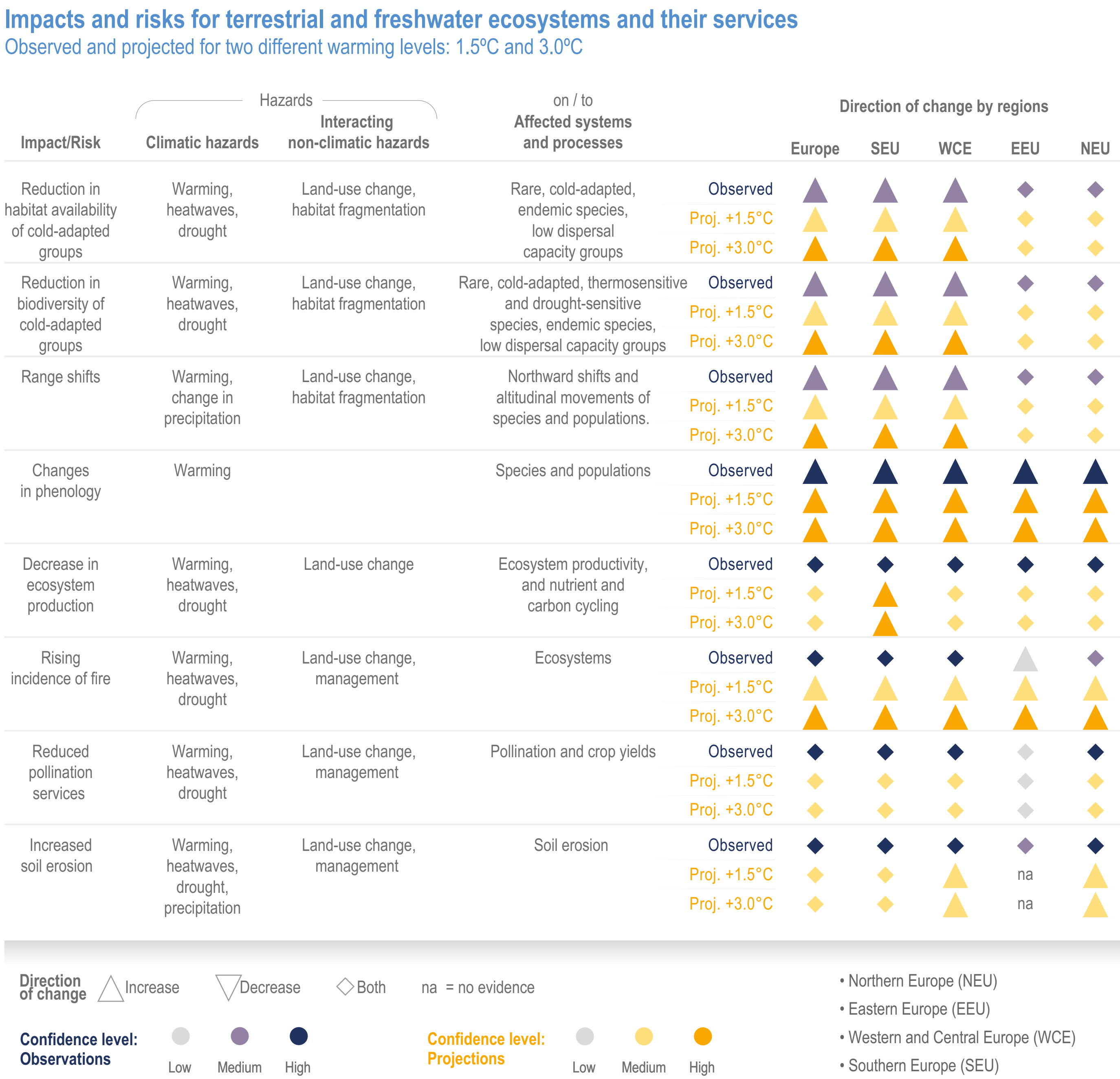


**Figure 13.8 | Summary of major impacts on, and risks for, terrestrial and freshwater ecosystems in Europe for 1.5°C and 3°C GWL** (Table SM13.2)

