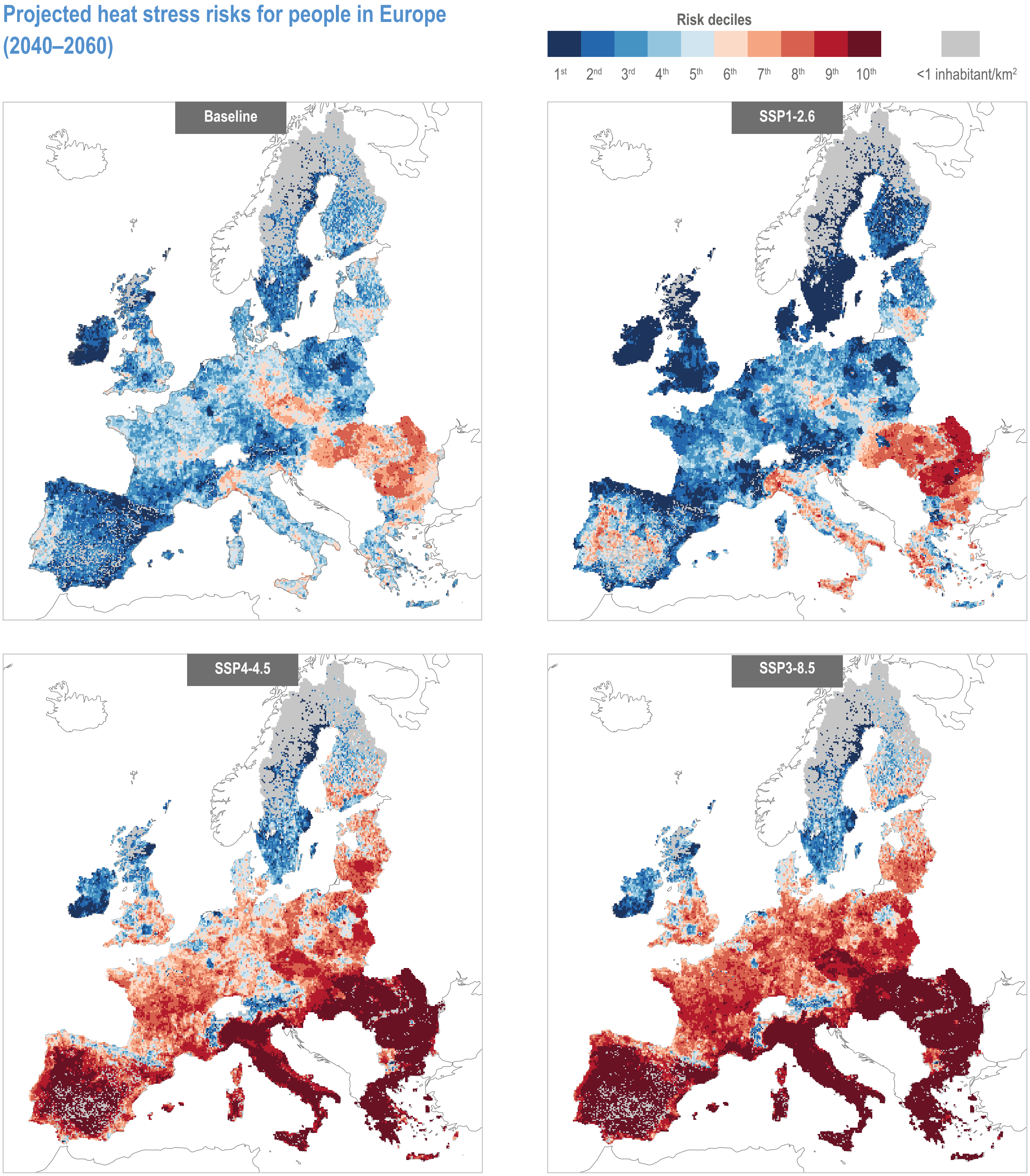


Figure 13.22 | Scenario matrix for multi-model median heat stress risks for the baseline 1986–2005, and different SSP–RCP combinations for the period 2040–2060. The SSPs are extended for Europe (EU28+). Heat stress risk is calculated by geometrical aggregation of the hazard (heatwave days), population vulnerability and exposure. Risk values are normalised using a z-score rescaling with a factor-10 shift. Details of the methodology are provided by Rohat et al. (2019).

Impacts and risks of climate sensitive infectious diseases

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

Direction of change: Increase; Decrease; Both; no observation; / = no evidence; * only the case for the Baltic region

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

Confidence level: Observations Low Medium High

Confidence level: Projections Low Medium High

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

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

13.7.1.3 Climate-Sensitive Infectious Diseases

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

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

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

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

13.7.1.4. Allergies and Pollen

The main drivers of allergies are predominantly non-climatic (e.g., increased urbanisation, adoption of westernised lifestyles, social and genetic factors), but climate change strongly contributes to the spread of some allergenic plants, thus exacerbating existing allergies and causing new ones in people across Europe (*high confidence*) (D'Amato et al., 2016; EASAC, 2019). The prevalence of hay fever (allergic rhinitis), for example, is between 4 and 30% among European adults (Pawankar et al., 2013). The invasive common ragweed (*Ambrosia asteraceae*) is a key species already causing major allergy in late summers (including hay fever and asthma), particularly in Hungary, Romania and parts of Russia (Ambelas Skjøth et al., 2019). Across Europe, sensitisation to ragweed is expected to increase from 33 million people in 1986–2005 to 77 million people at 2°C GWL (Lake et al., 2017).

Warming will result in an earlier start of the pollen season and extending it, but this differs across regions, species, traits and flowering periods (Ziello et al., 2012; Bock et al., 2014; EASAC, 2019; Revich et al., 2019). For instance, in different parts of WCE and NEU, the start of birch-season flowering has been shifted and extended up to 2 weeks earlier during recent decades (Biedermann et al., 2019). Airborne pollen concentrations are projected to increase across Europe (Ziello et al., 2012). In south-eastern Europe, where pollen already has a substantive impact, the pollen count could increase more than 3 to 3.5 times at 2.5°C GWL and can become a more widespread health problem across Europe, particularly where it is currently uncommon (*medium agreement, low evidence*) (Lake et al., 2017).

13.7.1.5. Labour Productivity and Occupational Health

Extreme heat and cold waves have been linked to an increased risk of occupational injuries (Martinez-Solanas et al., 2018) and changes in labour productivity (Orlov et al., 2019; García-León et al., 2021), while evidence on the consequences of other extreme events is lacking. The sectors with a high percentage of high-intensity outdoor work in Europe, mainly agriculture and construction, have the highest risk of increased injury and labour productivity losses, but also manufacturing and service sectors can be affected when air conditioning is not available (Section 13.6.1.3; Gosling et al., 2018; Szewczyk et al., 2018; Dellink et al., 2019; Orlov et al., 2019). The heatwaves of August 2003, July 2010 and July 2015 were concentrated in SEU and led to reductions in monthly worker productivity of on average 3–3.5% in SEU, ranging up to 8–9% in Cyprus (2003, 2010) and Italy (2015) (Orlov et al., 2019); in contrast, the heatwave of 2018 centred on NEU but also led to pronounced productivity reductions in WCE and SEU (García-León et al., 2021). Each of these major European heatwaves led to considerable economic losses in agriculture and construction (*high confidence*) and reduced GDP in Europe (except EEU) by 0.3–0.5% (García-León et al., 2021). At 2.5°C GWL and beyond, GDP losses are projected to increase fivefold compared with 1981–2010, ranging from 2–3.5% in SEU to 0.5–1.5% in WCE, and below 0.5% in NEU and EEU (Section 13.10.3; Roson and Sartori, 2016; Takakura et al., 2017; Szewczyk et al., 2018; Dellink et al., 2019; García-León et al., 2021).

13.7.1.6. Food Quality and Nutrition

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

13.7.1.7. Mental Health and Well-Being

Extreme weather events can trigger post-traumatic stress disorder (PTSD), anxiety and depression; this is well-documented for flooding in Europe (*high confidence*) but less for other extreme weather events. For example, in the UK, flooded residents suffered stress and identity loss from the flood event itself, but also from subsequent disputes with insurance and construction companies (Carroll et al., 2009; Greene et al., 2015). Residents displaced from their homes for at least 1 year due to 2013–2014 floods in England were significantly more *likely* to experience PTSD, depression and anxiety, with stronger effects in the absence of advance warning (Munro et al., 2017; Waite et al., 2017). There is emerging evidence across Europe that young people may be experiencing anxiety about climate change, although it is unclear how widespread or severe this is (Hickman, 2019). In northern Italy, the number of daily emergency psychiatric visits and mean daily air temperature has been linked (Cervellin et al., 2014).

13.7.2 Solution Space and Adaptation Options

Adaptation to health impacts has generally received less attention compared with other climate impacts across Europe (EASAC, 2019). Progress on health adaptation can be observed. Between 2012 and 2017, at least 20 European countries instituted new governance mechanisms, such as interdepartmental coordinating bodies for health adaptation and adopted health adaptation plans (Kendrovski and Schmoll, 2019). Progress on city-level health adaptation is generally limited (Araos et al., 2015), with most activities occurring in SEU (*high agreement, medium evidence*) (Paz et al., 2016).

Figure 13.24 presents the assessment of the feasibility and effectiveness of key heat-related health adaptation actions. It shows that substantial social–cultural and institutional barriers complicate widespread implementation of measures; studies on the implementation of new blue–green spaces in existing urban structures in, for example, Sweden (Wihlborg et al., 2019), the UK (Carter et al., 2018) and the Netherlands (Aalbers et al., 2019), point to important feasibility challenges (e.g., access to financial resources, societal opposition, competition for space) (*high confidence*). Lower perception of health risks has been observed among vulnerable groups which, in conjunction with perceived high costs of protective measures, act as barriers to implementing health adaptation plans (van Loenhout et al., 2016; Macintyre et al., 2018; Martinez et al., 2019). Key barriers to mental health adaptation actions include lack of funding, coordination, monitoring and training (e.g., psychological first aid) (Hayes and Poland, 2018). Existing health measures, such as monitoring and early warning systems, play an important role in detecting and communicating emerging climate risks and weather extremes (*high confidence*) (Confalonieri et al., 2015; Casanueva et al., 2019; Linares et al., 2020). Stricter enforcement of existing health regulations and policies can have a positive effect in reducing risks (Berry et al., 2018).

The effectiveness of most options in reducing climate-induced health risks is determined by many co-founding factors, including the extent of the risk, existing sociopolitical structure and culture, and other adaptation options in place (*high agreement, medium evidence*). Successful examples include the implementation of heatwave plans (Schifano et al., 2012; van Loenhout and Guha-Sapir, 2016; de'Donato et al., 2018), improvements in health services and infrastructure of homes (Section 13.10.2.1; Vandentorren et al., 2006). A study of nine European cities, for example, showed lower numbers of heat-related deaths in SEU and attributed this to the implementation of heat prevention plans, a greater level of individual and household adaptation, and growing awareness about exposure to heat (de'Donato et al., 2015). Long-term national prevention programmes in NEU have been shown to reduce temperature-related suicide (Helama et al., 2013). The physical fitness of individuals may increase resilience to extreme heat (Schuster et al., 2017). Combining multiple types of adaptation options into a consistent policy portfolio may have an amplifying effect in reducing risks, particularly at higher GWL (*medium confidence*) (Chapter 7; Lesnikowski et al., 2019).

