14

North America

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Executive Summary

Since AR5, climate-change impacts have become more frequent, intense and have affected many millions of people from every region and sector across North America (Canada, USA and Mexico). Accelerating climate-change hazards pose significant risks to the well-being of North American populations and the natural, managed and human systems on which they depend (*high confidence*[1]). Addressing these risks has been made more urgent by delays due to misinformation about climate science that has sowed uncertainty and impeded recognition of risk (*high confidence*). {14.2, 14.3}

Without limiting warming to 1.5°C, key risks to North America are expected to intensify rapidly by mid-century (*high confidence*). These risks will result in irreversible changes to ecosystems, mounting damages to infrastructure and housing, stress on economic sectors, disruption of livelihoods, and issues with mental and physical health, leisure and safety. Immediate, widespread and coordinated implementation of adaptation measures aimed at reducing risks and focused on equity have the greatest potential to maintain and improve the quality of life for North Americans, ensure sustainable livelihoods and protect the long-term biodiversity, and ecological and economic productivity, in North America (*high confidence*). Enhanced sharing of resources and tools for adaptation across economic, social, cultural and national entities enables more effective short- and long-term responses to climate change. {14.2, 14.4, 14.5, 14.6, 14.7}

Past and Current Impacts and Adaptation

Over the past 20 years, climate-change impacts across North America have become more frequent, intense and affect more of the population (*high confidence*). Despite scientific certainty of the anthropogenic influence on climate change, misinformation and politicisation of climate-change science has created polarisation in public and policy domains in North America, particularly in the USA, limiting climate action (*high confidence*). Vested interests have generated rhetoric and misinformation that undermines climate science and disregards risk and urgency (*medium confidence*). Resultant public misperception of climate risks and polarised public support for climate actions is delaying urgent adaptation planning and implementation (*high confidence*). Drawing upon Indigenous knowledge, enhancing communication and outreach and undertaking collaborations to co-create equitable solutions are critical for successful climate action. {Box 14.1, 14.3, 14.7}

Climate change has negatively impacted human health and well-being in North America (*very high confidence*). High temperatures have increased mortality and morbidity (*very high confidence*), with impacts that vary by age, gender, location and socioeconomic conditions (*very high confidence*). Changes in temperature and precipitation have increased risk of vector-borne (*very high confidence*), water-borne (*high confidence*) and food-borne diseases (*very high confidence*). Changes in climate and extreme events have been linked to wide-ranging negative mental health outcomes (*high confidence*). The loss of access to marine and terrestrial sources of protein has impacted the nutrition of subsistence-dependent communities across North America (*high confidence*). Climate change has increased the extent of warmer and drier conditions favourable for wildfires (*medium confidence*) that increase respiratory distress from smoke (*very high confidence*). {14.5.2, 14.5.6, Box 14.2}

North American food production is increasingly affected by climate change (*high confidence*), with immediate impacts on the food and nutritional security of Indigenous Peoples. Climate change and extreme weather events have impacted North American agroecosystems (*high confidence*), with crop-specific effects that vary in direction and magnitude by event and location. Climate change has generally reduced agricultural productivity by 12.5% since 1961, with progressively greater losses moving south from Canada to Mexico and in drought-prone rain-fed systems (*high confidence*) while favourable conditions increased yields of maize, soybeans in regions like the USA Great Plains. Loss of availability and access to marine and terrestrial sources of protein has impaired food security and nutrition of subsistence-dependent Indigenous Peoples across North America (*high confidence*). Climate change has impacted aquaculture (*high confidence*) and induced rapid redistribution of species (*very high confidence*), and population declines of multiple key fisheries (*high confidence*). {14.5.4, 14.5.6, 14.7}

Climate change has impaired North American freshwater resources and reduced supply security (*high confidence*). Reduced snowpack and earlier runoff (*high confidence*) have adversely affected aquatic ecosystems and freshwater availability for human uses (*medium confidence*). Recent severe droughts, floods and harmful algal and pathogen events have caused harm to large populations and key economic sectors (*high confidence*). Heavy exploitation of limited water supplies, especially in the western USA and northern Mexico, and deteriorating freshwater management infrastructure, have heightened the risks (*high confidence*). Effective examples of freshwater resource adaptation planning are already underway, but coordinated adaptation implementation across multiple conflicting interests and users is complicated and time-consuming (*high confidence*). {14.5.1, 14.5.2, 14.5.3}

