high risk) (*medium confidence*) (Figures 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 (Section 13.2; Vousdoukas et al., 2020). Sea levels are committed to rise for centuries (Fox-Kemper et al., 2021), submerging at least 10% of the territory in

## Burning embers and illustrative adaptation pathways for inland and coastal flooding in Europe (Key Risk 4)

(a) Inland flooding risks



(b) Adaptation pathways riverine flood risk



i. Continuing a protect pathway by strengthening existing dyke systems is cost-effective, but with regional variation in benefit cost ratio. This comes with increasing path-dependency and residual risk (•••).

ii. In cities where there is no place or no support to further heighten structure, upstream retention and movable barriers combined with an early warning system can be added (••).

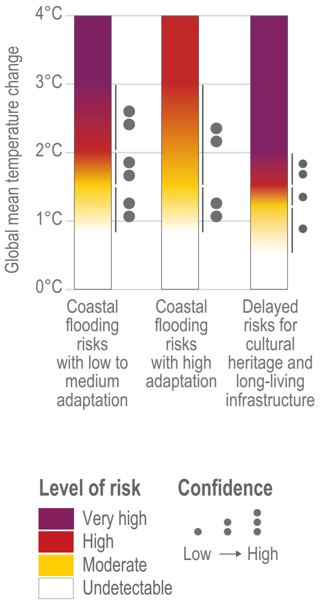
iii. Natural retention and diversion of peak flows can reduce risk effectively and have co benefits for the environment and climate mitigation. A combination with flood defenses in highly urbanized regions can further reduce risk (•••).

iv. Insurance can limit consequences of residual risk for people (•••).

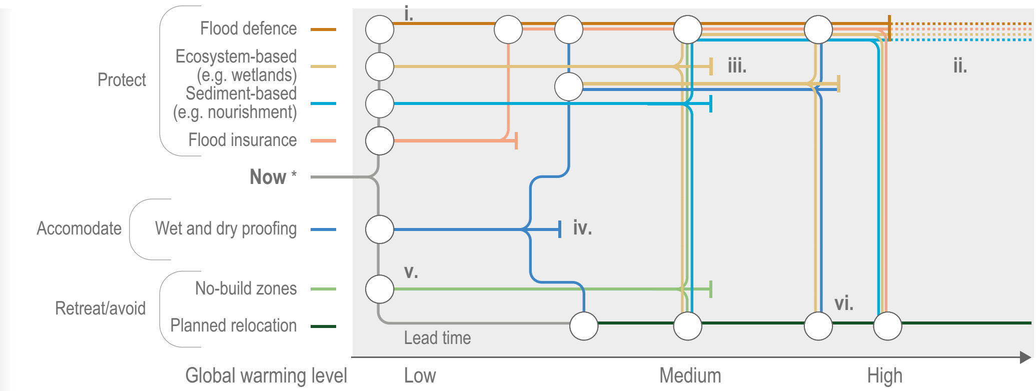
v. Wet and dry proofing can be taken at household level and can reduce residual risk as levees are raised (••).

vi. Planned relocation has been implemented locally to restore floodplain both pre and post-hoc events and can ultimately remove risk (•••).

(c) Coastal flooding risks



(d) Adaptation pathways coastal flood risk



i. Continuing a protect pathway has a high benefit cost ratio in particular in urbanized coast, but comes with path-dependency and residual risk (•••).

ii. There is lack of evidence of long-term consequences and the need to switch to alternative measures under long-term and/or high global warming level (GWL) (•••).

iii. Ecosystem based solutions (e.g. wetlands) can reduce waves and provide co-benefits for the environment and climate mitigation. They can be effective to low to medium GWL. Beyond they can reduce costs for flood defences (•••).

iv. Wet and dry proofing measures are effective under low GWL. A combination with protection could extend the functional lifetime. Floating houses are in experiment stage (••).

v. No-build zones exist and can mitigate risk (•••). With higher GWL planned relocation is an option. Impacts can be delayed by wet and dry proofing of buildings (•).

vi. Planned relocation has been implemented locally for ecosystem restoration and in support of coastal defence, but is increasingly considered for less populated areas and ultimately removes risk (•••).

* Mostly flood defences and early warning.