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

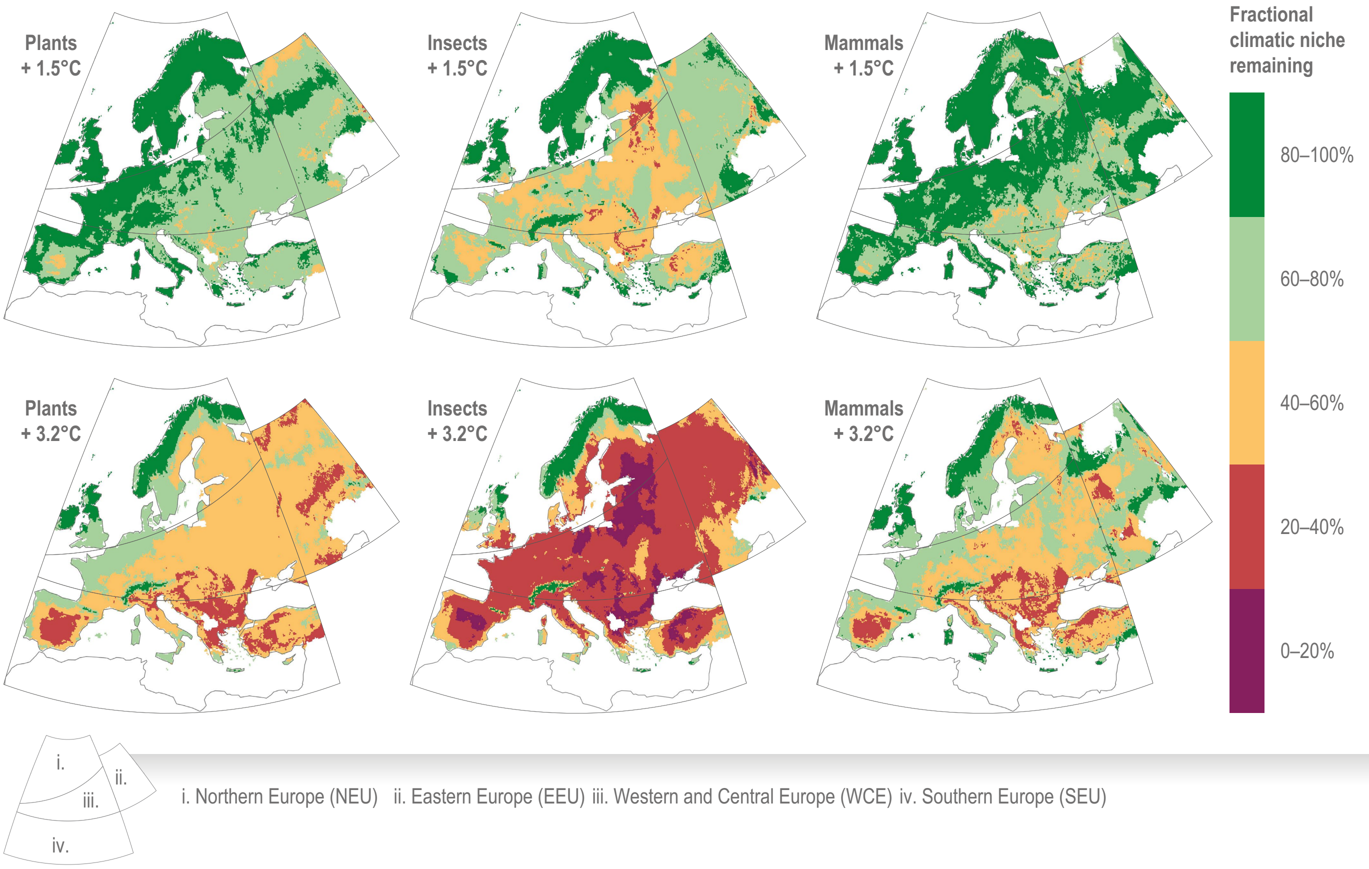


**Figure 13.9 | Species projected to remain within their suitable climate conditions at increasing levels of climate change.** Colour shading represents the proportion of species projected to remain within their suitable climates averaged over 21 CMIP5 climate models (Warren et al., 2018). Areas shaded 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., Observed fire weather in European regions (1980–2019)

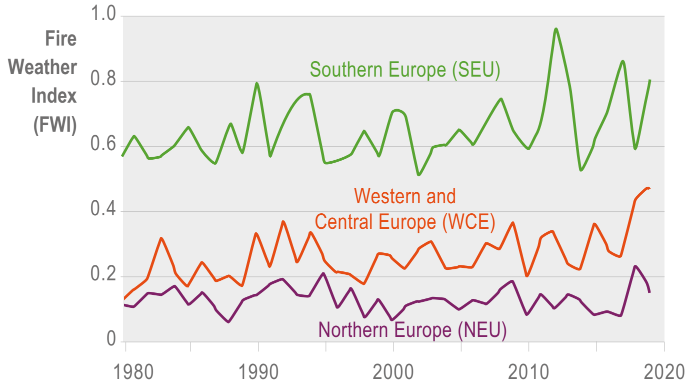


**Figure 13.10 | Geographical variability and dynamic changes in fire danger in Europe over recent decades.** Significant increases in fire hazard at the multi-decadal scale and unprecedented years of elevated fire hazard have occurred over the past decade in Southern and Western Central Europe (SEU, 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