Health adaptation actions have demonstrable synergies and trade-offs (Cross-Chapter Box HEALTH in Chapter 7). For example, increasing green–blue spaces in Europe's densely populated areas can be effective in improving microclimates, reducing the impact of heatwaves, improving air quality and improving mental health by increasing access to fresh air and green (restorative) environments (Gascon et al., 2015; Kondo et al., 2018; Kumar et al., 2019). Health adaptations can also have negative trade-offs, be inconsistent with mitigation ambitions and could lead to maladaptation. Green–blue spaces, for example, may create new nesting grounds for carriers of vector-borne diseases, increase pollen and allergies (Kabisch et al., 2016), enlarge freshwater use for irrigation (Reyes-Paecke et al., 2019) and could raise climate equity and justice issues such as green gentrification (Yazar et al., 2019). Similarly, air conditioning and cooling devices are considered highly effective but have low economic and social feasibility as well as negative trade-offs due to increasing energy consumption, raising energy costs which is particularly challenging for the poor (Section 13.8.1.1), enhancing the UHI effect and increasing noise pollution (Fernandez Milan and Creutzig, 2015; Hunt et al., 2017; Macintyre et al., 2018).

The solution space for implementing health adaptation options is slowly expanding in Europe. Health adaptation can build on, and integrate into, established health system infrastructures, but these differ significantly across Europe, as do existing capacities to deal with climate-related extreme events (Austin et al., 2016; Austin et al., 2018; Orru et al., 2018; Watts et al., 2018; Austin et al., 2019; Martinez et al., 2019). Despite some

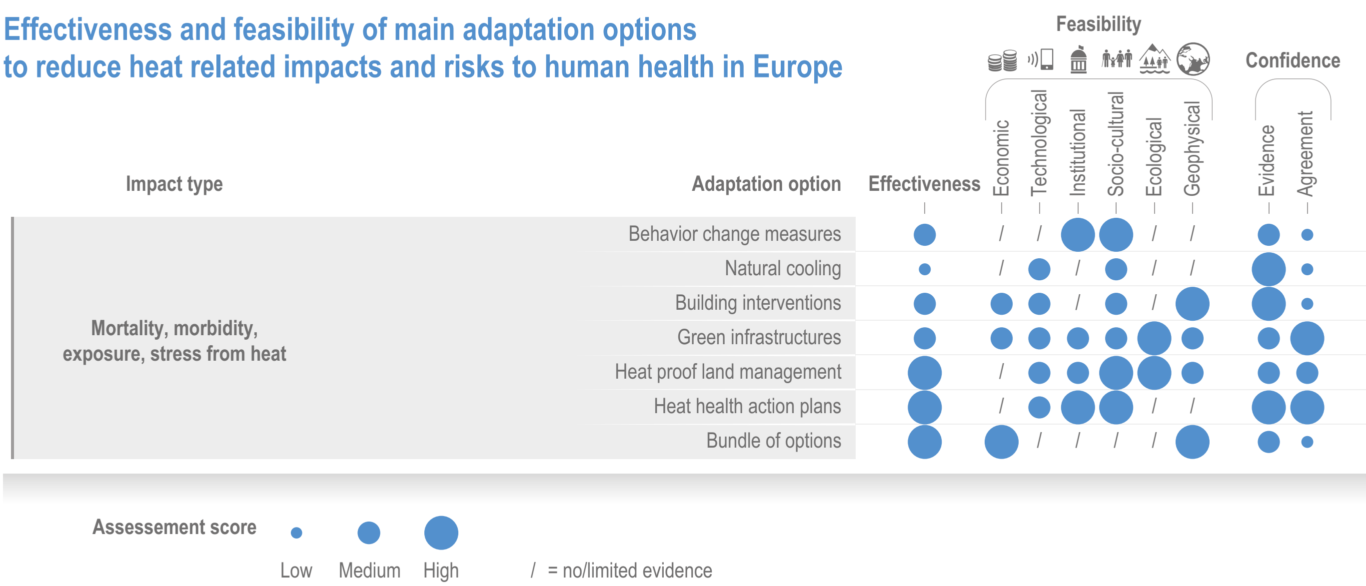


Figure 13.24 | Effectiveness and feasibility of the main adaptation options to reduce heat-related impacts and health risks in Europe (Section SM13.9, Table SM 13.19)

progress, limited mainstreaming of climate change has been observed, particularly due to low societal pressure to change, confidence in existing health systems and lack of awareness of links between human health and climate change (*medium confidence*) (Austin et al., 2016; WHO, 2018b; Watts et al., 2021). Coordination of health adaptation actions across scales and between public sectors is needed to ensure timely and effective responses for a diversity of health impacts (*high confidence*) (Austin et al., 2018; Ebi et al., 2018). Key enabling conditions to extend the solution space include increasing the role for national and regional governments in facilitating knowledge sharing across scales, allocating dedicated financial resources, and creating dedicated knowledge and policy programmes on climate and health (Wolf et al., 2014; Akin et al., 2015; Curtis et al., 2017). Investing in public healthcare systems more broadly increases their capacity to respond to climate-related extreme events and will ensure wider societal benefits as the COVID-19 pandemic has demonstrated (Cross-Chapter Box COVID in Chapter 7).

Despite a range of options available, there are limits to how much adaptation can take place, and residual risks remain. These risks are predominantly discussed in the context of excess mortality and morbidity due to heat extremes (Hanna and Tait, 2015; Martinez et al., 2019). Future heatwaves are expected to stretch existing adaptation interventions well beyond levels observed in response to the observed events of 2003 and 2010 (Section 13.10.2.1; Hanna and Tait, 2015).

13.7.3 Knowledge Gaps

Literature on the link between public health, climate impacts, vulnerability and adaptation is skewed across Europe, with most studies focusing on region-specific impacts (e.g., flood injuries in WCE, heatwaves in SEU). In general, attributing health impacts to climate change remains challenging, particularly for mental health and well-being, (mal)nutrition and food quality and climate-sensitive infectious diseases, where other socioeconomic determinants play an important role. The connection between climate change and health risks under different socioeconomic development pathways is hardly studied comprehensively for Europe, with some exceptions for extreme events; however, these interactions seem to play an important role in better understanding projected risks and inform choices on adaptation planning.

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

The solution space for public health adaptation in Europe, and the effectiveness of levers for interventions, are hardly assessed. Although health adaptations are documented, these are particularly around mortality and injuries due to extreme events, predominantly floods (Section 13.2.1) and heatwaves (Section 13.7.1.1). There are very few studies assessing the barriers and enablers of health adaptations, nor systematic assessment of the effectiveness of (the portfolio of) options. Limited insights into what works, and where, hamper upscaling these insights across Europe and constrains the ability to evaluate whether investments in health adaptation have actually reduced risks.

13.8 Vulnerable Livelihoods and Social Inequality

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

13.8.1 Observed Impacts and Projected Risks

13.8.1.1 Poverty and Social Inequality

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

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

The health of the poor is disproportionately affected, for example, during heatwaves in the Mediterranean (Jouzel and Michelot, 2016). Women, those with disabilities and the elderly are disproportionately affected by heat (Section 13.7.1). Floods in the Western Balkans in 2014 resulted in heavy metal pollution of water and land threatening the health condition of the poorer rural population (Filijović and Đorđević, 2014). Access to water and sanitation is less available to poorer households and marginalised groups in Europe (Ezbakhe et al., 2019; Anthonj et al., 2020); this effect could be intensified by increasing water scarcity in certain parts of Europe under future climate change (Section 13.10.3).

Food self-provisioning is a widespread practice in many parts of Europe (Aleynikov et al., 2014; Corcoran, 2014; Church et al., 2015; Mustonen and Huusari, 2020), reaching over half of German rural areas (Vávra et al., 2018). While it strengthens resilience for disadvantaged households (Church et al., 2015; Boost and Meier, 2017; Promberger, 2017; Vávra et al., 2018; Ančić et al., 2019; Pungas, 2019) and renews their local knowledge, it can become a risk in regions with projected crop yield reductions (*high confidence*) (Hallegatte et al., 2016; Quiroga and Suárez, 2016; Myers et al., 2017b; Inuit Circumpolar Council, 2020), and after extreme weather events (Filijović and Đorđević, 2014).

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

Table 13.2 | Examples of losses and damages to vulnerable livelihoods in Europe, differentiated by category according to non-economic loss and damage (Table SM13.20)

Human life	Communal and production sites and intrinsic value
Sense of place	Agency and identity
Cultural artefacts	Psychological and emotional distressTeiltabellen zusammengezogen. Bitte prüfen.
Biodiversity and ecosystems	

Climate hazard	Change in exposure and vulnerability	Observed impact and/or projected risk
Loss of livelihood, culture, health and well-being of the Sámi and the Nenets		
Decrease and alterations in snow and ice sheet, unstable winter weather, especially in the form of rain-on-snow events; increased precipitation and thawing permafrost, in tundra; unstable loss/flux of marine ice cover	Land-use change (e.g., expansion of renewable energy) resulting in pasture loss and disconnection of ecosystems	Loss of livelihood (e.g., reindeer herding), food security (for cold-dependent species), culture, health (impact on safety; psychological impacts from stress to reindeer and indigenous way of life), and cultural and linguistic well-being; release of anthrax from permafrost soils in the Nenets area
Loss of key species in high-Arctic freshwater habitats, proliferation of introduced species and disruption of local food systems in Greenland, Finland, Sweden, northwest Russia and Scotland		
Warmer water temperatures in high-Arctic freshwater habitats (Section 13.3.1) increase productivity in oligotrophic systems and eventually lead to loss of oxygen in water; warming temperatures and changes to ice cover and cryosphere lead to access issues to freshwater fisheries.	Introduced Pacific pink salmon has expanded in range since the 1970s, affecting endemic species through competition and reducing their abundance. Increased nutrient loading of rivers and rapid expansion of algae increase the risks for cold-dependent fish.	Shifts in freshwater aquatic habitats and loss of endemic cold-dependent fish, such as Arctic char and Arctic salmon, cause disruptions to local food supply, and local extinctions threaten livelihood safety and cultural well-being.
Warmer winters leading to loss of income from ice fishing and cultural heritage in Finland		
The start of ice cover on lakes, e.g., Lake Puruvesi (Finland), has changed from November to February; ice breakup occurs much earlier in the year.	The quality of the water in the lakes used for fishing depend on ice cover during most of the year, and the season of open water is now much longer, increasing nutrient flow and loss of water quality in these lakes.	Lack of winter ice combined with delayed freeze-up and earlier ice breakup reduce fish harvest for important species by up to 50% and impacts local safety, ecosystems, oral-history maintenance and the local economy.
Changes to marine food web resulting in loss of Indigenous knowledge and food insecurity in Greenland		
Warmer ocean waters are moving further north (so-called atlantification of Greenland waters); higher temperatures are melting sea ice.	Traditional practices and knowledge based on sea ice uses and hunting are being lost; species are being replaced with southern fish.	Loss of Indigenous knowledge of how to deal with and use sea ice regarding species and navigation is occurring, as is loss of access to seals and walruses, as well as food insecurity.
Reduced yields on managed alpine grasslands decreasing the self-sufficiency of pastoral livestock farming in the Austrian, French and Swiss Alps		
Increase in heat, precipitation variability and agricultural as well as hydrological drought; less snow on the ground, increase in glacier melt, landslide susceptibility and erosion	Land-use change resulting in natural reforestation of abandoned pastoral land; shifts in alpine plant communities; more intensive cultivation of grasslands; change in agricultural markets and support policy	Abandonment of summer pastures and farms, with negative consequences for farming income, tourism, and cultural and aesthetic values