**Figure 13.32 | Burning embers and illustrative adaptation pathways for inland and coastal flooding (Key Risk 4)**

**(a)** Burning ember diagrams for the risks from riverine and pluvial flooding, with and without adaptation, are shown.

**(b)** Illustrative adaptation pathways to riverine flooding risks.

**(c)** Burning ember diagrams for the risks from coastal flooding, with and without adaptation, are shown.

**(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 imply that the measure has reached a tipping point (Tables SM13.30, SM13.31).

12 countries in Europe if GWL exceed 1.5°C–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; Cross-Chapter Paper 4; 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 urbanisation (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, for example, 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 KR 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; Figure 13.32d). Continuing a protection pathway is cost-effective in urbanised regions for this century (Vousdoukas et al., 2020), but there is *high agreement* that it comes with 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 increases and an increased rate of SLR combined with a 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 a 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, 13.6.2). Residual risks can be reduced through early warning and evacuations, insurance and accommodate measures (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 (*medium confidence*) (Alfieri et al., 2016; Dottori et al., 2020). 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 achieve positive outcomes, long lead times are needed (Haasnoot et al., 2021a).

### 13.10.3 Consequences of Multiple Climate Risks for Europe

European regions are affected by multiple KRs simultaneously. While there is a wide range in quantifications, there is *high agreement* that the consequences for socioeconomic and natural systems can be substantial, with more severe consequences in the south than in the north (*very high confidence*); and there is some indication also for a west-to-east gradient, with higher uncertainty in eastern WCE and EEU, which makes adaptation more challenging (*medium confidence*). Furthermore, the food–water–energy–land 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 (*high confidence*) (Cramer et al., 2018; Forzieri et al., 2018; Guerreiro et al., 2018). The number of people exposed to multiple KRs in Europe are projected to at least double at 3°C GWL compared with 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 (*medium confidence*) (Figure 13.28).

Economic losses and damages for European economies from multiple KRs are projected to increase (*high confidence*) (Figure 13.34; Szewczyk et al., 2018; Feyen et al., 2020; Kalkuhl and Wenz, 2020) and potentially quadruple at 3°C GWL compared with 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 3 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 will remain particularly for warming above 3°C GWL (*medium confidence*) (De Cian et al., 2016; Bosello et al., 2018; Parrado et al., 2020).