Extreme events and climate hazards are adversely affecting economic activities across North America and have disrupted supply chain infrastructure and trade (*high confidence*). Larger losses and adaptation costs are observed for sectors with high climate exposures, including tourism, fisheries, and agriculture (*high confidence*) and outdoor labour (*medium confidence)*. Disaster planning and spending, insurance, markets, and individual and household-level adaptation have acted to moderate effects to date (*medium confidence)*. Entrenched socioeconomic vulnerabilities have amplified climate impacts for marginalised groups,

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

including Indigenous Peoples, due to the impact of colonialism and discrimination (*medium confidence*). {14.5.4, 14.5.5, 14.5.6, 14.5.7, 14.5.9, Box 14.1, Box 14.5, Box 14.6}

North American cities and settlements have been affected by increasing severity and frequency of climate hazards and extreme events (*high confidence*), which has contributed to infrastructure damage, livelihood losses, damage to heritage resources and safety concerns. Impacts are particularly apparent for Indigenous Peoples for whom culture, identity, commerce, health and well-being are closely connected to a resilient environment (*very high confidence*). Higher temperatures have been associated with violent and property crime in the USA (*medium confidence*), yet the overall effects of climate change on crime and violence in North America are not well understood. {14.4, 14.5.5, 14.5.6, 14.5.8, 14.5.9, Box 14.1}

Terrestrial, marine and freshwater ecosystems are being profoundly altered by climate change across North America (*very high confidence*). Rising air, water, ocean and ground temperatures have restructured ecosystems and contributed to the redistribution (*very high confidence*) and mortality (*high confidence*) of fish, bird and mammal species. Extreme heat and precipitation trends on land have increased vegetation stress and mortality, reduced soil quality and altered ecosystem processes including carbon and freshwater cycling (*very high confidence*). Warm and dry conditions associated with climate change have led to tree die-offs (*high confidence*) and increased prevalence of catastrophic wildfire (*medium confidence*) with an increase in the size of severely burned areas in western North America (*medium confidence*). Nature-based Solutions (NbS) and ecosystem-based management have been effective adaptation approaches in the past but are increasingly exceeded by climate extremes *(medium confidence*). {14.5.1–3, Box 14.7}

Climate-driven changes are particularly pronounced within Arctic ecosystems and are unprecedented based on observations from multiple knowledge systems (*very high confidence*). Climate change has contributed to cascading environmental and sociocultural impacts in the Arctic (*high to very high confidence*) that have adversely, and often irreversibly, altered Northern livelihoods, cultural activities, essential services, health, food and nutritional security, community connectivity and well-being (*high confidence*). {14.5.2, 14.5.4, 14.5.6, 14.5.7, 14.5.8, Box 14.6}

Future Risks and Adaptation

Climate hazards are projected to intensify further across North America (*very high confidence*). Heatwaves over land and in the ocean, as well as wildfire activity, will intensify; subarctic snowpack, glacial mass and sea ice will decline (*virtually certain*); and sea level rise will increase at geographically differential rates (*virtually certain*). Humidity-enhanced heat stress, aridification and extreme precipitation events that lead to severe flooding, erosion, debris flows and ultimately loss of ecosystem function, life and property are projected to intensify (*high confidence*). {14.2}

Health risks are projected to increase this century under all future emissions scenarios (*very high confidence*), but the magnitude and severity of impacts depends on the implementation and effectiveness of adaptation strategies (*very high confidence*). Warming is projected to increase heat-related mortality (*very high confidence*) and morbidity (*medium confidence*). Vector-borne disease transmission, water-borne disease risks, food safety risks and mental health outcomes are projected to increase this century (*high confidence*). Available adaptation options will be less effective or unable to protect human health under high-emission scenarios (*high confidence*). {14.5.6, Box 14.2}

Climate-induced redistribution and declines in North American food production are a risk to future food and nutritional security (*very high confidence*). Climate change will continue to shift North American agricultural and fishery suitability ranges (*high confidence*) and intensify production losses of key crops (*high confidence*), livestock (*medium confidence*), fisheries (*high confidence*) and aquaculture products (*medium confidence*). In the absence of mitigation, incremental adaptation measures may not be sufficient to address rapidly changing conditions and extreme events, increasing the need for cross-sectoral coordination in implementation of mitigation and adaptation measures (*high confidence*). Combining sustainable intensification, approaches based on Indigenous knowledge and local knowledge, and ecosystem-based methods with inclusive and self-determined decision making, will result in more equitable food and nutritional security (*high confidence*). {14.5.1–4, 14.5.6, 14.7, Cross-Chapter Box INDIG in Chapter 18, Cross-Chapter Box MOVING PLATE in Chapter 5}