Reduced yields on semi-natural grasslands, compromising livestock feeding in winter and ultimately decreasing viability of pastoralism in the Spanish Pyrenees		
Higher temperatures and more variable precipitation, less snow, change in seasonality and drought	Demographic change, change in policy and market conditions, simplification of pastoral practices and agroecosystems, land abandonment or afforestation of marginal pastoral lands and intensification of more favourable lands in the lowlands, troublesome coexistence with tourism and nature conservation initiatives	Decreasing viability of pastoralism, concentration of pastoral production on most profitable locations for intensive rearing of livestock with abandonment of the rest of the land; pastoral land encroachment both by shrubs and other activities; grassland degradation; biodiversity loss
Retreating glaciers and changes in the landscape leading to loss of identity, culture and self-reliance in the Italian Alps (Alto Adige)		
Glacier volume loss from increasing temperatures	Vulnerability mainly driven by reliance on tourism	Loss of sense of community through shared memories, and history; sadness caused by the loss of what feels like 'home'; loss of well-being due to uncertainty and fear of the future
Drought resulting in a reduction of provisioning (water) and regulating services (protection against floods) in the Western and Eastern Alps, Iberian Mountains and Dinaric Mountains		
Increase in drought, particularly under high-end GWL	Forest management strategies, including that of natural forests, which can enhance or reduce vulnerability	Critical importance of alpine natural forests and meadows for regulating services; negative impacts of climate change found mainly at low elevations and for specific species (e.g., Norway spruce); decrease in soil moisture due to abandonment of pastoralism resulting in reduced water provision for downstream water users
Increase in sea temperature leading to shifts in distribution of cold-water species, reducing productivity at lower latitudes; artisanal fisheries in southern European coastal areas (Mediterranean) that rely on local, nearshore stocks can have difficulties to adapt		
Increase in sea temperature	Substitution of artisanal fisheries by industrial fisheries; less support by governments; shift in employment (e.g., tourism) which does not match the skill sets, education or desires of small-scale fishers; national quota system leading to prices too high to buy or lease quotas and an immense amount of bureaucracy and regulations	Due to their low investment capacity and boat size, fishers are limited in their movement to other fishing places when local fish stocks decline. Increasing sea temperatures are increasing the threat of invasive species in coastal ecosystems.

13.8.1.2 Migration and Displacement of People

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

Migration of people within Europe is predominantly triggered by economic disparities among European countries (Fischer and Pfaffermayr, 2018). There is *limited evidence* and *low agreement* for climate-driven impacts on these movements (Hoffmann et al., 2020). Small-scale climate-induced displacement within Europe occurs in the aftermath of flood and drought disasters and over short distances (Cattaneo et al., 2019). The unequal distribution of future climate risks (Section 13.1) and adaptive capacity across European regions may increase pressure for internal migration (Williges et al., 2017; Forzieri et al., 2018). For instance, projected SLR (Section 13.2.1; Cross-Chapter Box SLR in Chapter 3) may result in planned relocation of coastal settlements and inland migration in the UK, the Netherlands and the northern Mediterranean (Mulligan et al., 2014; Antonioli et al., 2017). The number of people living in areas at risk in Europe is projected to increase with future SSPs increasing exposure (Merkens et al., 2016; Byers et al., 2018; Harrison et al., 2019).

13.8.1.3 Loss and Damage to Vulnerable Livelihoods in Europe

A number of livelihoods maintaining unique cultures in Europe are particularly vulnerable to climate change (Table 13.2): indigenous communities in the European polar region because of their dependence

Box 13.2 | Sámi Reindeer Herding in Sweden

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

Temperatures in Arctic and sub-Arctic regions have increased on average by 2°C over the past 30 years (*very high confidence*) (Ranasinghe et al., 2021). Future warming is expected to further increase winter precipitation (*high confidence*) (Ranasinghe et al., 2021) and rain-on-snow events, creating a hard ice crust on the snow after refreezing (Bokhorst et al., 2016; Rasmus et al., 2018).

The documented and projected impacts on reindeer are complex and varied. Warming and CO_2 increase result in higher plant productivity (Section 13.3), changes in plant community composition and higher parasite harassment; unstable ice conditions affect migration; extreme weather conditions during critical winter months, more frequent forest fires and changes in plant community composition reduce pasture quality (*medium confidence*) (see Figure Box 13.2.1; Mallory and Boyce, 2018). High snow depth and rain-on-snow events impede reindeer access to ground lichen in winter and delay spring green-up during the critical calving period; both cause malnutrition and negative impacts on reindeer health, mortality and reproductive success (*medium confidence*) (Hansen et al., 2014; Forbes et al., 2016; Mallory and Boyce, 2018). Lower slaughter weights and increased mortality reduce the income of herders (*high confidence*) (Tyler et al., 2007; Helle and Kojola, 2008).

Reindeer herders already autonomously adapt to changing conditions through flexible use of pastures and supplementary feeding (*high confidence*), reducing and thereby hiding some of the negative impacts of climate change (Uboni et al., 2016). However, adaptive herding practices have themselves added significant burden through increased workload, costs and stress (*high confidence*) (Furberg et al., 2011; Löf, 2013; Rosqvist et al., 2021). Supplementary feeding increases the risk of infectious diseases and implies culturally undesirable herding practices (*low confidence*) (Lawrence and Kløcker Larsen, 2019; Tryland et al., 2019).

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

Reindeer herding is significantly affected by climate change directly and indirectly (Figure Box 13.2.1) (Pape and Löffler, 2012; Andersson et al., 2015). The cumulative effects of land-use and climate change have already increased vulnerability and reduced the adaptive capacity of reindeer herding to the extent that its long-term sustainability is threatened (*medium confidence*) (Löf, 2013; Horstkotte et al., 2014; Kløcker Larsen et al., 2017).

Maintaining and improving the solution space to adapt reindeer herding is crucial for reducing existing impacts and projected risks of climate and land-use change (Andersson et al., 2015; Turunen et al., 2016; AMAP, 2017; Hausner et al., 2020). Lack of control over land use is the biggest and most urgent threat to the adaptive capacity of reindeer herding and the right of Sámi to their culture (*high confidence*) (Pape and Löffler, 2012; Andersson et al., 2015; Kløcker Larsen and Raitio, 2019).

Box 13.2 (continued)

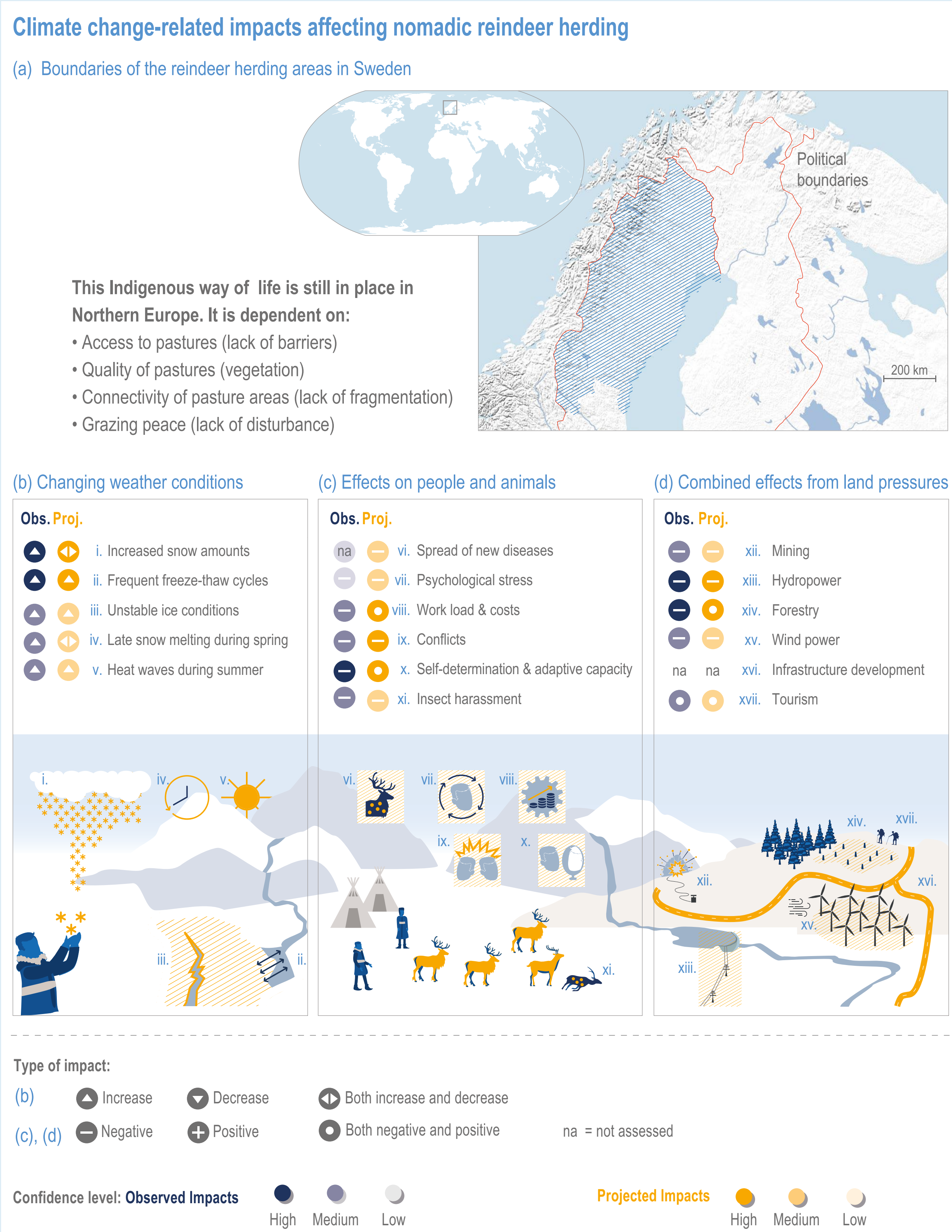


Figure Box 13.2.1 | Cumulative impacts of climate and land-use change on reindeer herding as a traditional, semi-nomadic Sámi livelihood (Table SM13.21)

on cryosphere ecosystems (*high confidence*) (Cross-Chapter Paper 6; Hayashi, 2017; Huntington et al., 2017; Hock et al., 2019; Meredith et al., 2019; Inuit Circumpolar Council, 2020; Douville et al., 2021; Fox-Kemper et al., 2021) and communities dependent on small-scale fisheries, traditional farming and unique cultural landscapes (*medium confidence*) (Kovats et al., 2014; Ruiz-Díaz et al., 2020).

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

13.8.1.4 Cultural and Natural Heritage

Climate change poses a serious threat to the preservation of cultural heritage in Europe, both tangible and intangible (*high confidence*) (Haugen and Mattsson, 2011; Daire et al., 2012; Dupont and Van Eetvelde, 2013; Macalister, 2015; Phillips, 2015; Fatorić and Seekamp, 2017; Graham et al., 2017; Carroll and Aarrevaara, 2018; Sesana et al., 2018; Iosub et al., 2019; Daly et al., 2020). At higher GWL, building exteriors and valuable indoor collections become at risk (Leissner et al., 2015). Coastal heritage, such as along the North Sea and Mediterranean, are under water-related threats (see Box 13.1; Cross-Chapter Paper 4; Reimann et al., 2018b; Walsh, 2018; Harkin et al., 2020).