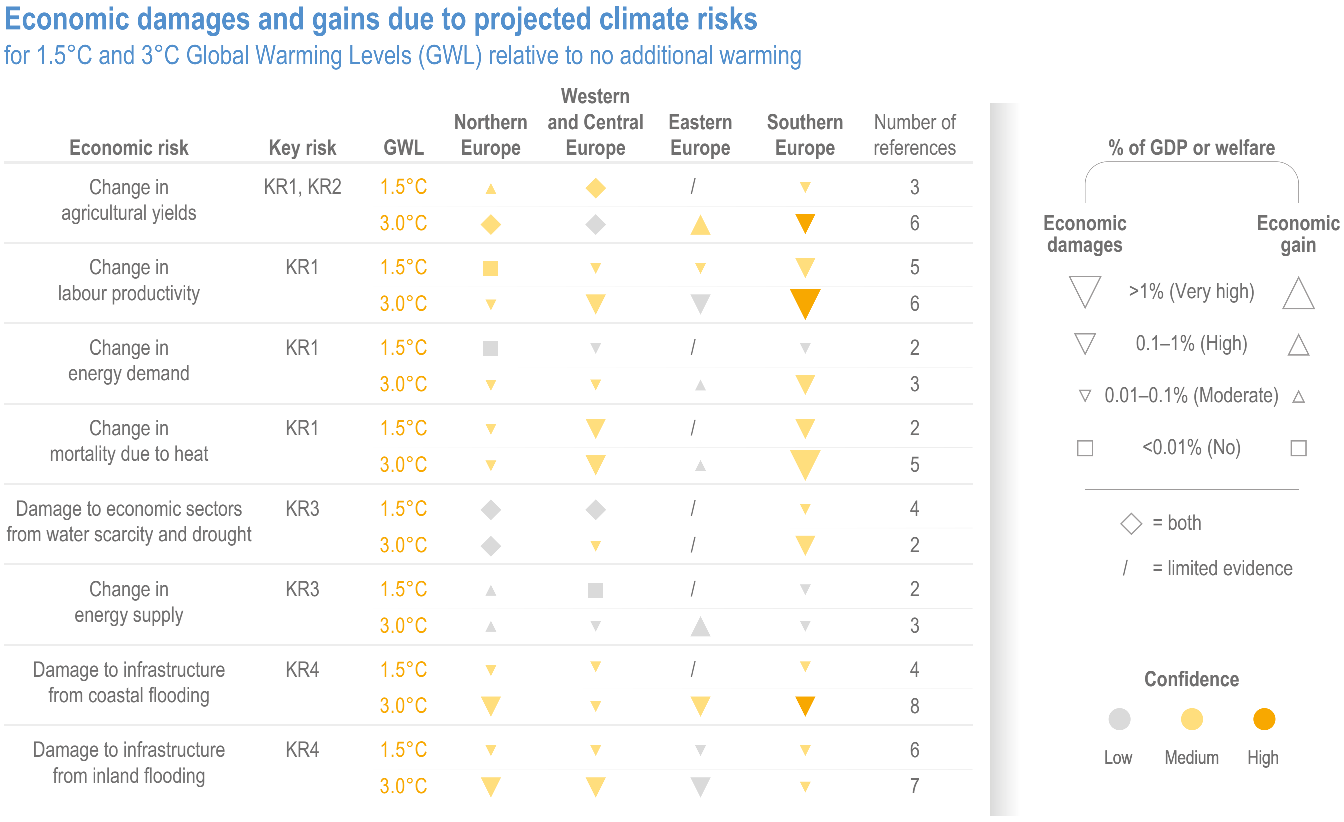


**Figure 13.33 | Economic damages and gains due to projected climate risks are shown for 1.5°C and 3°C GWL relative to no additional warming; macroeconomic effects are measured in GDP or welfare.** Effects for EEU are reported for Russia as a whole country, deviating from the definition of EEU in this chapter. Effects may deviate from sectoral assessments in Sections 13.2–13.7 due to different degrees 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 KRs. 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 (Cross-Chapter Paper 4; 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 socioeconomic 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, 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 of 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 could have catastrophic 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, regions and vulnerable groups to assess how climate-change impacts are being responded to generally by state (Section 13.11.1) and non-state (Section 13.11.2) actors, and their synergies and dependencies. Section 13.11.3 assesses 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