Escalating climate-change impacts on marine, freshwater and terrestrial ecosystems (*high confidence*) will alter ecological processes (*high confidence*) and amplify other anthropogenic threats to protected and iconic species and habitats (*high confidence*). Hotter droughts and progressive loss of seasonal water storage in snow and ice will tend to reduce summer season stream flows in much of western North America, while population growth, extensive irrigated agriculture and the needs of threatened and endangered aquatic species will continue to place high demands on those flows (*high confidence*). {14.2.2, 14.5.1, 14.5.2, 14.5.3, 14.5.4, 14.5.6, Box 14.7.1}

Market and non-market economic damages are projected to increase to the end of the century from climate impacts (*high confidence*). Estimates for the costs of climate inaction are substantial across economic sectors, infrastructure, human health and disaster management. Hard limits to adaptation may be reached for outdoor labour (*medium confidence*) and nature-based winter tourism activities (*very high confidence*). At higher levels of warming, climate impacts may pose systemic risks to financial markets through impacts on transportation systems, supply chains and major infrastructure, as well as global-scale challenges to trade (*medium confidence*). {14.2.2, 14.5.4, 14.5.8, 14.5.7, 14.5.9, 14.5.5, Box 14.5, Box 14.6}

Solution Space and Governance

Self-determination for Indigenous Peoples is critical for effective adaptation in Indigenous communities (*very high confidence*). Throughout North America, Indigenous Peoples are actively addressing the compound impacts of climate change, and historical and ongoing forms of colonialism (*very high confidence*). Indigenous knowledge underpins successful understanding of, responses to, and governance of climate-change risks. Western scientific practices and technology may not be sufficient in addressing future natural resource management challenges. Supporting Indigenous self-determination, recognising Indigenous Peoples' Rights, and supporting adaptation underpinned by Indigenous knowledge are critical to reducing climate-change risks to achieve adaptation success (*very high confidence*). {14.7.3, Box 14.1}

Equitable, inclusive and participatory approaches that integrate climate-impact projections into near- and long-term decision making reduce future risks (*high confidence*). Government and private investment are increasingly focusing on early warning and rapid response systems, climate and ecological forecasting tools, and integrated climate scenario planning methods. Widespread adoption of these practices and tools for infrastructure planning, disaster risk reduction, ecosystem management, budgeting practices, insurance, and climate risk reporting supports planning for a future with more climate risks (*high confidence*). Increased capacity to support the equitable resolution of existing and emerging resource disputes (local to international) will reduce climate impacts on livelihoods and improve the effectiveness of resource management (*high confidence*). {14.5.5, 14.5.10, 14.7}

Near- and long-term adaptation planning, implementation and coordination across sectors and jurisdictions supports equitable and effective climate solutions (*high confidence*). Recognition of the need for adaptation across North America is increasing, but action has been mostly gradual, incremental and reactive (*high confidence*). Current practices will be increasingly insufficient without coordination and integration of efforts through equitable policy focused on modifying land-use impacts, consumption patterns, economic activities and emphasising NbS (*high confidence*). Transformational, long-term adaptation action that reduces risk and increases resilience can address rapidly escalating impacts in the long-term, especially if coupled with moderate to high mitigation measures (*high confidence*). {14.7}

14.1 Introduction and Point of Departure

Earth's climate is currently changing in significant ways as a result of human activities, and future projections indicate continued and possibly accelerating change without reductions in greenhouse gas (GHG) emissions (Gutiérrez et al., 2021; IPCC, 2021). Climate change affects human and natural systems; this chapter provides an assessment of present and future climate-change impacts, risks and adaptation for North America, including Mexico, Canada, the USA and coastal waters within the 370-km exclusive economic zone. We do not consider Hawaii and other island territories of the USA in depth as they are assessed in Chapter 15. Chapter 14 assesses evidence from Arctic Canada and Alaska, which is synthesised in Cross-Chapter Paper 6 Polar Regions (CCP6).

Evidence from Indigenous knowledge (IK) systems is included in this chapter to assess climate-change risks and solutions in North America following the framing provided in Chapter 1 Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Abram et al., 2019) and Special Report on Climate Change and Land (SRCCL) (IPCC, 2019a). Indigenous contributing authors provided this assessment, reflecting the importance of meaningfully including IK in assessment processes (Ford, 2012; Ford et al., 2016; Hill et al., 2020). This addition represents an important advancement since AR5 (IPCC, 2013; IPCC, 2014).