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

13.8.2 Solution Space and Adaptation Options

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

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

IKLK, embedded, for example, in fishers, farmers and navigators, can be a vehicle for detecting, monitoring and observing impacts (Section 13.11.1.3; Arctic Council, 2013; Brattland and Mustonen, 2018; Madine et al., 2018; Meredith et al., 2019). Regarding risks to northern traditional livelihoods and indigenous communities, small-scale adaptation is taking place, for example, by ecological restoration of habitats (Section 13.3; Mustonen and Kontkanen, 2019); however, limited access to resources outside the jurisdictions of the communities limits the scope of community-based adaptation (Arctic Council, 2013; Mustonen et al., 2018; Meredith et al., 2019).

European cultural heritage in general and world heritage sites specifically lack adaptation strategies to preserve key cultural assets (Haugen and Mattsson, 2011; Howard, 2013; Heathcote et al., 2017; Reimann et al., 2018b; Harkin et al., 2020). Key reasons are the underdeveloped adaptation actions available, resources for implementing them and the absence of overarching policy guidance (Phillips, 2015; Fernandes et al., 2017; Sesana et al., 2018; Daly et al., 2020; Fatorić and Biesbroek, 2020; Sesana et al., 2020).

13.8.3 Knowledge Gaps

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

13.9 Inter-regional Impacts, Risks and Adaptation

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

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

Recent literature (Wenz and Levermann, 2016; Hedlund et al., 2018; Benzie et al., 2019) strengthens the confidence in the AR5 statement that 'with increasing globalisation, the impacts of climate change outside the European region are *likely* to have implications for countries

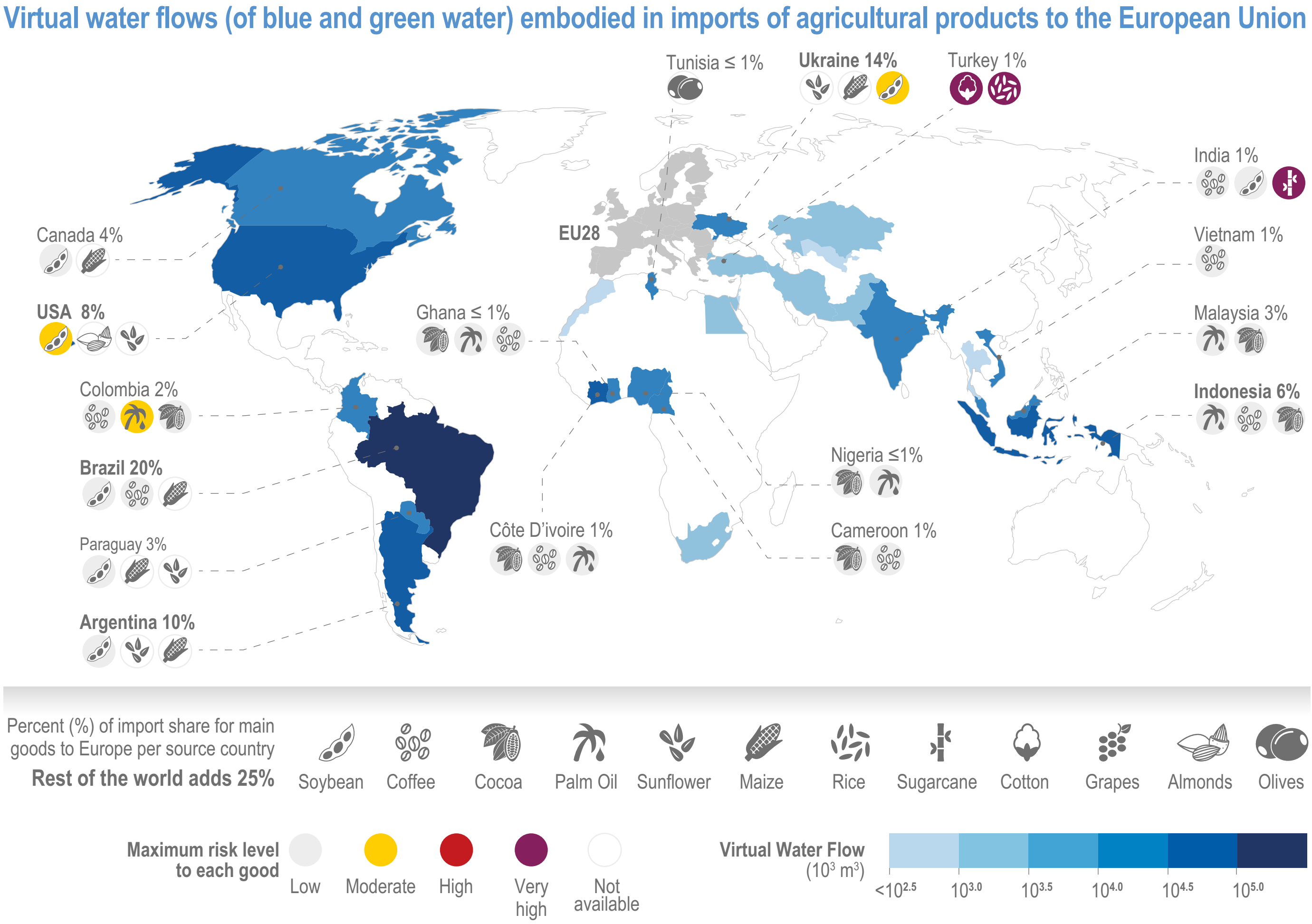


Figure 13.25 | Trans-European climate risks in trade: virtual water flows embodied in agricultural imports to Europe in 2018 and the vulnerability to climate change of the most important crops in the originating countries (Dolganova et al., 2019; Ercin et al., 2019)

within the region' (Kovats et al., 2014). The exposure of European countries to trans-European climate impact and risk pathways varies depending on their territorial settings, national policies and position in the global supply chain (*high confidence*) (Berry et al., 2015; Hedlund et al., 2018; Benzie et al., 2019). There is *limited evidence* that Europe is more exposed to inter-regional risks than North America, and less than Africa and Asia (Hedlund et al., 2018). The social and governance context in Europe make the region less vulnerable to conflicts driven by climate change than other regions, at least up to 2°C GWL (Buhaug et al., 2014; Mach et al., 2019; Ide et al., 2020).

Climate risks in other parts of the world can be transmitted to European economies via trade networks (Figure 13.25). European agricultural imports exert a high water footprint in originating countries already today (Dolganova et al., 2019; Ercin et al., 2019), and some crop imports, such as tropical fruits, are highly vulnerable to future climate change (Brás et al., 2019). Simultaneous breadbasket failures, and trade restrictions, increase risks to food supply (*medium confidence*) (Fellmann et al., 2014; d'Amour et al., 2016; Gaupp et al., 2017; Gaupp et al., 2020). There is *high confidence* that the European economy could be negatively affected by supply chain disruptions due to flooding destroying facilities, heatwaves and malaria reducing productivity in labour-intensive industries and regions (Section 13.7.1), and SLR affecting ports and cities along coastlines (Section 13.6.1.2; Nicholls and Kebede, 2012; Challinor, 2016; Wenz and Levermann, 2016; Hedlund et al., 2018; Koks, 2018; Szewczyk et al., 2018; Willner et al., 2018; Knittel et al., 2020; Kulmer et al., 2020; Carter et al., 2021).

13.9.2 Inter-regional Consequences of Climate Risks and Adaptation Emerging from Europe

New literature since AR5 suggests that climate risks in Europe can propagate worldwide in response to 3°C GWL (*medium confidence*). Key concerns include climate impacts on European agriculture threatening global food security (Section 13.5.1; Berry et al., 2017; van der Velde et al., 2018) and the European demand limiting the adaptation potential for ecosystems in South America, Africa and Asia (IPBES, 2018; Pendrill et al., 2019; Fuchs et al., 2020). Emerging literature suggests that coastal and riverine flood risks in Europe could be amplified through the global financial system and generate a systemic financial crisis (Figure 13.26; Mandel et al., 2021). For 3°C GWL and without adaptation, northern Atlantic flight routes and European ports are projected to be increasingly disrupted by changing winds, waves and SLR (Section 13.6.1.2; Williams and Joshi, 2013;

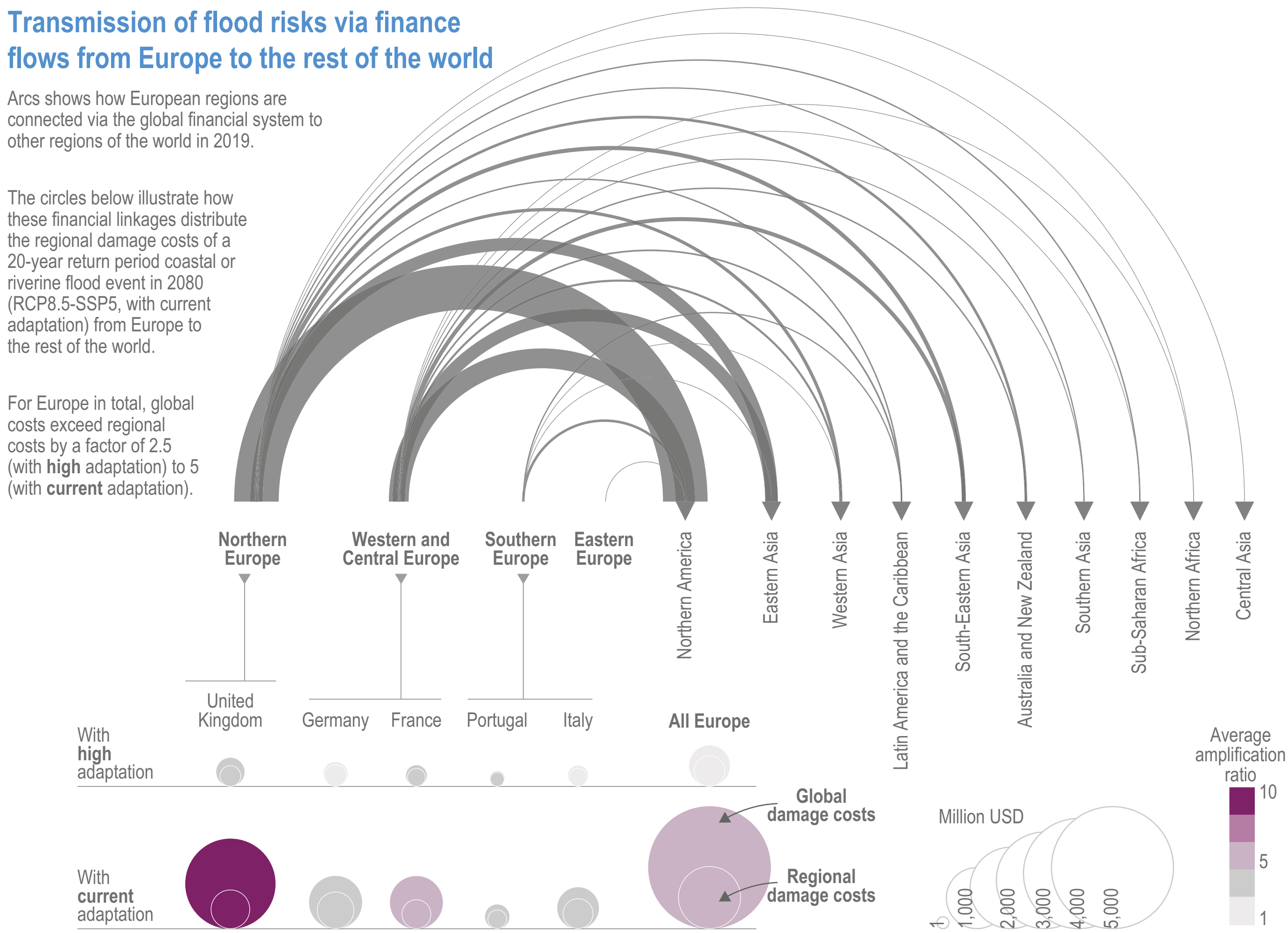


Figure 13.26 | The transmission of coastal and riverine flood risks via finance flows from Europe to the rest of the world. (From Mandel et al., 2021).