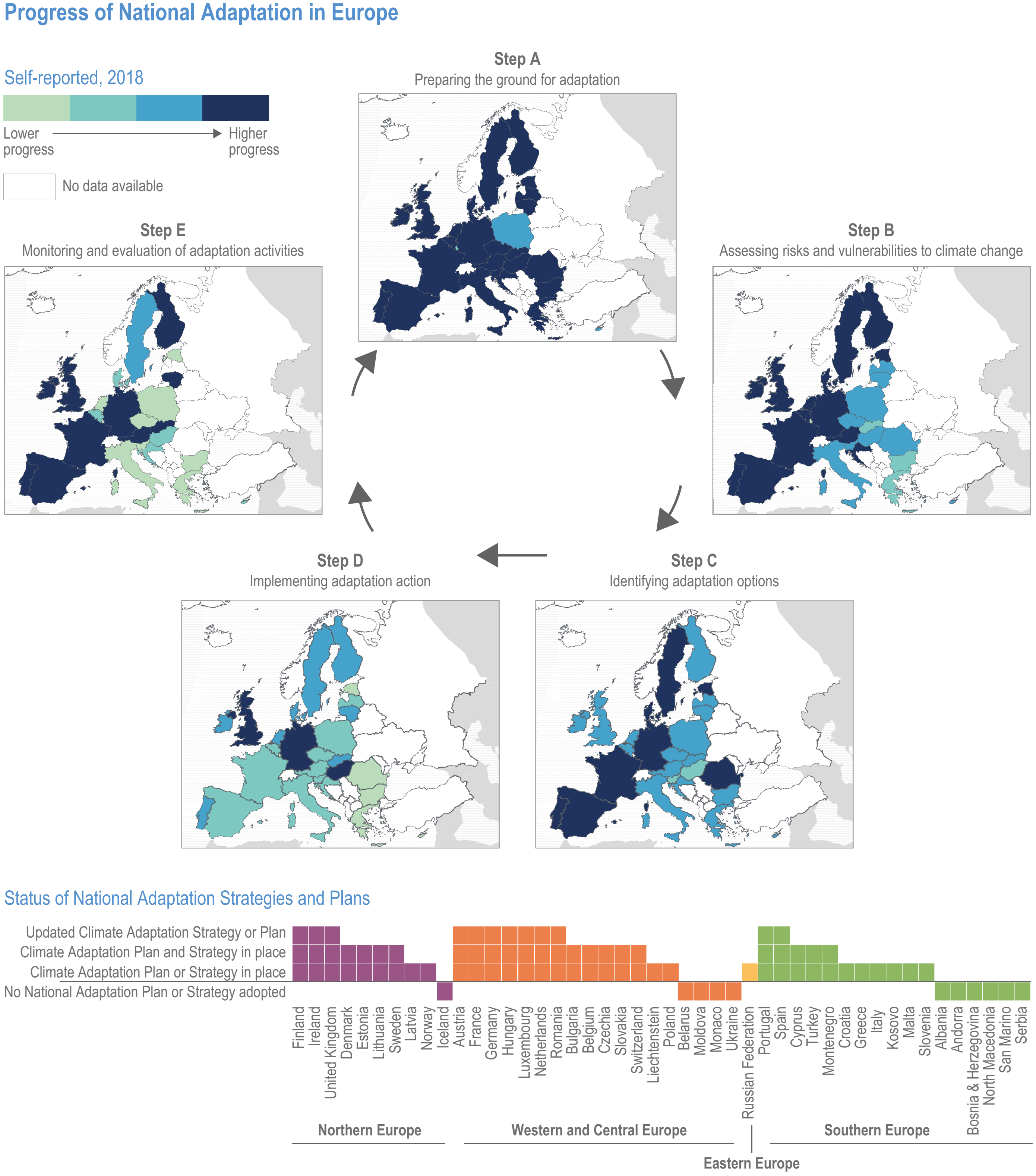


**Figure 13.34 | Progress of national adaptation in Europe in 2018 and status of national adaptation plans and strategies in 2020.** Data on the progress of national adaptation are from the self-reported status of EU member states, as documented in the Adaptation Scoreboard for Country fiches (SWD(2018)460).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

## 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 programmes (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, 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 well-being, 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 300,000):** Since the 1990s, Malmö has been transitioning towards 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 based on them, for example, considering gender in the use, access and safety of public spaces, and emphasising 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 1.4 million):** 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 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 emphasises institutionalisation 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.

climate risks across scales of government (*high confidence*) (Lesnikowski et al., 2016; Russel et al., 2020). 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 EU 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, 2020b; Pietrapertosa et al., 2021), and locally, with an increasing number of European cities planning for climate risks (*high confidence*) (Section 13.6.2.1; see Box 13.3; Chapter 6; Aguiar et al., 2018; Reckien et al., 2018; Grafakos et al., 2020). There is evidence of action across sectors and scales, even in European countries where national adaptation frameworks are absent (*medium confidence*) (Figure 13.34; De Gregorio

Hurtado et al., 2015; Pietrapertosa et al., 2018; Reckien et al., 2018). However, the implementation gap identified in AR5 (Chambwera et al., 2014), that is, 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 knowledge, human and financial resources appears important for proactive adaptation (Termeer et al., 2012; Sanderson et al., 2018), while adaptation is also strongly dependent on economic and social development (*high confidence*) (Sanderson et al., 2018). 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 (Steps A–C in Figure 13.34) and to ensure adequacy of implementation (Steps 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 recognised, 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, sexual orientation, as well as other social equality issues (Cross-Chapter Box GENDER in Chapter 18; Boeckmann and Zeeb, 2014; Allwood, 2020).

Many near-term investment decisions have long-term consequences, and planning and implementation (Steps C and D in Figure 13.34) can take 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., socioeconomic developments and systems transitions) and to broaden the range of considered possible impacts (e.g., Frantzeskaki et al., 2019; Marchau, 2019; 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 socioeconomic 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 socioeconomic and climatic changes. For adaptation to SLR 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 also have been developed for planning urban water supply (Kingsborough et al., 2016; Erfani et al., 2018), urban drainage (Babovic and Mijic, 2019) and wastewater systems (Cross-Chapter Box DEEP in Chapter 17; Sadr et al., 2020). 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 done only in some European countries (Step E in Figure 13.34) 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 overreaction to climate risks (Peters et al., 2017; Biesbroek and Candel, 2019), prevent redistributing vulnerability and maladaptive actions (Atteridge and Remling, 2018; Albizua et al., 2019; Neset et al., 2019), and ensure timely implementation (*high confidence*) (Benson and Lorenzoni, 2017). 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, and WCE depending on impact) (*high confidence*) (Section 13.11.2; Lesnikowski et al., 2016; Biesbroek and Delaney, 2020; Booth et al., 2020). Despite evidence of emerging bottom-up (e.g., citizens and business) and top-down initiatives (e.g., governmental plans and instruments to ensure action), there are considerable barriers to mainstreaming adaptation (*high confidence*) (Runhaar et al., 2018).