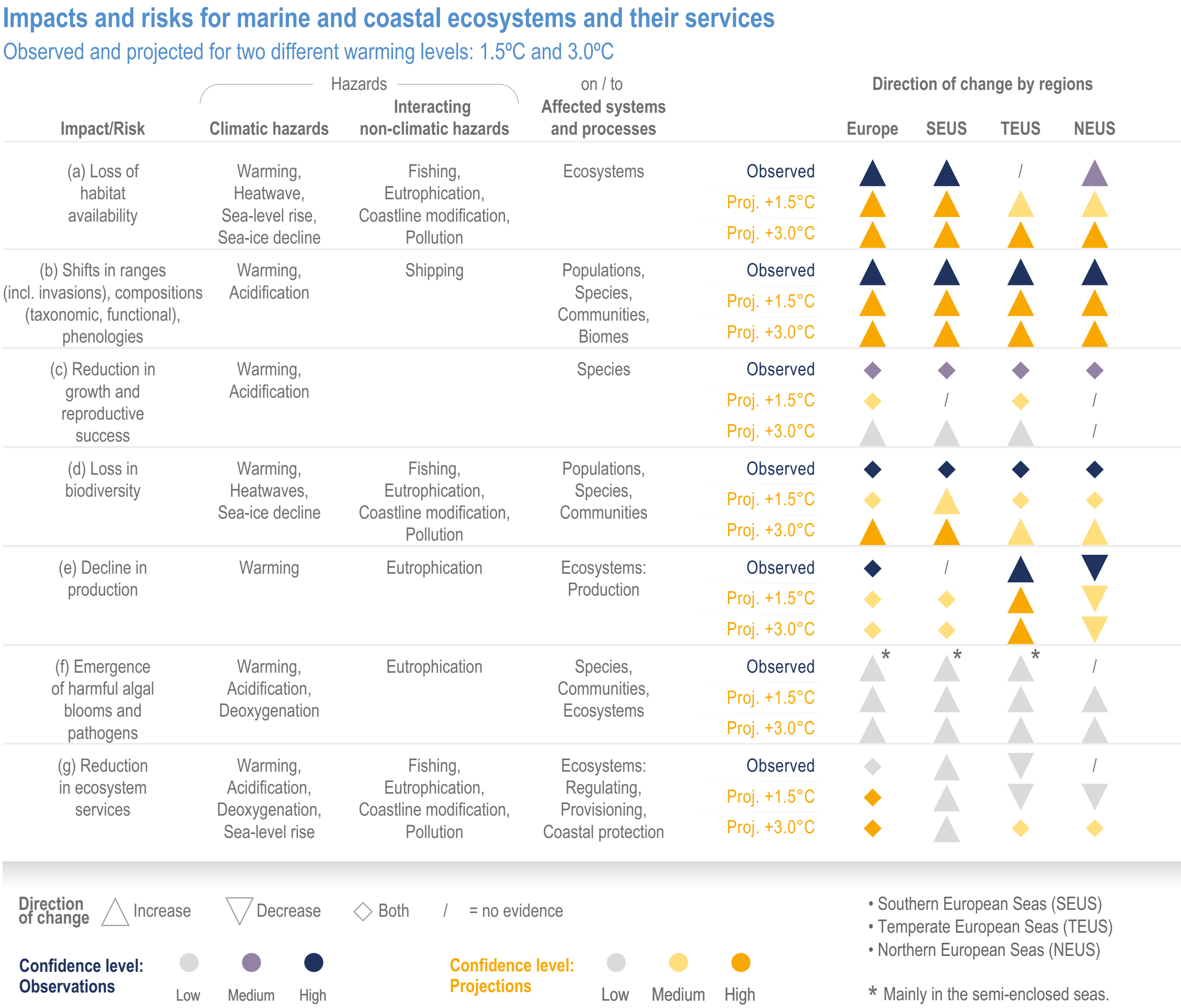


**Figure 13.11 | Major impacts and risks for marine and coastal ecosystems in Europe for observed and projected 1.5°C and 3.0°C GWL** (Table SM13.4)

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 km$^2$). 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

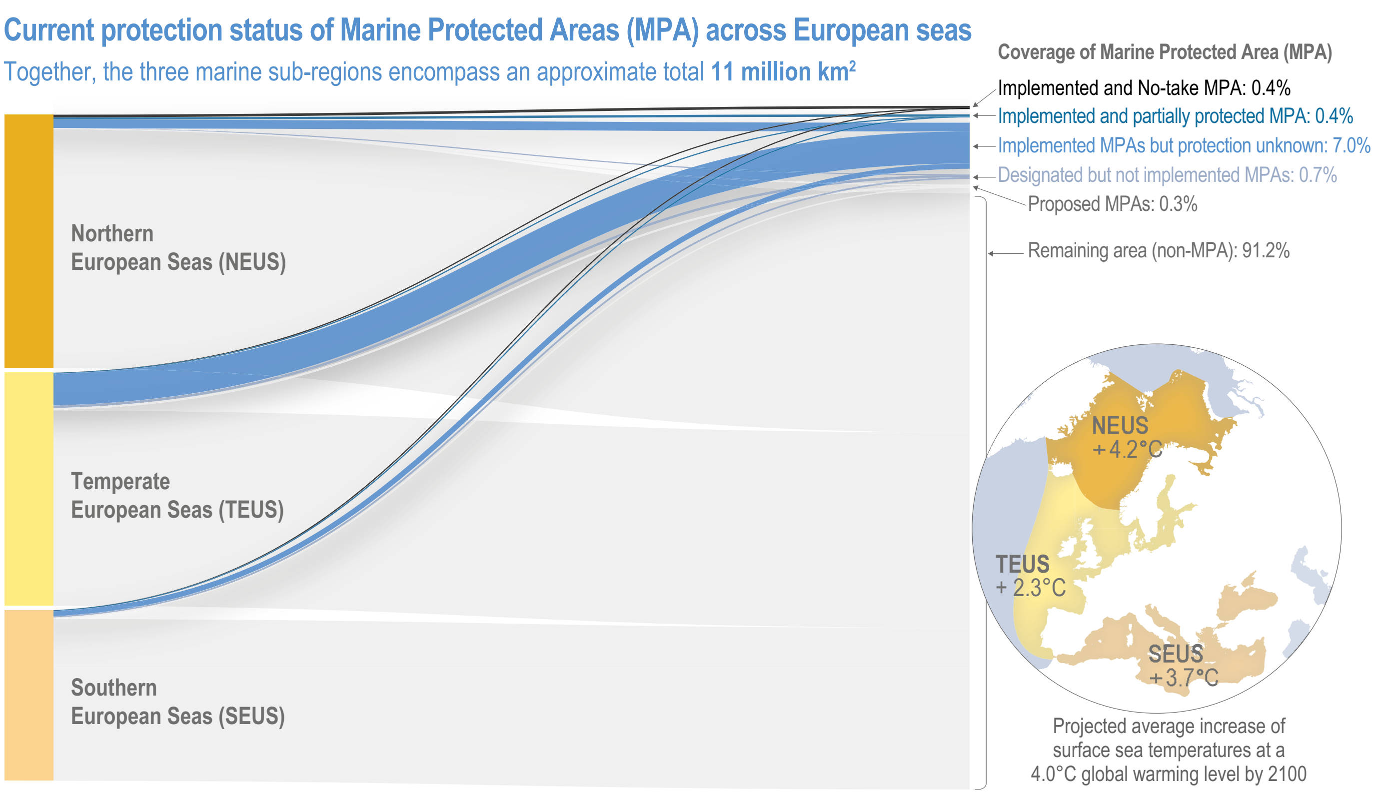


**Figure 13.12 | Marine protected areas (MPAs) in European seas.** Shown are proportions of designated and proposed MPAs in the total areas of northern (NEUS), temperate (TEUS) and southern (SEUS) European seas, as well as the shares of no-take, partial, unimplemented and unknown protection levels of 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).