Our main point of departure was the Fifth Assessment Report (AR5) for WGII (IPCC, 2014). Key findings drawn from the Executive Summary for the North America chapter are summarised in Table 14.1. Subsequent IPCC reports, such as Special Report on Global Warming of 1.5°C (SR1.5) (Hoegh-Guldberg et al., 2018; IPCC, 2018), SROCC (IPCC, 2019b) and SRCCL (IPCC, 2019a), also informed the assessment. We additionally incorporated recent national climate assessments of the USA (USGCRP, 2018) and Canada (Bush and Lemmen, 2019; Warren and Lulham, 2021) as well as the Sixth National Communication of Mexico to the United Nations Framework Convention on Climate Change (SEMARNAT and INECC, 2018).

Chapter 14 sections are organised to address themes and content as contained in the IPCC-approved outline for regions. Regional climate changes assessed within North America are keyed to Figure 14.1 using four-letter abbreviations (e.g., CA-ON, US-SE, MX-NW). The assessment addresses recent and future climate for North America, the impacts, risks and adaptations within sectors, key risksacross sectors (KR), the nature of adaptation and sustainable development pathways as well as two additional sections on Indigenous Peoples and perceptions of climate change. Seven boxes are used to highlight topics of interdisciplinary nature while four frequently asked questions (FAQ) were produced in plain language for communication to the public. The chapter utilises the framework as well as designated terms in the standardised process for evaluating and characterising the degree of certainty in assessment findings developed through the expert judgement process (Section 1.3.4; Mach et al., 2017). The Glossary [Annex II] provides definitions for terms and concepts used across the report.