While mainstreaming of adaptation into other policy domains has been advocated as an enabler for adaptation, it may have resulted in 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, 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 knowledge 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*) (Chapter 17; Russel et al., 2020). 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, 2020a). 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, 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, 2020a).

With higher warming levels, financing needs are *likely* to increase (*high confidence*) (Mochizuki et al., 2018; Bachner et al., 2019; Parrado et al., 2020), and 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 in 2008 (López-Dóriga et al., 2020). Governments can shift the financial burden to beneficiaries of adaptation, as suggested, for example, 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, 2020a).

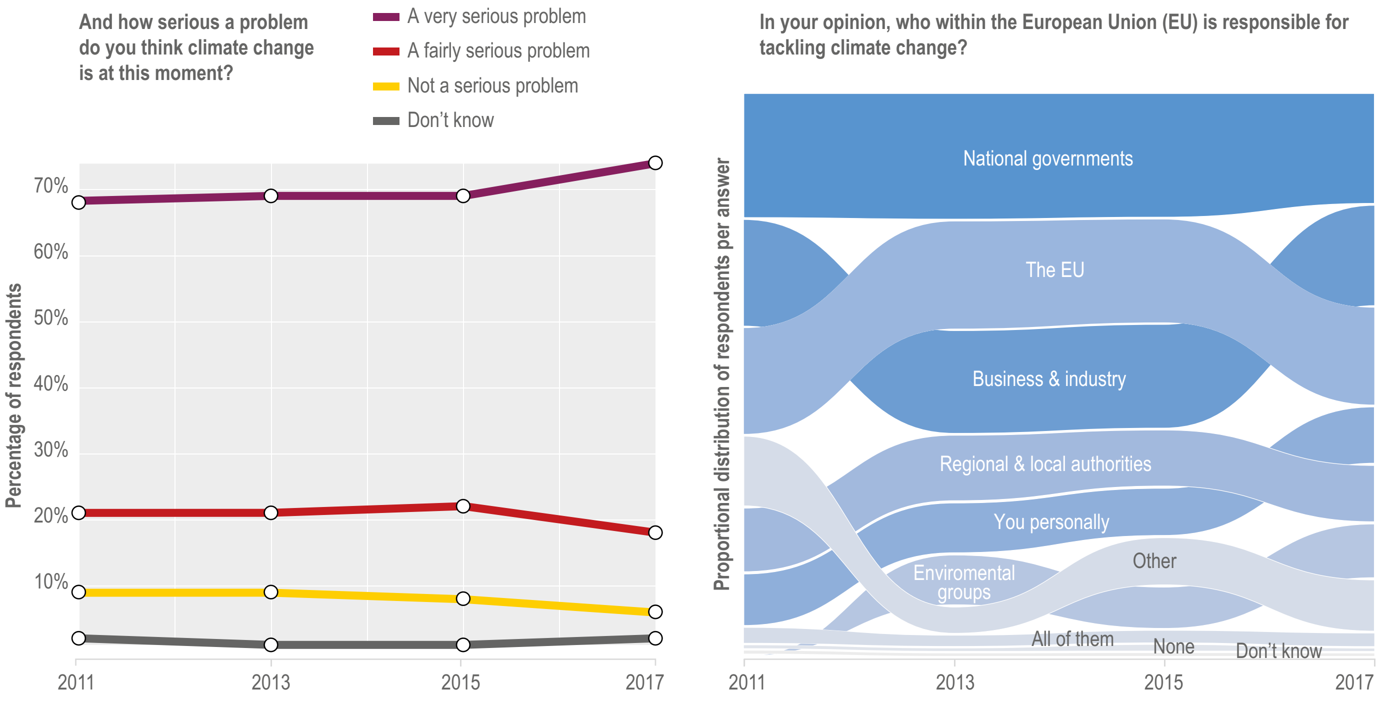
Since AR5, new evidence has emerged that climate change may deteriorate financial stability both at the global and European scales (Campiglio et al., 2018; Dafermos et al., 2018; Lamperti et al., 2019; ECB, 2021a). The European Central Bank, the European Systemic Risk Board, and several national central 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., 2019). Whereas some sectors, such as flood management, banking and insurance, and energy (Bank of England, 2015; Gasbarro and Pinkse, 2016; Bank of England, 2019; Botzen et al., 2019), have generally made moderate progress on adaptation planning across Europe, there are key vulnerable economic sectors that are in earlier stages, including aviation (Burbidge, 2018), ports and shipping (Becker et al., 2018; Ng et al., 2018), and ICT (*high confidence*) (EEA, 2018b). 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 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 (Table 13.1; Pinkse and Gasbarro, 2019). For example, key barriers to adaptation among Greek firms include both external (e.g., lack of support and/or guidance) and internal factors (e.g., Trends in perceived climate change risks and responsibility for tackling climate change across Europe