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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

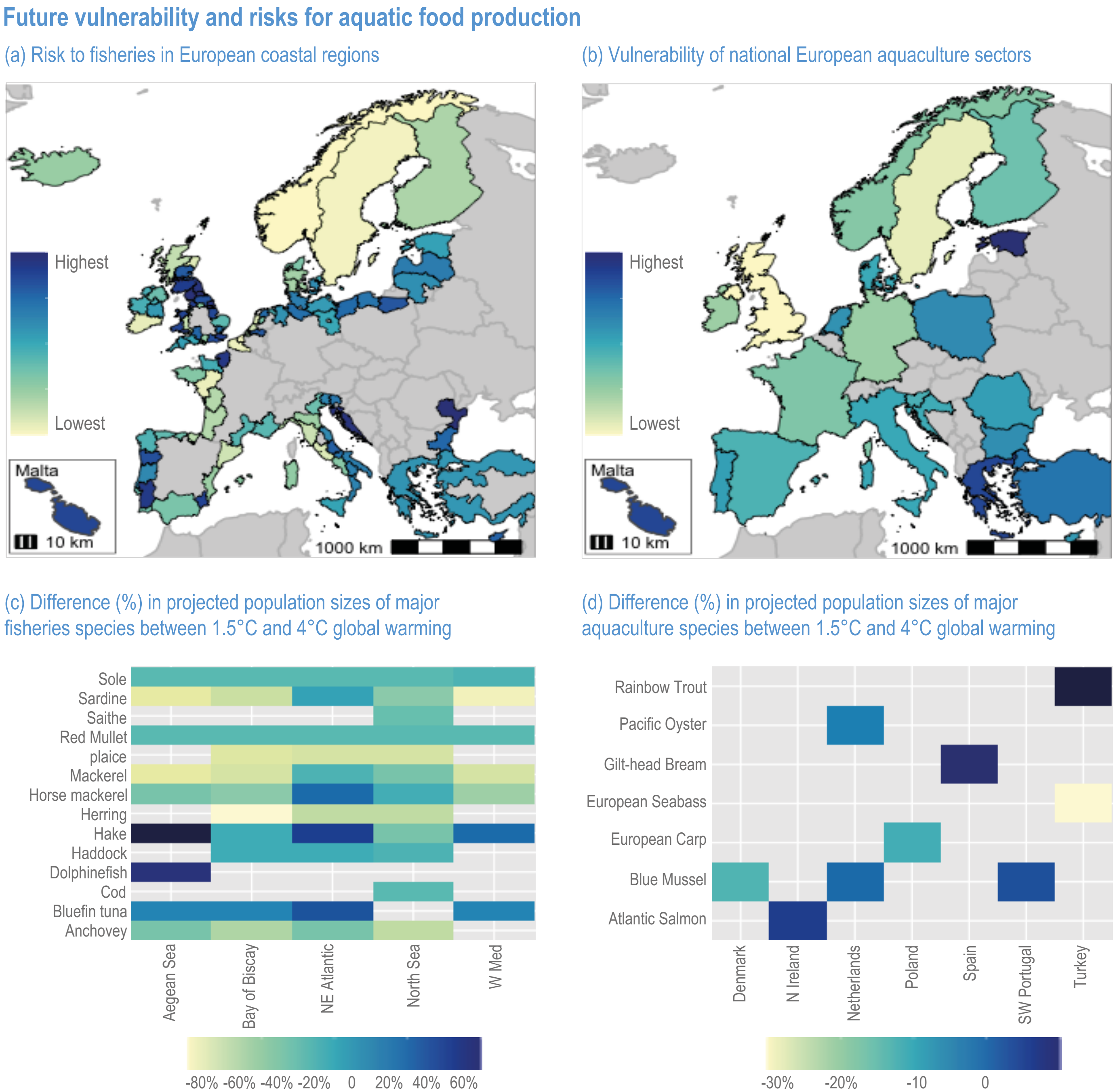


**Figure 13.13 | Future vulnerability and risks for aquatic food production:**

**(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).

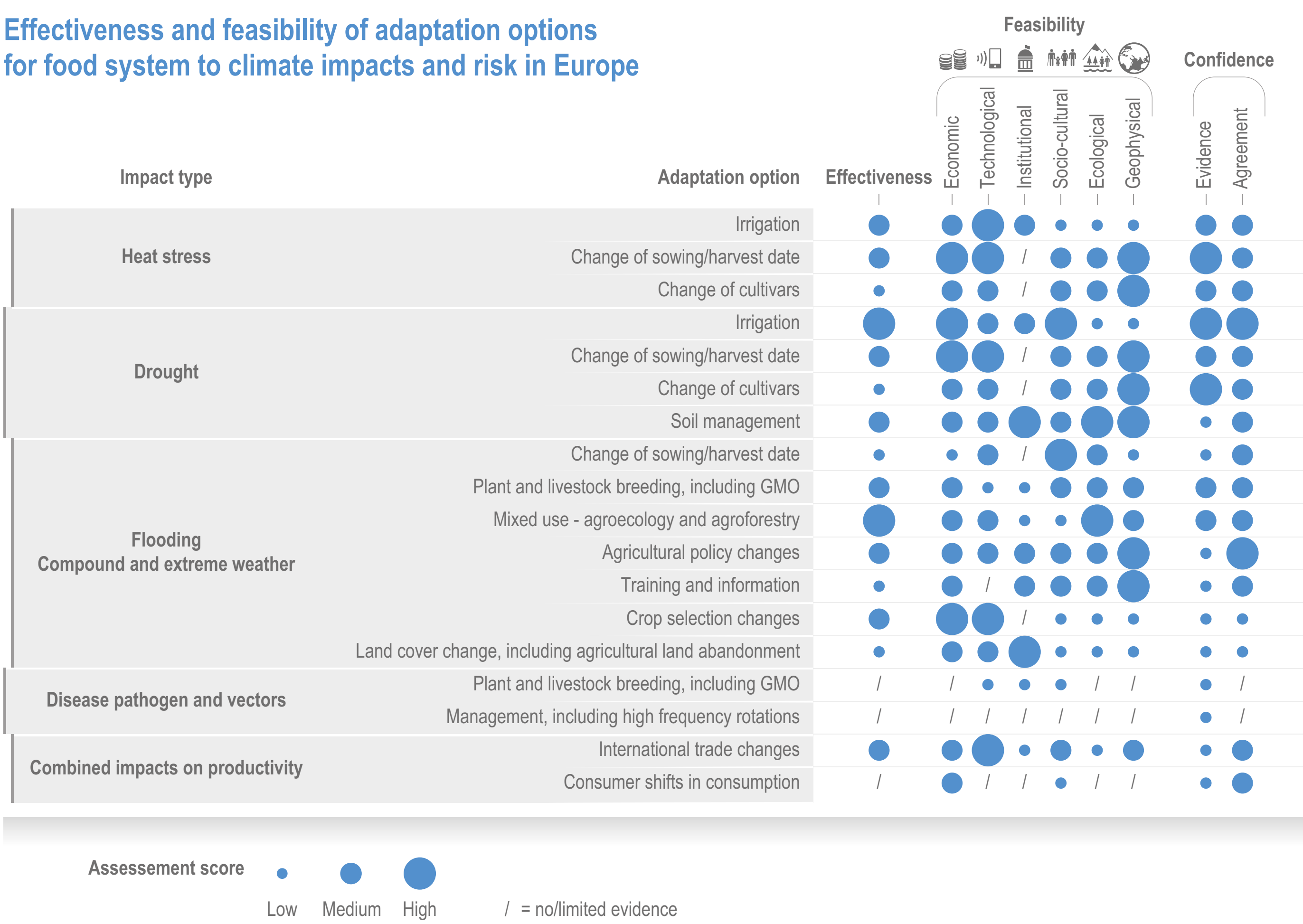


**Figure 13.14 | Effectiveness and feasibility of the main adaptation options for food systems in Europe** (Section SM13.9, Table SM13.5)