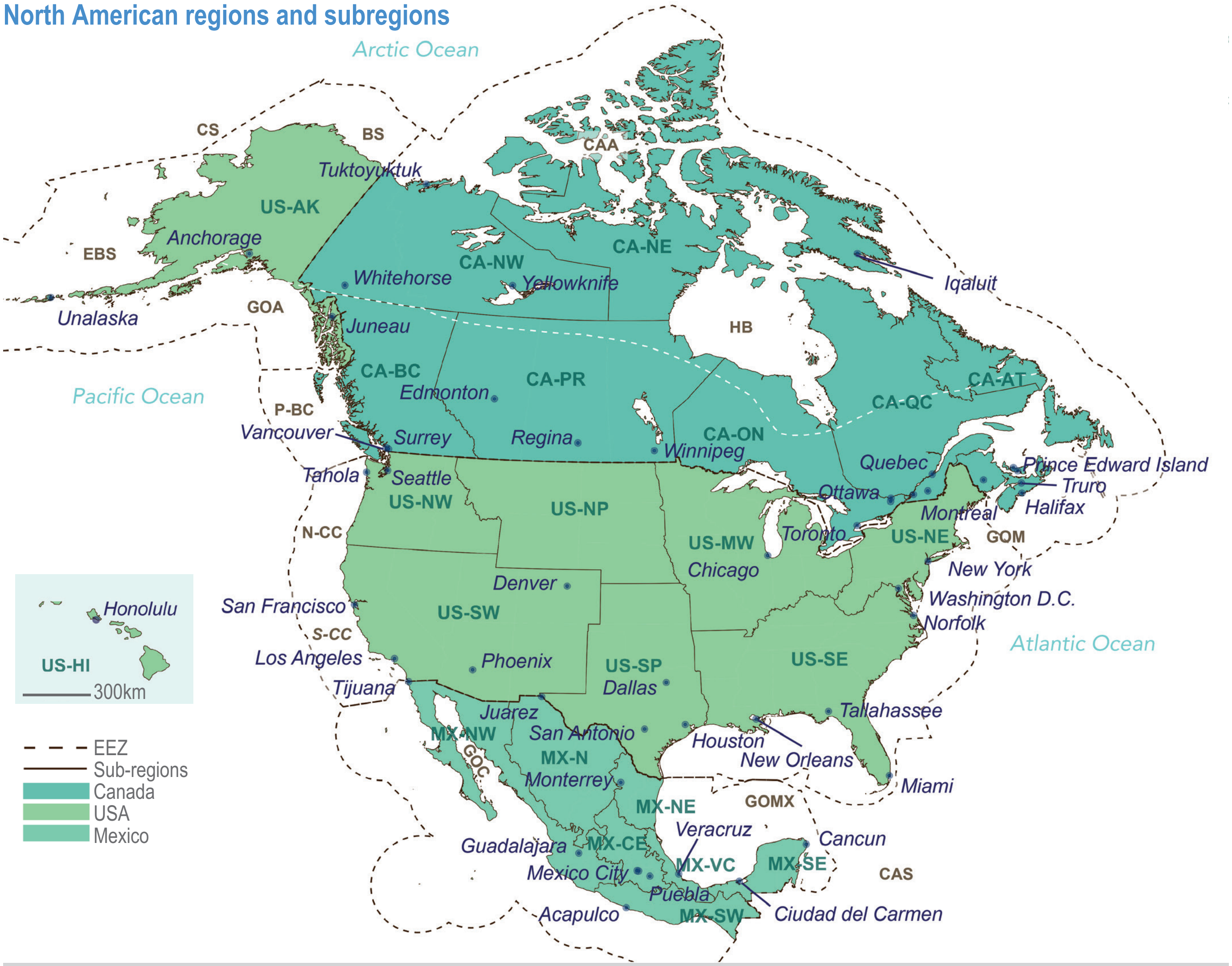
14.1.1 Context

With a 2019 total population of over 494 million people (USA 329 million, Mexico 128 million and Canada 37 million), North America comprises 6.4% of the global population. Relative to other countries, North American countries have low population densities per square kilometre (Mexico 64 people, USA 35 people and Canada 4 people) (United Nations, 2019). Population projections indicate a steady growth in the three countries, which will exert pressure on consumption and increase risks under climate change (United Nations, 2019). North America is also responsible for about a quarter of global greenhouse gas (GHG) emissions. Since 1990, North American GHG emissions have increased by almost 18% (Ritchie and Roser, 2020), and in 2019 the region was responsible for 5.9 $MtCO_2$ emissions worldwide (Friedlingstein et al., 2020). In terms of annual CO_2 emissions per capita, in 2019 Canada had 15 metric tons of CO_2 per person (tCO_2 per person), the USA had 16 tCO_2 per person and Mexico had 3.4 tCO_2 per person (Friedlingstein et al., 2020).

Table 14.1 | Key findings from AR5 North America chapter (Romero-Lankao et al., 2014b)

General topic	AR5 finding
Climate hazards	Climate has changed in North America, with some changes attributed to human activities.
	Climate hazards, especially related to heatwaves, heavy precipitation and snowpack, are expected to change in ways that are adverse to natural and human systems.
Natural ecosystems	Warming, increasing carbon dioxide (CO_2) concentrations, sea level rise (SLR) and climate extremes are stressing ecosystems.
Human systems	Water resources that are already stressed in many parts of North America are expected to become further stressed by climate change. Current adaptation options can address water supply deficits, but responses to flooding and water quality concerns are more limited.
	Climate change has affected yields of major crops, and projections indicate continued declines, although with variability.
	Extreme climate events have affected human health, although climate-change-related trends and attribution to climate change have not been confirmed.
	Multiple aspects of climate change have affected livelihoods, economic activities, infrastructure and access to services.
	Much infrastructure is vulnerable to extreme weather events, and unless adaptation investments are made, vulnerability to future climate change will persist and increase.
	Most sectors of the North American economy have been affected by and have responded to extreme weather, including hurricanes, flooding and intense rainfall.
Adaptation	Technological innovation, institutional capacity-building, economic diversification and infrastructure design are adaptations for reducing current climate impacts as well as future risks due to a changing climate.
	North American governments predominantly have undertaken incremental adaptation assessment and planning at the municipal level. Limited proactive, anticipatory adaptation is directed at long-term investment for energy and public infrastructure.