(a) Perceived seriousness of climate change

(b) Perceived responsibility for tackling climate change

**Figure 13.35 |** **Trends in perceived climate-change risks and responsibility for tackling climate change across EU-28; data collected from around 1000 respondents per country for each year surveyed (European Comission, 2017)**

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 (Section 13.16.2.2; Dinca et al., 2014; André et al., 2017; Romagosa and Pons, 2017; Esteve et al., 2018; Luís et al., 2018; Ng et al., 2018). 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 among European households (*high confidence*), with few examples that can be considered transformative (e.g., structural, long-term, collective) (*medium confidence*) (Wilson et al., 2020). 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 (Sections 13.2.1, 13.6.1; Stojanov et al., 2015); for example, there is 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., the UK and the Netherlands) countries is increasing (Section 13.2; Aparicio, 2017). Among 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 (Section 13.7; van Valkengoed and Steg, 2019).

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 sociopolitical events (*high confidence*) (Capstick et al., 2015). On average across Europe, and particularly in relation to gradual change, compared with experts, non-experts continue to underestimate climate-change risks (*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 among 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 barriers to adoption; and lack of standards as well as societal hesitation may explain low levels of water reuse in Europe (Section 13.2; EEA, 2017b). Conversely, water meters and higher tariffs have been found to reduce water consumption only in combination with other measures (EEA, 2017b; Bryan et al., 2019).

As well as temporal trends in climate-change risk perception, the literature since AR5 continues to show much heterogeneity (both within and between nations) among householders in respect of risk perception (*high confidence*). Higher climate-change risk perceptions have been observed in Spain, Portugal, Iceland and Germany (Figure 13.2); at the 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 multi-level governance and institutional capabilities, and enables lifestyle and behavioural change as well as 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 (see Box 13.3). Transformative options may be better able to exploit new opportunities and co-benefits (see Box 13.3; Cross-Chapter Box HEALTH in Chapter 7; EEA, 2019a). Transitions towards more adaptive and climate-resilient systems are often the result of responses to crises which create windows of opportunity for systemic changes (Chapter 18; Johannessen et al., 2019). This includes extreme weather events, financial crises, for example in Malmö (Anderson, 2014; Isaksson and Heikkinen, 2018), and the COVID-19 pandemic (e.g., Milan), all of which have disrupted the status quo and accelerated innovation and implementation (e.g., Milan; see Box 13.3; Cross-Chapter Box COVID in Chapter 7).

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 (*high confidence*) (Johannessen et al., 2019; Roberts and Geels, 2019). 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 (i.e., political) will, (un)learning of practices, resources, and evidence of what works. Trade-offs exist between the depth, scope and pace of change in transitioning from one system to another, suggesting that designing system transformations is a delicate balancing act (Termeer et al., 2017). Aspiring in-depth and comprehensive transformational changes might create a consensus framework to which to aspire, 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 socioeconomic 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 13.5–13.7, 13.10). As noted in Section 13.8, addressing poverty (SDG 1)–including energy poverty (SDG 7) and hunger (SDG 2); and addressing 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 NbS, 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) (Sections 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 and/or engineering) measures. Beyond the urban context, biodiversity co-benefits from agroecology are also recognised (Section 13.5). Sustainable behaviour-change measures have been found to be particularly *likely* to lead to synergies with SDGs (Papadimitriou et al., 2019).