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

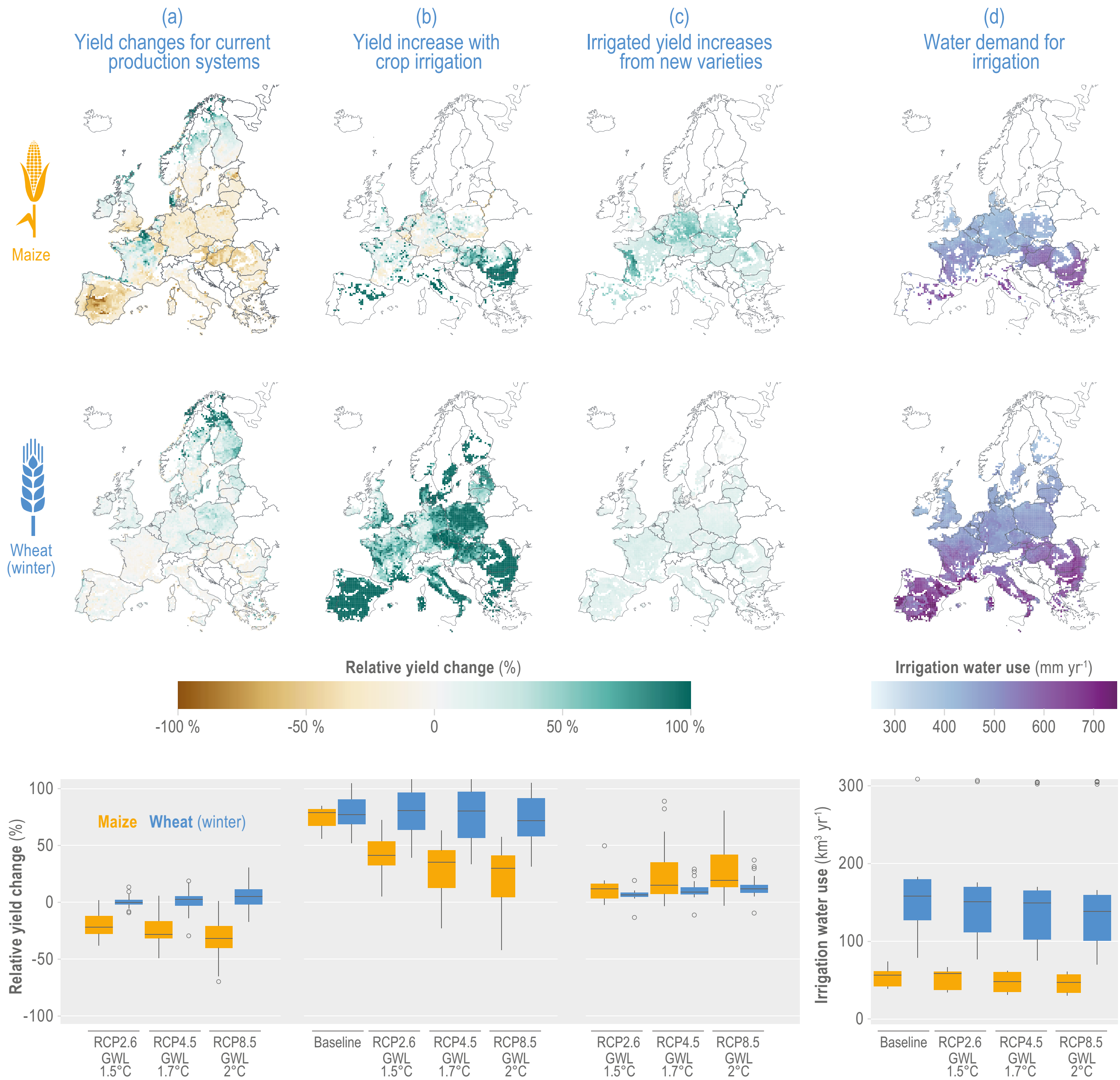


**Figure 13.15 | Projected yield changes with climate change for 1.5°C (RCP2.6), 1.7°C (RCP4.5) and 2°C GWL (RCP8.5).** Altered crop management and associated water demand shows:

**(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

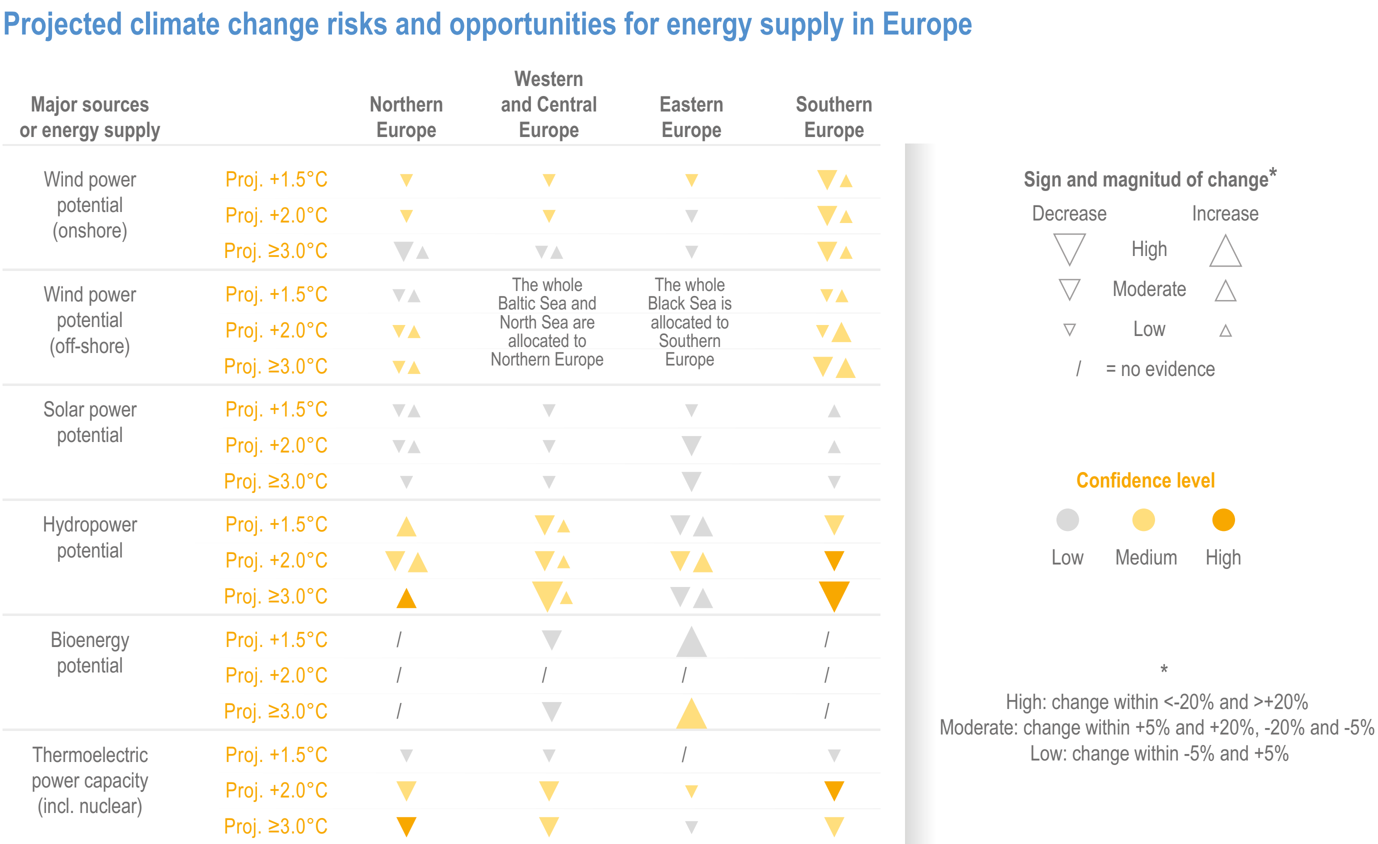


**Figure 13.16 | Projected climate-change risks for energy supply in Europe for major sources and under 1.5°C, 2°C and >3°C GWL (Tables SM13.5–13.13)**

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).