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

13.9.3 European Territories Outside Europe

European territories outside Europe are critically exposed to climate risks such as increased forest fires (e.g., in Russian Siberia) (Chapter 10; Sitnov et al., 2017), climate-change-induced biodiversity losses and SLR (e.g., in British, Spanish, Portuguese, French and Dutch overseas regions and territories) (Chapters 12, 15; Ferdinand, 2018; Sieber et al., 2018). Climate risks emerging from these territories include smoke and dust from Siberian forest fires (Sitnov et al., 2017) and, depending on European health-risk mitigation measures, dengue and other mosquito-transmitted diseases (Section 13.7; Schaffner and Mathis, 2014). Some MPAs (Section 13.4.3) in European overseas territories are increasingly affected by changes originating in far-field upstream areas. These changes ultimately undermine their ability to curb biodiversity losses and provide ecosystem services (Schaffner and Mathis, 2014; Robinson et al., 2017). Adaptation options and regulations developed within Europe apply in these territories, despite *low confidence* that they meet local and regional adaptation challenges and address the aspiration for social justice, promotion of local solutions and consideration of traditional knowledge (Ferdinand, 2018; Terorotua et al., 2020).

13.9.4 Solution Space and Adaptation Options

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

13.10 Detection and Attribution, Key Risks and Adaptation Pathways

13.10.1 Detection and Attribution of Impacts

Since AR5, scientific documentation of observed changes attributed to global warming have proliferated (*high confidence*). These include ecosystem changes detected in previous assessments, such as earlier annual greening and onset of faunal reproduction processes, relocation of species towards higher latitudes and altitudes (*high confidence*), and impacts of heat on human health and productivity (*high confidence*) (Figure 13.27; Table SM13.22; Vicedo-Cabrera et al., 2021). Formal attribution of impacts of compound events to anthropogenic climate change is just emerging, for example, in the recent crop failures due to heat and drought (Toreti et al., 2019a). Also, there is *high agreement* and *medium evidence* that particular events attributed to climate

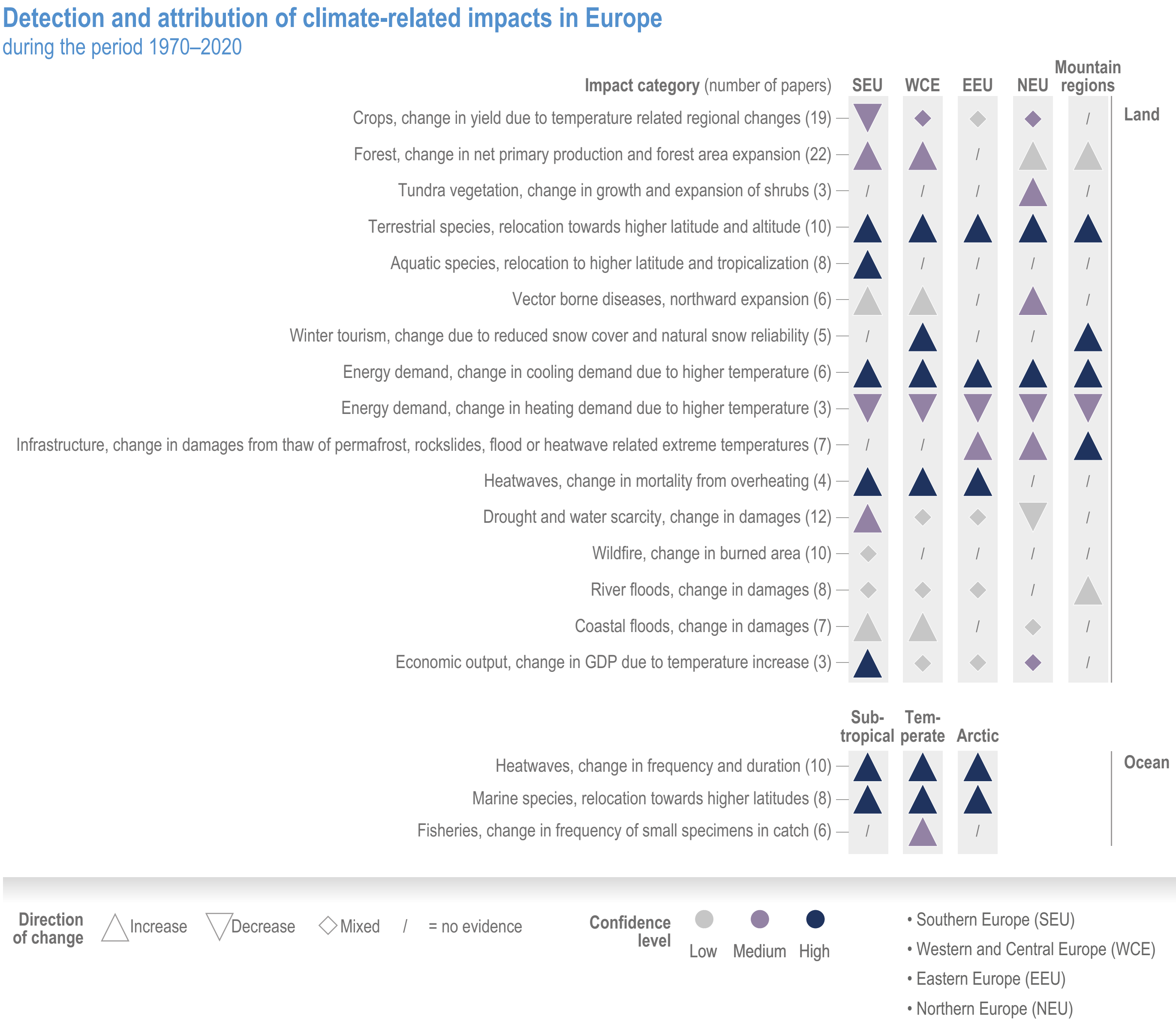


Figure 13.27 | Detected changes and attribution (D&A) of climate-related impacts on land (top) and in the ocean (bottom) are shown. Assessment is based on peer-reviewed literature in this chapter that reported observed evidence with at least 90% significance (usually with 95% significance or more) (Table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

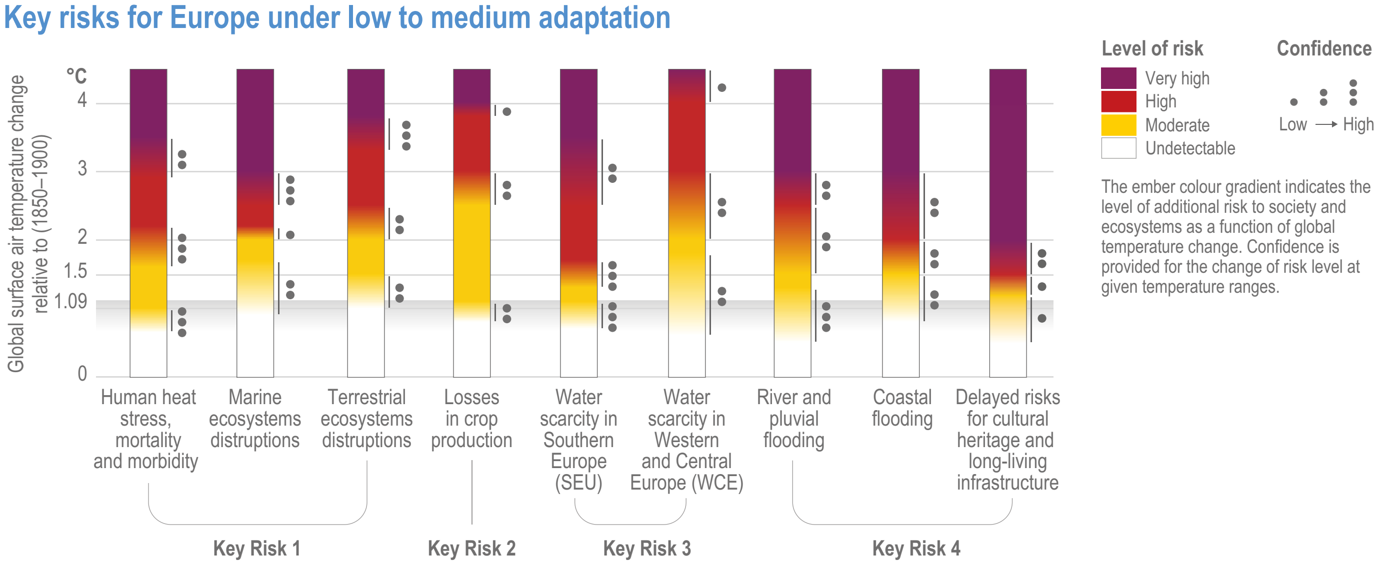


Figure 13.28 | Burning ember diagrams for low to medium adaptation. (More details on each burning ember are provided in Sections 13.10.2.1–13.10.2.4 and SM13.10. Some burning embers are shown again in Figures 13.29–13.34 alongside burning embers with high adaptation.)