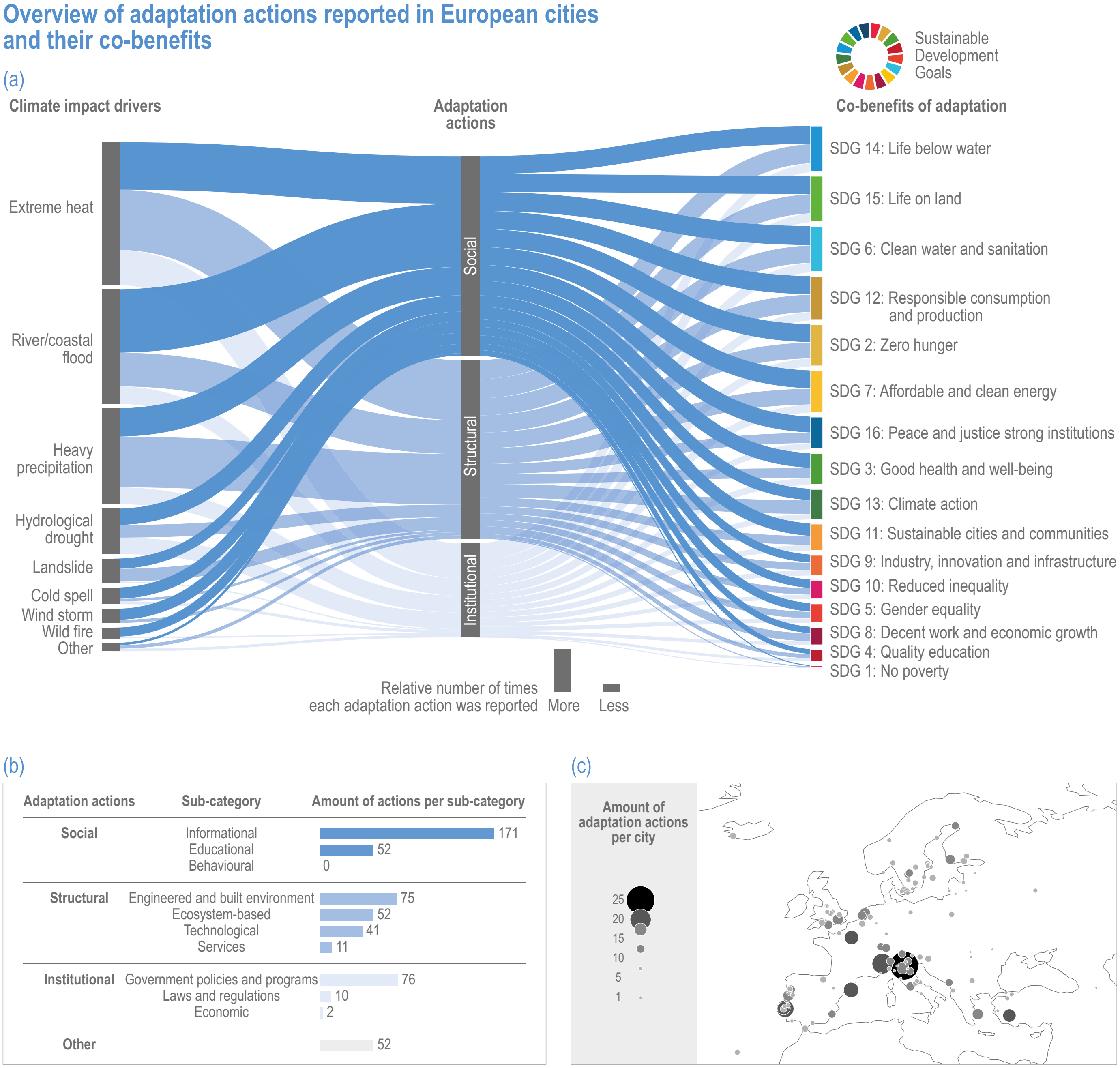


**Figure 13.36 | Co-benefits for SDGs from adaptation actions.** Shown is how European cities have assessed the sustainability co-benefits of taking adaptation actions. Data were extracted from the Carbon Disclosure Project (CDP) database using the 2019 dataset; of the 861 European cities submitting data, 167 provided data on their adaptation actions, and these data are shown here (CDP, 2019). The CDP categories of climate hazards were re-categorised into WGI Climate Impact Drivers (e.g., cold spell, heavy precipitation); CDP adaptation actions were re-classified into AR5 adaptation options ('social', 'structural' and 'institutional'; 'other' includes actions falling outside these AR5 categories); and CDP co-benefits were re-categorised as SDGs. The upper panel 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. The lower left panel shows that societal actions were most common, followed by structural, then institutional. Informational measures were particularly common. The lower right panel shows how many actions were taken by different European cities.

Frequently Asked Questions

## 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 EU, about 20% of the population (109 million people) live under conditions of poverty or social exclusion. Moreover, poverty is unequally distributed across Europe, with higher poverty levels in EEU. 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 SEU. 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 (i.e., Komi, Sámi, 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 health care 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 SEU and EEU 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 CRD that consider social equity which integrate a gender-inclusive perspective in its sustainable urban planning, including designing public spaces and transit to ensure that women, persons with disabilities and other groups can access, and feel safe using, these public amenities.

Frequently Asked Questions

## 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.

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 GWL, including fishes and lake and river ecosystems. At 3°C GWL, 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 heatwaves 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 GWL. NbS, 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 NbS, trade-offs and unintended side effects should be considered. On one hand, engineering coastal protection measures (seawalls, breakwaters and similar infrastructure) in response to SLR reduce the space available for coastal ecosystems. One the other hand, NbS 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.

Frequently Asked Questions

## FAQ 13.3 | How can people adapt at individual and community level to heatwaves 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 heatwave strikes. Implementing adaptation measures are important to reduce the risks of future heatwaves.*

Heatwaves 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 SEU and increasingly in EEU and WCE. The severity of heat-related risks will be highest in large cities, due to the UHI effect.