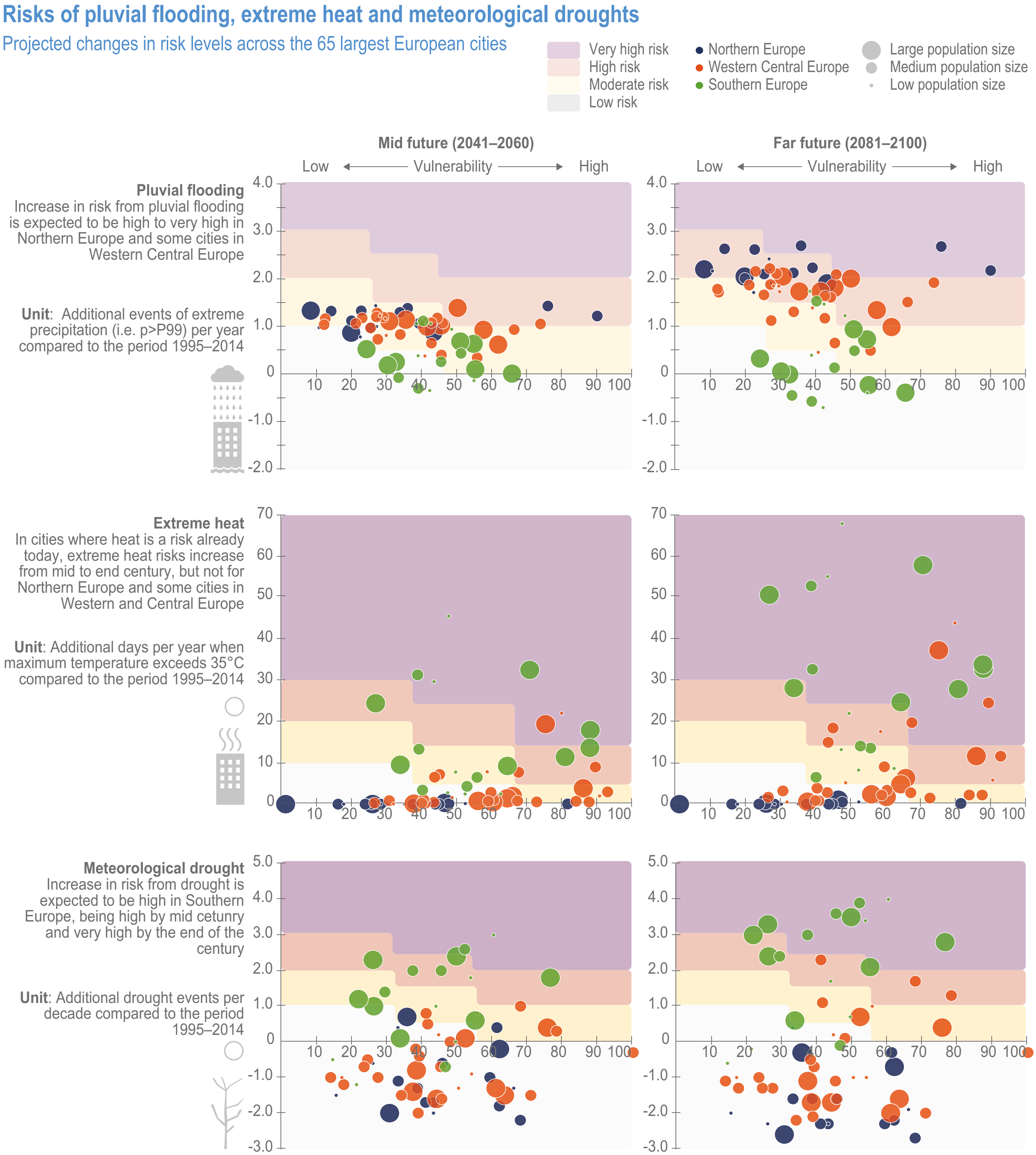


**Figure 13.17 | Projected changes in pluvial flooding, extreme heat and meteorological drought risks for the 65 largest cities in EU-28 plus Norway and Switzerland for 2.5°C and 4.4°C GWL compared with the baseline (1995–2014) (Tapia et al., 2017).** Exposure is expressed in terms of current population.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