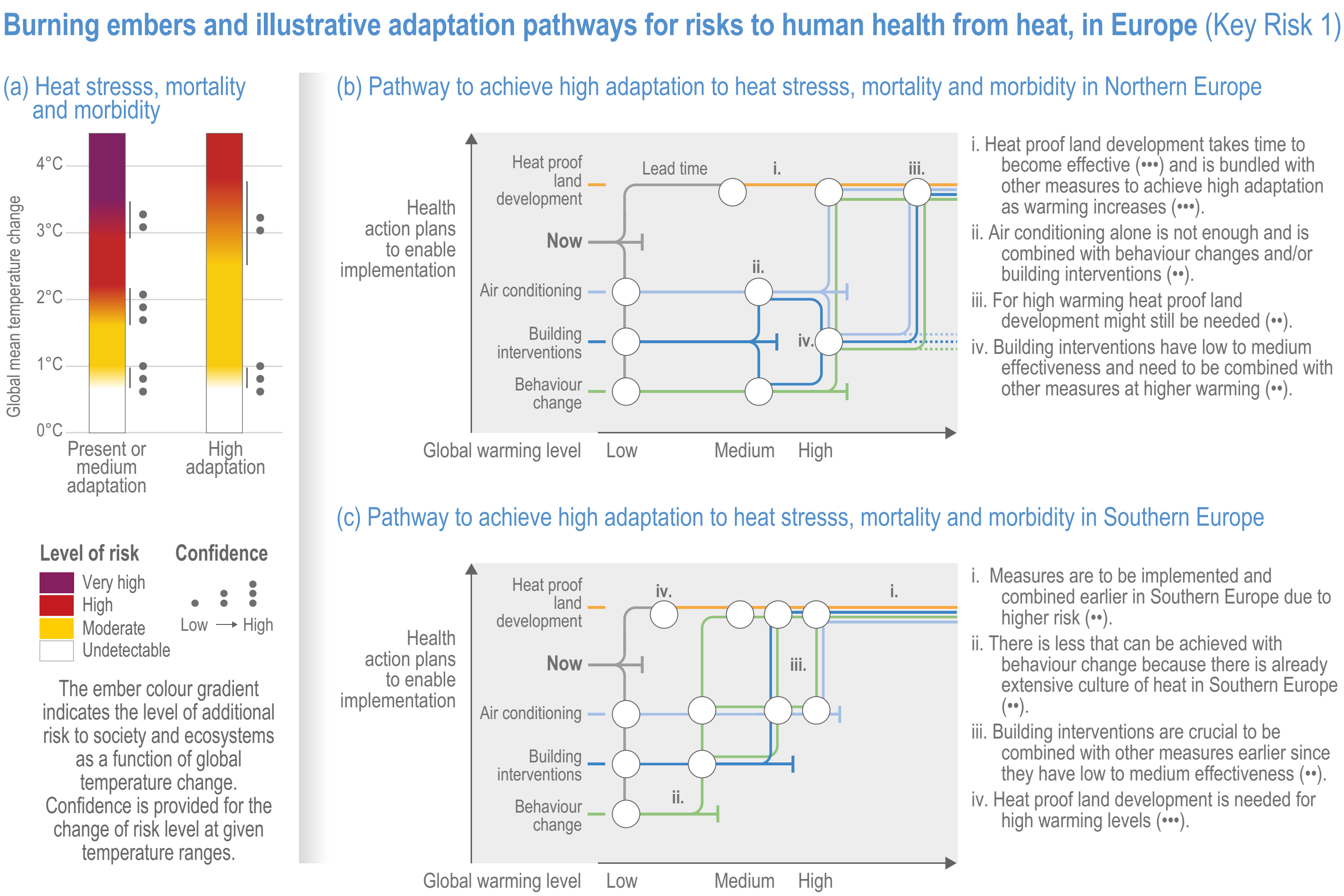


Figure 13.29 | Burning embers and illustrative adaptation pathways for risks to human health from heat (Key Risk 1)

(a) Burning ember diagrams for the risk to human health from heat are shown. The low to medium adaptation scenario corresponds to present, SSP2 and SSP4 socioeconomic conditions. The high adaptation includes SSP1 and adaptation needed to maintain current risk levels.

(b,c) Illustrative adaptation pathways for NEU (top) and SEU (bottom), and key messages based on the feasibility and effectiveness assessment in Figures 13.20 and 13.24. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars imply that the measure has reached a tipping point (Tables SM13.24, SM13.25).

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

13.10.2 Key Risks Assessment for Europe

Key risks (KRs) are defined as a subset of climate risks that can potentially become, or are already, severe (Section 16.5). The selection process included a review of KRs already identified in AR5 Chapter 23 (Kovats et al., 2014) and a review of the large body of new evidence on projected risks presented in Sections 13.2–13.9. Key risks are reinforced by evidence from the detection and attribution assessment (Section 13.10.1) and new evidence from WGI AR6 Chapters 11 and 12 on regional climatic impact drivers and extremes (Ranasinghe et al., 2021; Seneviratne et al., 2021). Several expert opinion workshops of lead and contributing authors led to further refinements, adjustment and consensus building around the characteristics of KRs, which ultimately guided the construction of the burning embers (Figures 13.28–13.32; SM13.10). There is *high confidence* that under low or medium adaptation, high to very high risks are projected at 3°GWL (Figure 13.28; Sections 13.10.2.1–13.10.2.4). Most risks are assessed as moderate up to 1.5°GWL (Figure 13.28).

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

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

Key risk 1 has cut across humans and ecosystems, and severe consequences are mainly driven by an increasing frequency, intensity and duration of heat extremes and increasing average temperatures (*high confidence*) (Urban, 2015; Forzieri et al., 2017; Feyen et al., 2020; Naumann et al., 2020; Ranasinghe et al., 2021). The risk of human heat stress and mortality is largely influenced by underlying socioeconomic pathways, with consequences being more severe under SSP3, SSP4 and SSP5 scenarios than SSP1 (*very high confidence*) (Figure 13.22; Sections 13.6.1.5.2, 13.7.1.1; Hunt et al., 2017; Kendrovski et al., 2017; Rohat et al., 2019; Casanueva et al., 2020). The SSPs impact natural systems as well but are not yet well studied. The impact of warming in marine systems are often synergistic with SLR in coastal systems and ocean acidification driven by the rise in CO_2, while habitat fragmentation and land use have important synergies in terrestrial systems (*high confidence*) (Sections 13.3.1.2, 13.4.1.2). More intense heatwaves on land and in the ocean, particularly in Mediterranean Europe (Section 13.4; Cross-Chapter Paper 4; Darmaraki et al., 2019b; Fox-Kemper et al., 2021), are expected to cause mass mortalities of vulnerable species, and species extinction, altering the provision of important ecosystem goods and services (Marbà and Duarte, 2010).

The burning embers on risks for humans (Figure 13.29a) differentiate between present and medium adaptation conditions, drawing on SSP2 and SSP4 (and to a lesser extent SSP3), and high adaptation conditions, drawing on SSP1 and papers using various temperature adjustment methods (Table SM13.25). There is *high confidence* that the risk is already moderate now because it has been detected and attributed with *high confidence* (Section 13.10.1). The transition from moderate to high risk for human health is assessed to happen after 1.5°C GWL in a scenario with present to medium adaptation and implies a two- to threefold increase (compared with moderate risk levels) in magnitude of consequences such as mortality, morbidity, heat stress and thermal discomfort (Rohat et al., 2019; Casanueva et al., 2020; Naumann et al., 2020). At this level, the risk will also become more persistent across the continent due to increase in heat events exceeding critical thresholds for health (*high confidence* on the direction of change and temperature transition, but *medium confidence* on the magnitude) (Ranasinghe et al., 2021).

The burning embers on risk for terrestrial and marine ecosystems, and some of their services, are shown in Figure 13.28 (second and third ember from the left) (Tables SM13.26, SM13.27). The transition to moderate risk is currently happening as warming already results in changes in timing of development, species migration northward and upwards, and desynchronisation of species interactions, especially at the range limits, with cascading and cumulative impacts through ecosystems and food webs (*high confidence*) (Sections 13.3, 13.4; Figures 13.8, 13.12). While some terrestrial ecosystems are already impacted today, such as Alpine, cryosphere and peatlands, the impacts are not widespread and severe yet across a wide range of terrestrial systems. Around 2°C GWL, losses accelerate in marine ecosystem and appear across systems, including habitat losses especially in coastal wetlands (Roebeling et al., 2013; Clark et al., 2020), biodiversity and biomass losses (Bryndum-Buchholz et al., 2019; Lotze et al., 2019) and ecosystem services such as fishing (*high confidence* on the direction of change, but *medium confidence* on the local and regional magnitude) (Raybaud et al., 2017). The transition is happening at slightly higher warming in terrestrial systems due to a higher number of thermal refugia in terrestrial systems causing relocation but not already severe impacts (*medium confidence*) (Chapter 2).

There is *medium confidence* that high adaptation or conditions posing low challenges for adaptation (e.g., SSP1) in the context of human health can delay the transition from moderate to high risk (Åström et al., 2017; Ebi et al., 2021). The illustrative adaptation pathways in Figure 13.29b,c show the sequencing of options to a high adaptation future for NEU and SEU. Whether or not adaptation measures are effective to reduce risk severity for people's health depends on local context (*high confidence*) (Figure 13.29; Sections 13.6.2, 13.7.2). Some adaptation options are found to be highly effective across Europe irrespective of warming levels, including air conditioning and urban planning (*high confidence*) (Sections 13.6.2, 13.7.2; Jenkins et al., 2014b; Donner et al., 2015; Dodoo and Gustavsson, 2016; Åström et al., 2017; Dino and Meral Akgül, 2019; Venter et al., 2020), although air conditioning increasingly faces some feasibility constraints (Figure 13.20). Building interventions alone have low to medium effectiveness independent of the region. Many behavioural changes, such as personal and home heat protection, have already been implemented in SEU (Section 13.7.2; Martinez et al., 2019). To reach high adaptation, a combination of low, medium and high effectiveness measures in different sectors and sub-regions is needed, many of which entail systems' transformations (e.g., heat-proof land management) (Chapter 16) and remain effective at higher warming levels (*medium confidence*) (Díaz et al., 2019). These transformations have long lead times, thereby requiring timely start of implementation including regions that are not yet experiencing high heat stress (e.g., NEU) (*high agreement, medium evidence*).

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

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

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

Key risk 2 encompasses agriculture productivity (Figure 13.30a). It is mainly driven by the increase in the likelihood of compound heat and dry conditions and extreme weather, and their impact on crops. There is *high confidence* that climate change will increase the likelihood of concurrent extremely dry (Table SM13.28) and hot warm seasons with higher risks for WCE, EEU (particularly northwest Russia) and SEU leading to enhanced risk of crop failure and decrease in pasture quality (Section 13.5.1; Zscheischler and Seneviratne, 2017; Sedlmeier et al., 2018; Seneviratne et al., 2021). The risk is already moderately severe due to multiple crop failures in the past decade in WCE and Russia (Section 13.5.1; Hao et al., 2018; Pfleiderer et al., 2019; Vogel et al., 2019). Under high-end scenarios, heat and drought extremes are projected to become more frequent and widespread as early as mid-century (Toreti et al., 2019a). For present to moderate adaptation and at least up to 2.5°GWL, negative consequences are mostly in SEU (Bird et al., 2016; EEA, 2019c; Moretti et al., 2019; Feyen et al., 2020). The transition from moderate to high risk is projected to happen around 2.7°C GWL when hazards and risk will become more persistent and widespread in other regions (Section 13.1; Deryng et al., 2014; Donatelli et al., 2015; Webber et al., 2018; Ceglar et al., 2019; Ranasinghe et al., 2021; Seneviratne et al., 2021). This temperature increase will trigger shifts in agricultural zones, onset of early heat stress, losses in maize yield of up to 28% across EU-28 and regional disparity in losses and gains in wheat, which are not able to offset losses across the continent (Deryng et al., 2014; Szewczyk et al., 2018; Ceglar et al., 2019). There will be also broader adverse impacts such as reduction of grassland biomass production for fodder, increases in weeds and reduction in pollination (*medium confidence*) (Castellanos-Frias et al., 2016; Nielsen et al., 2017; Brás et al., 2019). Combined with socioeconomic development, increased heat and drought stress, and reduced irrigation water availability, in SEU are projected to lead to abandonment of farmland (Holman et al., 2017). Around 4°C GWL, the risk is very high due to persistent heat and dry conditions (Ben-Ari et al., 2018) and the emergence of losses also in NEU which would be much higher without the assumed CO_2 fertilisation (Deryng et al., 2014; Szewczyk et al., 2018; Harrison et al., 2019).