In SEU, 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 heatwaves; however, there are limits to how much adaptation can be implemented. At 3°C GWL, there will be substantial risks to human lives and productivity, which cannot be avoided. In the parts of Europe where heatwaves are a relatively new phenomenon, such as many parts of NEU and WCE, public awareness of heat extremes is increasing and institutional capacity to respond is growing.

Preparing for heatwaves is an important first step. Implementing and sustaining effective measures, such as national or regional early warning and information systems, heatwave plans and guidelines, and raising public awareness through campaigns, are successful responses. Evidence suggests that such measures have contributed to reduced mortality rates in SEU and WCE. At city level, preparing for heatwaves can sometimes require urban re-design. 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, 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 heatwaves, green roofs and green façades on their buildings.

During heatwaves, 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 including (a) decrease exposure to high temperatures (e.g., avoid outdoor during hottest times of the day, access cool areas, wear protective and appropriate clothing), (b) keep hydrated (e.g., drink enough proper fluids, avoid alcohol, etc.) and (c) be sensitive to the symptoms of heat illness (dizziness, heavy sweating, fatigue, cool and moist skin with goosebumps when in heat, etc.).

Once the heatwave has ended, evaluation of what worked well and how improvements can be made is key to prepare for the *next* heatwave. Governments can, for example, evaluate whether the early warning systems provided timely and useful information, whether coordination went smoothly and assess the estimated number of lives saved, to determine the effectiveness 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 heatwave strikes.

Frequently Asked Questions

## 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 (a) positive effects of warming for specific sectors and regions, such as agriculture in NEU, and (b) 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 well-being. 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-19 crisis, such as the European New Green Deal and Building Back Better.

As warming and droughts impact SEU 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 southwest Mediterranean and reduced energy demand for heating across Europe. While climatic conditions for tourist activities are projected to decrease for winter tourism (e.g., insufficient snow amount) and summer tourism in some parts of Europe (e.g., too much heat), 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 NEU and EEU particularly by the end of the century.

Indirect opportunities emerge from the co-benefits of implementing adaptation actions. Some of these co-benefits are widespread but need careful consideration in order to be utilised. For example, an NbS approach 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 as well as COVID-19 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 SDGs.

Inclusive, equitable and just adaptation is critical for CRD considering SDGs, gender as well as IKLK and practices. Implementation requires political commitment, persistence and consistent action across scales of government. Upfront mobilisation 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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