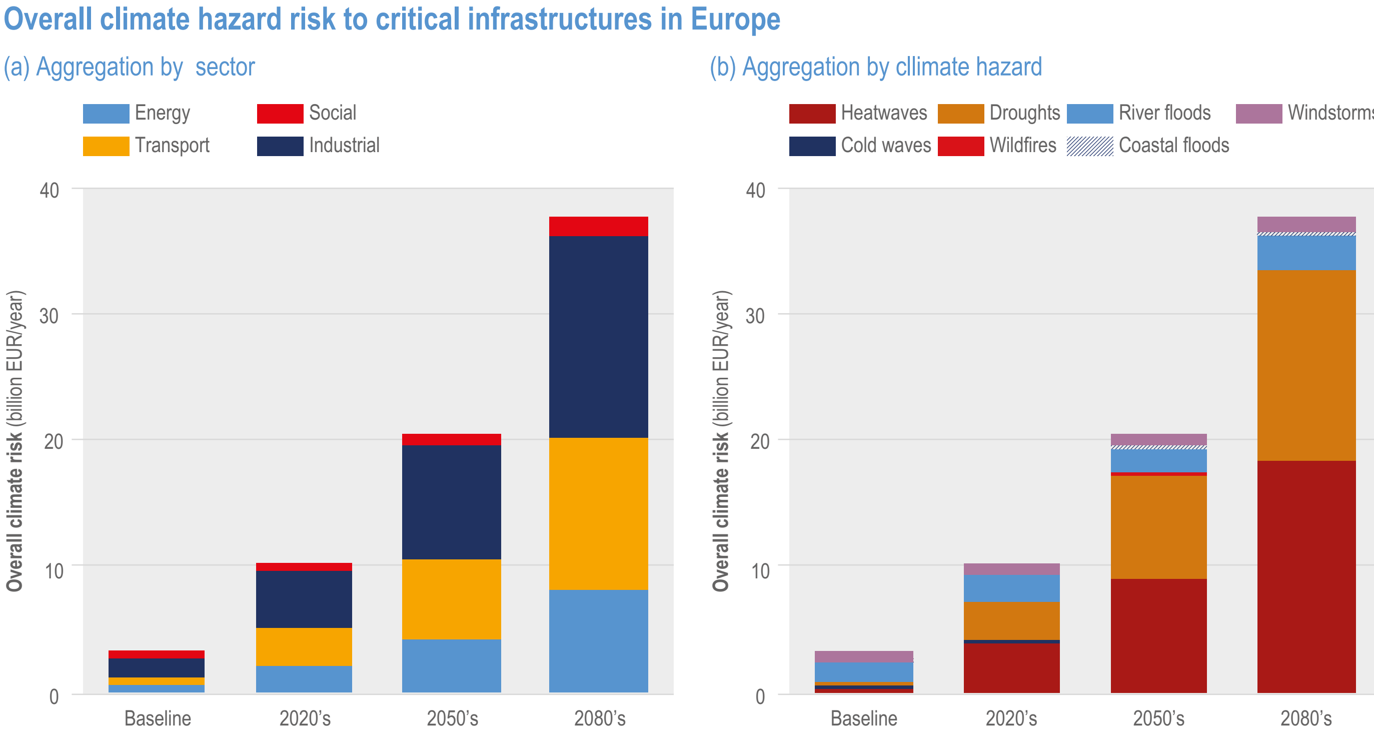


**Figure 13.18 | Climate risks to critical infrastructures, aggregated at European (EU+) level under the SRES A1B scenario (Forzieri et al., 2018).** Baseline: 1981–2010; 2020s: 2011–2040; 2050s: 2041–2070; 2080s: 2071–2100

*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. |

Legend: 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


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

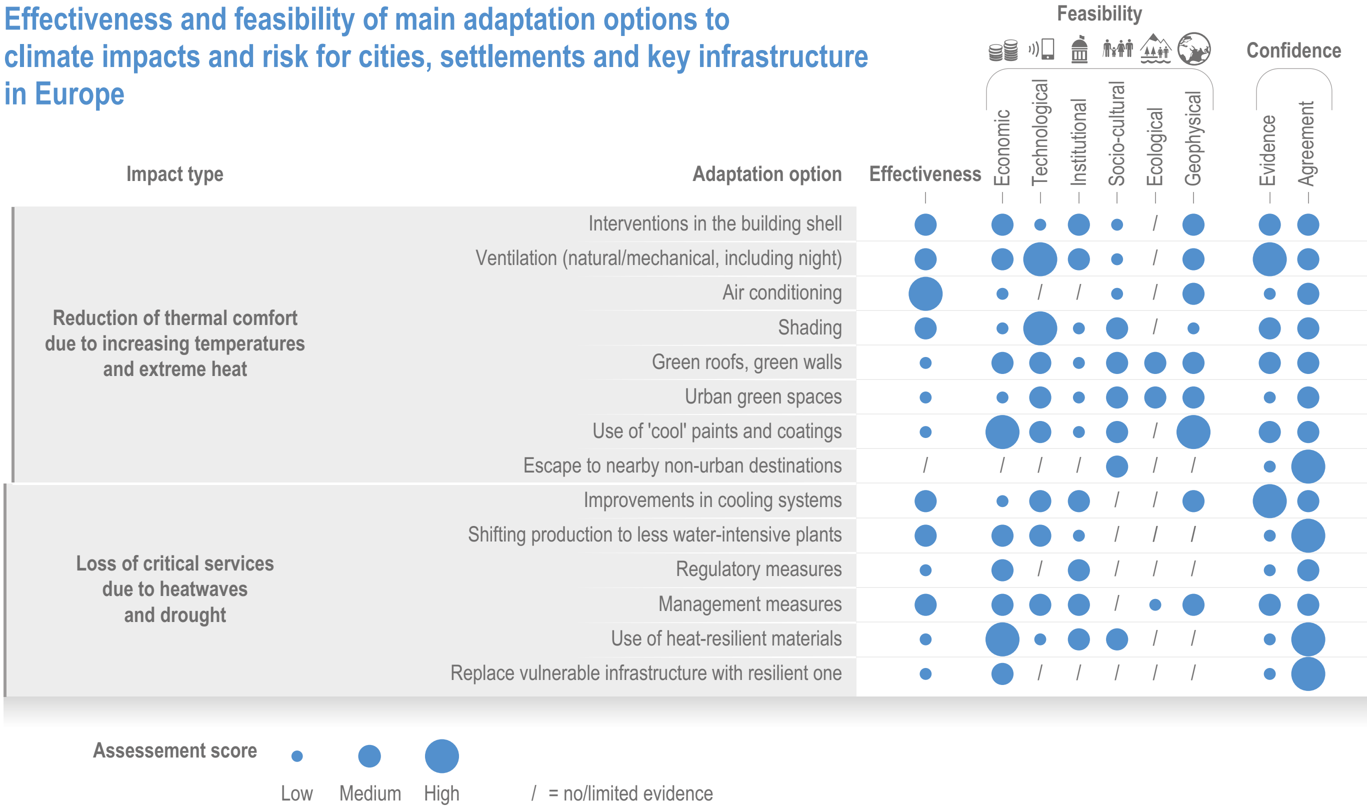


**Figure 13.20 | Effectiveness and feasibility of the main adaptation options for cities, settlements and key infrastructures in Europe** (Section SM13.9; Table SM13.8)

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