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

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

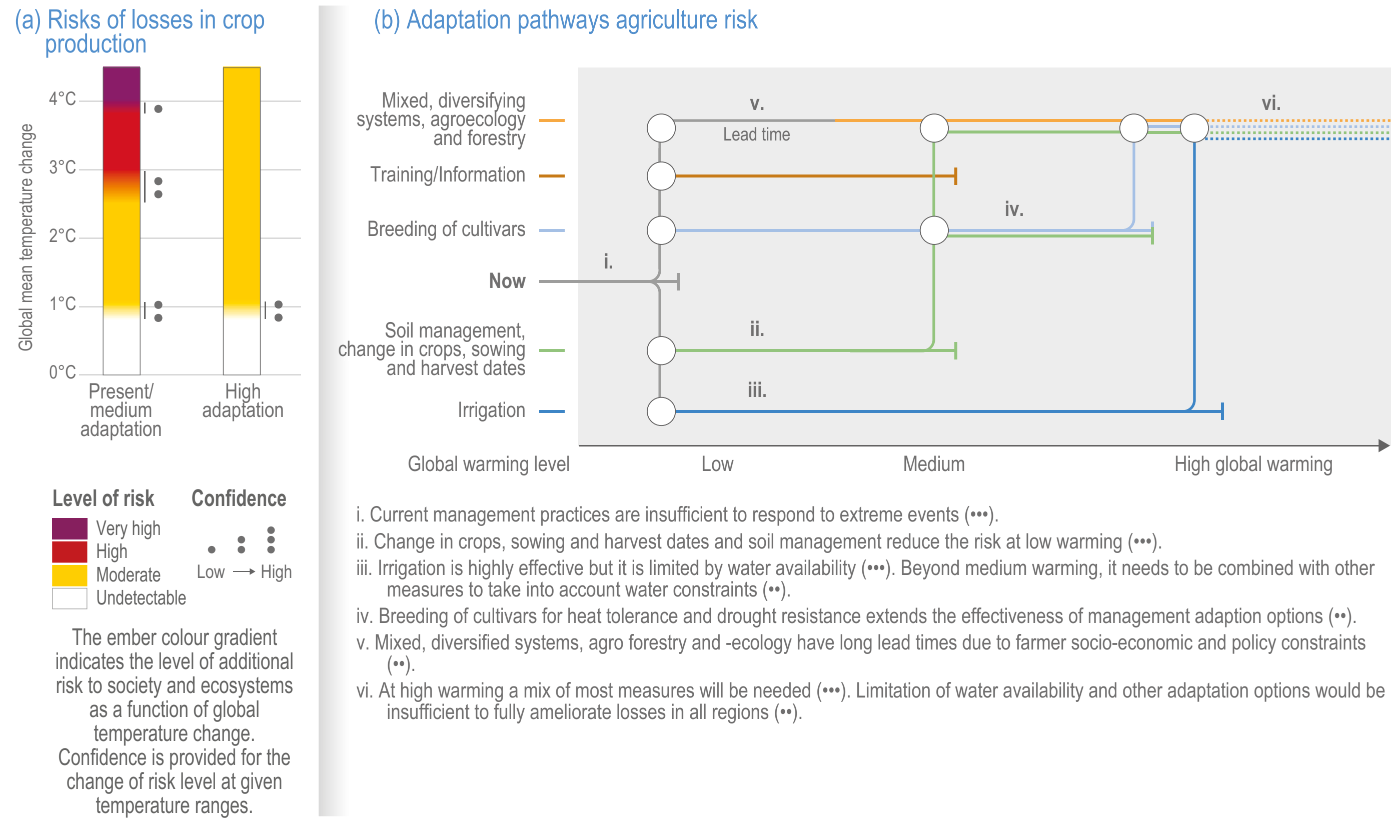


Figure 13.30 | Burning embers and illustrative adaptation pathways for losses in crop production (Key Risk 2)

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

(b) Illustrative adaptation pathways and key messages based on the feasibility and effectiveness assessment in Figure 13.14. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars imply that the measure has reached a tipping point (Table SM13.28).

13.10.2.3 KR3: Risk of Water Scarcity to Multiple Interconnected Sectors

Risks related to water scarcity across multiple sectors can become severe in WCE and, to a much larger extent, in SEU based on projections of drought damage, population and sectors exposed, and they increase in water exploitation (Figure 13.31a; Table SM13.29). In EEU, uncertainty in hydrological drought projections and risk consequences is higher (Greve et al., 2018; Ranasinghe et al., 2021; Seneviratne et al., 2021) and the available number of publications is lower, not allowing a conclusion on how risk levels change with GWL. Yet, there is emerging evidence that drought-related risks increase with warming beyond 3°C GWL also in EEU (Seneviratne, 2021, for hydrological drought and 4°C GWL; Kattsov and Porfiriev, 2020). Evidence from the detected changes and attribution assessment suggests that the risk is already moderate in SEU (e.g., 48 million people exposed to moderate water scarcity between 1981 and 2010) (*high confidence*) (Section 13.10.1; Figure 13.31a).

Risk of water scarcity has a high potential to lead to cascading impacts well beyond the water sector. These materialize in a number of highly interconnected sectors from agriculture and livestock farming to energy (hydropower and cooling of thermal power plants) and industry (e.g., shipping) (Blauhut et al., 2015; Stahl et al., 2016; Bisselink et al., 2020; Cammalleri et al., 2020). Extensive water extraction will augment pressures on water reserves, impacting the ecological status of rivers and ecosystems dependent on them (Grizzetti et al., 2017). Socioeconomic conditions contributing to severe consequences are when more residents settle in drought-prone regions, or when the share of agriculture in GDP declines (*high confidence*). For Europe, risks of water scarcity will be higher under SSP5 and SSP3 than under SSP1 (*medium confidence*) (Byers et al., 2018; Arnell et al., 2019; Harrison et al., 2019). Transition to high risks is projected to occur below 2°C GWL in SEU and be associated with more persistent droughts (Section 13.1.3), and at 2°C GWL to show a 54% increase of the population facing at least moderate levels of water shortage (Byers et al., 2018). This transition will happen at higher warming in WCE since risks are projected to increase less rapidly (transition between 2°C and 3°C GWL) (*medium confidence*) (Section 13.2.1.2; Byers et al., 2018). At 3°C GWL and beyond, water scarcity will become much more widespread and severe in already water-scarce areas in SEU (*high confidence*) and will expand to currently non-water-scarce regions in WCE (*medium confidence*) (Section 13.2.1.2; Bisselink et al., 2018; Naumann et al., 2018; Harrison et al., 2019; Koutroulis et al., 2019; Cammalleri et al., 2020; Spinoni et al., 2020). Decrease in hydropower potential in SEU and WCE are expected beyond 3°GWL (Figure 13.16).

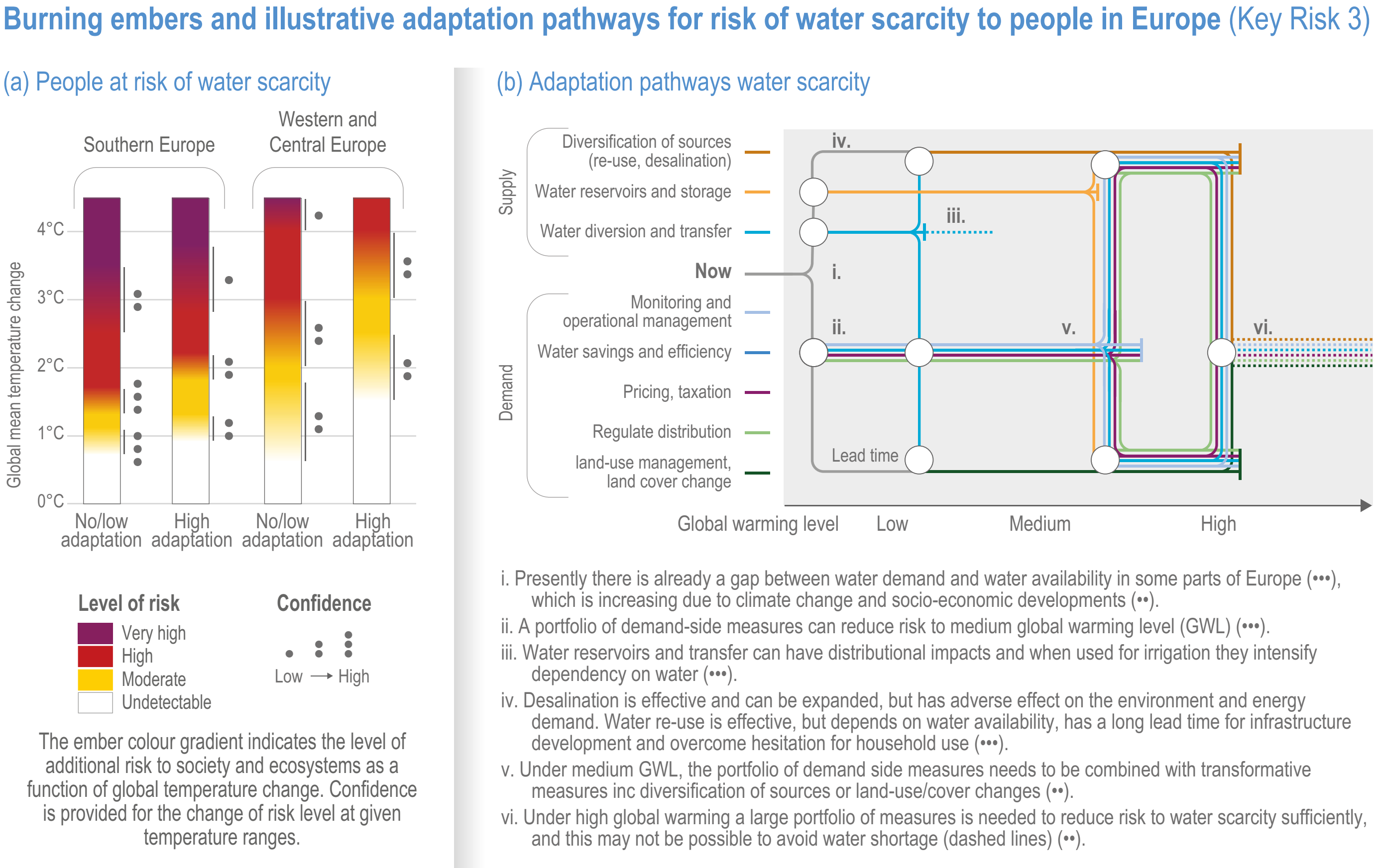


Figure 13.31 | Burning embers and illustrative adaptation pathways for risk of water scarcity to people (Key Risk 3)

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

(b) Illustrative adaptation pathways and key messages (see Figure 13.6). Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars imply that the measure has reached a tipping point (Table SM13.29).

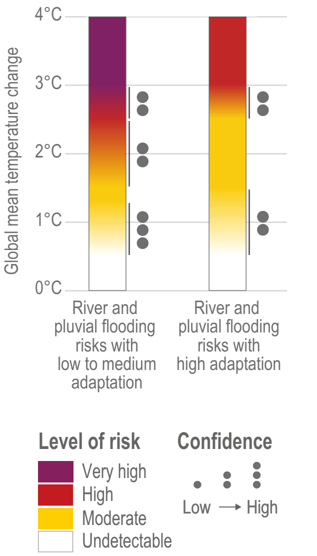
To reduce risk to water scarcity, adaptation measures, at both the supply and the demand side, have been suggested (Section 13.2.2; Figures 13.6, 13.31b; Garnier and Holman, 2019; Hagenlocher et al., 2019). Several measures are already in place showing high technical and institutional feasibility (Sections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

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

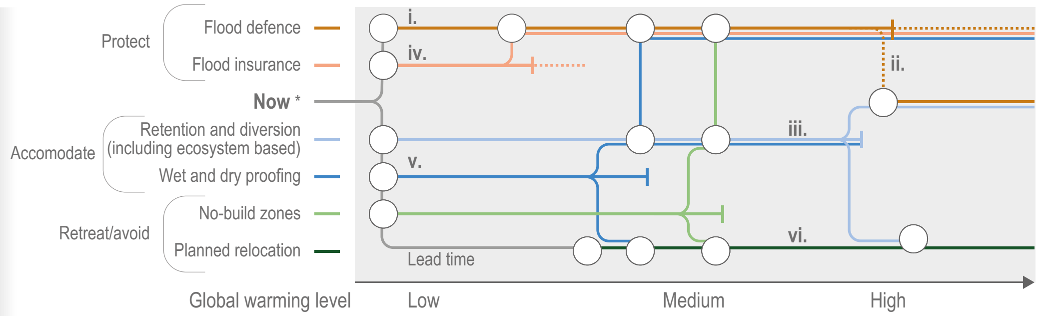
Damages and losses from coastal and river floods are projected to increase substantially in Europe over the 21st century (*high confidence*) (Section 13.2.1; SM13.10). Coastal areas have already started to be affected by SLR (see Box 13.1; Section 13.10.1) and human exposure to coastal hazards is projected to increase in the next decades (*high confidence*), but less under SSP1 (20%) than SSP5 (50%) by the end of the century (*medium confidence*) (Merkens et al., 2016; Reimann et al., 2018a). Under low adaptation (i.e., coastal defences are maintained but not further strengthened), severe consequences include an increase in expected annual damage by a factor of at least 20 for 1.5°C–2.1°C GWL (i.e., high risks) and by two to three orders of magnitude between 2°C and 3°C GWL in EU-28 (i.e., very high risk) (*medium confidence*) (Figures 13.28, 13.34c; Section 13.2.1.1; Vousdoukas et al., 2018b; Haasnoot et al., 2021b). Under high adaptation (i.e., lowlands are protected where it is economically efficient), expected annual damages still increase by a factor of 5 above 2°C GWL (Section 13.2; Vousdoukas et al., 2020). Sea levels are committed to rise for centuries (Fox-Kemper et al., 2021), submerging at least 10% of the territory in

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

(a) Inland flooding risks



(b) Adaptation pathways riverine flood risk



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

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

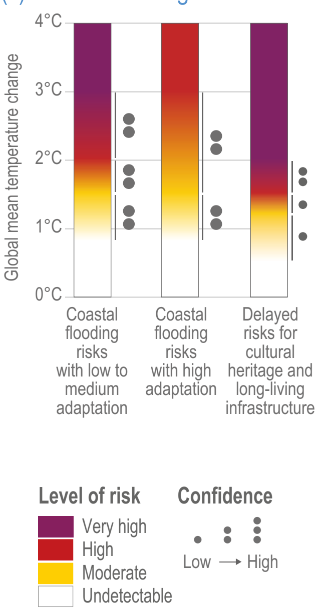
iii. Natural retention and diversion of peak flows can reduce risk effectively and have co benefits for the environment and climate mitigation. A combination with flood defenses in highly urbanized regions can further reduce risk (•••).

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

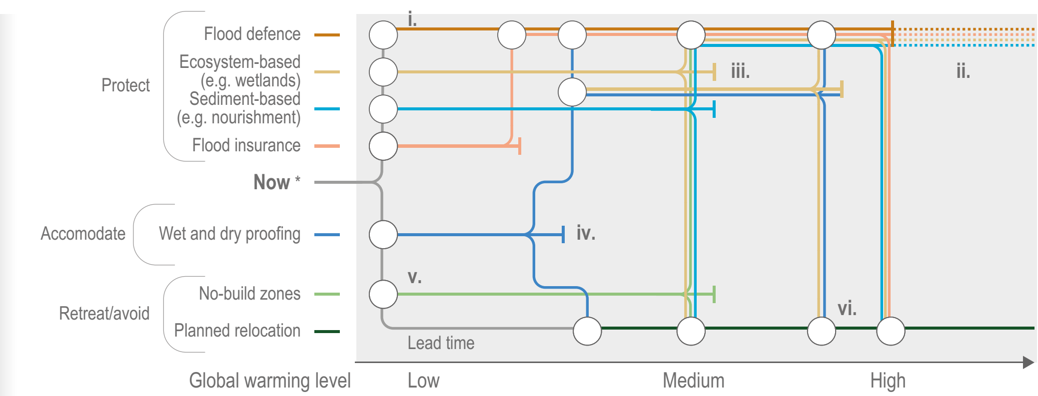
v. Wet and dry proofing can be taken at household level and can reduce residual risk as levees are raised (••).

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

(c) Coastal flooding risks



(d) Adaptation pathways coastal flood risk



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

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

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

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

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

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

* Mostly flood defences and early warning.

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

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

(b) Illustrative adaptation pathways to riverine flooding risks.

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

(d) Illustrative adaptation pathways to coastal flooding risks. Grey shading means long lead time and dotted lines signal reduced effectiveness. The circles imply transfer to another measure and the bars imply that the measure has reached a tipping point (Tables SM13.30, SM13.31).

12 countries in Europe if GWL exceed 1.5°C–2.5°C (Clark et al., 2016), and this represents a major threat for the European and Mediterranean cultural heritage (Figure 13.28; Cross-Chapter Box SLR in Chapter 3; Cross-Chapter Paper 4; Marzeion and Levermann, 2014; Reimann et al., 2018b).

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

A range of adaptation options to coastal flooding exists, and adaptation is possible in many European regions if started on time (Section 13.2; Figure 13.32d). Continuing a protection pathway is cost-effective in urbanised regions for this century (Vousdoukas et al., 2020), but there is *high agreement* that it comes with residual risk if coastal defences fail during a storm. This residual risk can be reduced through early warning and evacuations, insurance and accommodate measures (Section 13.2.2). Soft limits to protection have been identified under high GWL, in particular due to the rate of change and delayed impacts of long-term SLR (*medium confidence*) (Hinkel et al., 2018; Haasnoot et al., 2020a). Ecosystem-based solutions, such as wetlands, can reduce waves' propagation, provide co-benefits for the environment and climate mitigation, and reduce costs for flood defences (*medium confidence*) (Section 13.2.2.1). At higher GWL, ecosystems are projected to experience reduced effectiveness due to temperature increases and an increased rate of SLR combined with a lack of sediment and human pressures (Cross-Chapter Box SLR in Chapter 3). Retention and diversion can be effective for compound flooding or for estuaries with a limited storm surge duration, but there is a lack of knowledge on their effectiveness (Sections 13.2.2).

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

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

13.10.3 Consequences of Multiple Climate Risks for Europe

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

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

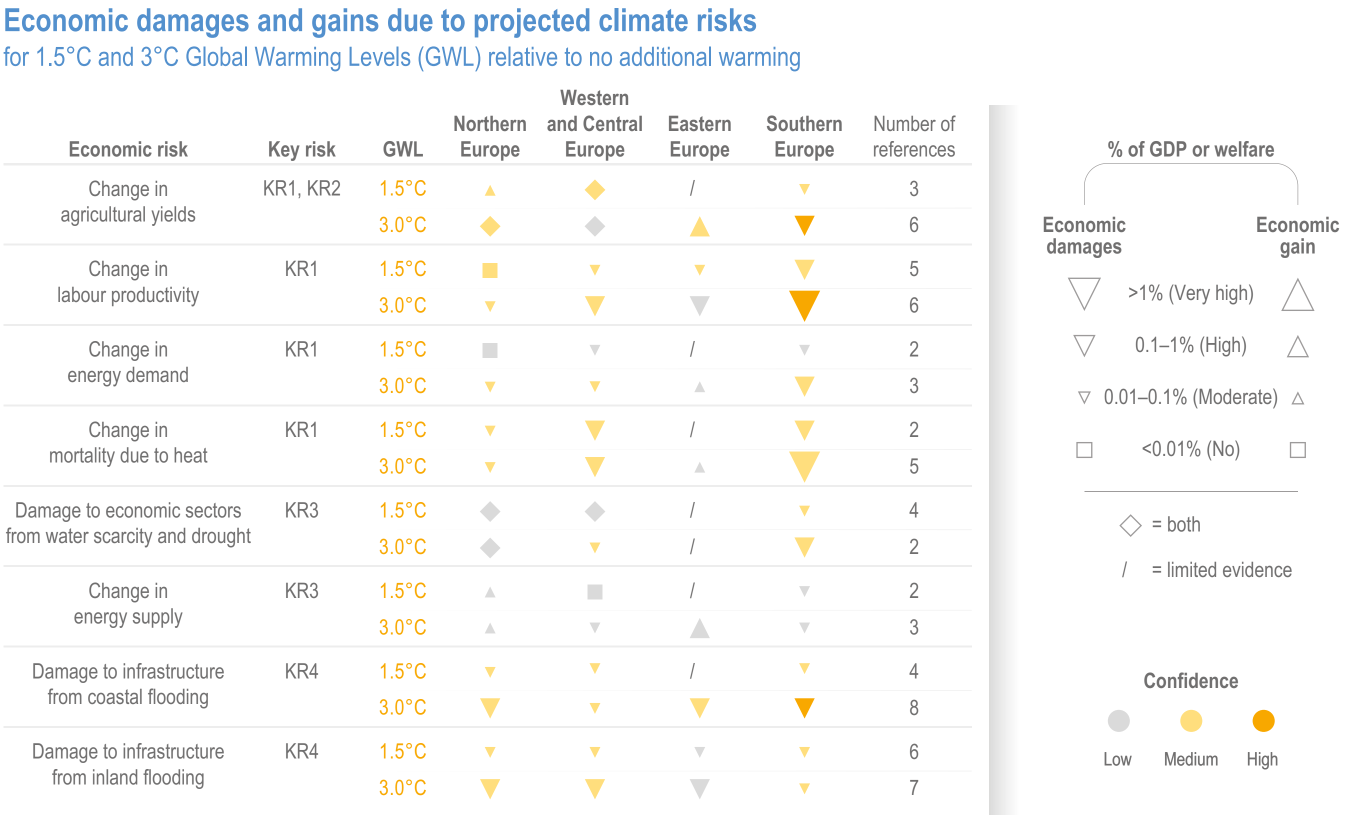


Figure 13.33 | Economic damages and gains due to projected climate risks are shown for 1.5°C and 3°C GWL relative to no additional warming; macroeconomic effects are measured in GDP or welfare. Effects for EEU are reported for Russia as a whole country, deviating from the definition of EEU in this chapter.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

13.10.4 Knowledge Gaps

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

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

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

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

Building on our sectoral analysis in previous sections, this section looks across European sectors, regions and vulnerable groups to assess how climate-change impacts are being responded to generally by state (Section 13.11.1) and non-state (Section 13.11.2) actors, and their synergies and dependencies. Section 13.11.3 assesses if and how system transformations have emerged and implications for the SDGs and climate resilient development pathways (CRDPs).

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