North American regions and subregions



North America Sub-Regions

CA-ON	Canada Ontario	US-MW	US Midwest	MX-NW	Mexico Northwest
CA-BC	Canada British Columbia	US-NW	US Northwest	MX-N	Mexico North
CA-PR	Canada Prairies	US-NP	US Northern Great Plains	MX-NE	Mexico Northeast
CA-QC	Canada Québec	US-NE	US Northeast	MX-SE	Mexico Southeast
CA-NW	Canada Western Arctic	US-SW	US Southwest	MX-SW	Mexico Southwest
CA-NE	Canada Eastern Arctic	US-SP	US Southern Great Plains	MX-VC	Mexico Veracruz
CA-AT	Canada Atlantic	US-AK	US Arctic	MX-CE	Mexico Centre
		US-SE	US Southeast		
		US-HI	US Hawaii		

North America Marine Basins

BS	Beaufort Sea
CAA	Canadian Arctic Archipelago
CAS	Caribbean Sea
CS	Chukchi Sea
EBS	Eastern Bering Sea
GOA	Gulf of Alaska
GOC	Gulf of California
GOM	Gulf of Maine
GOMX	Gulf of Mexico
HB	Hudson Bay
N-CC	Northern California Current
P-BC	British Columbia coast
S-CC	Southern California Current

Figure 14.1 | North American regions and sub-regions, adapted from national climate assessments, and city names, referred to in discussion of local and regional climate-change impacts and adaptation. White dashed line denotes the southern boundary across North America of the Arctic region defined in Cross-Chapter Paper 6.

14.2 Current and Future Climate in North America

Trends in observed and projected physical climate variables, and changes in extreme weather and climate events, are summarised in this section. Many of the assessments here are adapted from AR6 WGI (IPCC, 2021), especially Chapters 11 (Seneviratne et al., 2021) and 12 (Ranasinghe et al., 2021), and the Atlas (Gutiérrez et al., 2021a, b). Ranasinghe et al., 2021, Section 12.4.6, assesses North American climatic impact drivers without assessing their impacts or associated risks. The WGI assessments are augmented in this section with regionally specific support from recent national climate assessments or original literature.

14.2.1 Observed Changes in North American Climate

Climate changes directly related to increasing mean and extreme temperature, including reduced snowpack, sea and lake ice and glacier extent, and marine heatwaves (MHWs), can be attributed to human activity and are affecting most of North America (*high confidence*). Upward trends in annual mean temperature across North America since 1960 are widespread (Gutiérrez et al., 2021a) but non-uniform (Figure 14.2A). Pronounced polar amplification of warming is observed in high latitudes (Figure 14.2A), particularly in winter (Gutiérrez et al., 2021a; Vose et al., 2017; Zhang et al., 2019a). As average temperature rises, extreme high temperature records across North America are being set more frequently than extreme cold records (Meehl et al., 2016) and the probability of cold extreme events is reduced (WGI Chapter 11 [Seneviratne et al., 2021]). Trends in daily maximum and minimum temperature are significant in high latitudes (US-AK, CA-NW, CA-NE). Summer daily maximum temperature is increasing in southwest desert regions (US-SW, MX-NW) (Martinez-Austria et al., 2016; Martinez-Austria and Bandala, 2017; Navarro-Estupinan et al., 2018).

Annual precipitation has increased in recent decades in northern and eastern areas (CA-PR, CA-QU, US-NP, US-SP, US-MW, US-NE, US-AK) (*high confidence*), and has decreased across the western part of the continent (CA-BC, US-SW, US-NW, MX-NW) (*medium confidence*), with considerable spatial variability within these regions (Zhang et al., 2019a; Gutiérrez et al., 2021a). Elsewhere across North America there is *limited evidence* and *low agreement* on detection of observed trends in total precipitation and river flood hazards. The intensity and frequency of 1-day heavy precipitation events have *very likely*[2] increased since the mid-20th Century across most of the USA (US-NP, US-MW, US-NE, but not in US-SE) and in Mexico, but no detectable trend is reported in Canada (Seneviratne et al., 2021; Zhang et al., 2019a). Recent flooding events along the mid-latitude Pacific Coast have been attributed to increasingly intense atmospheric river events (Douville et al., 2021; Gershunov et al., 2019; Vano et al., 2019), but there is *low confidence* in detecting trends in atmospheric river activity.

Snowpack and snow extent across much of Canada and the western USA have declined as temperatures have increased (*very high confidence*) (Ranasinghe et al., 2021; Gutierrez et al., 2021a; Kunkel et al., 2016; Mote et al., 2018; Mudryk et al., 2018; Derksen et al., 2019). Warm 'snow droughts' describing a deficit of snowpack available for runoff, even in the absence of a winter precipitation deficit (Cooper et al., 2016; Harpold et al., 2017), have become more common in North American mountains (Sproles et al., 2016; Nicholls et al., 2018; Pershing et al., 2018). Glaciers have retreated over the past half-century at high elevation across North America (Frans et al., 2018; Zemp et al., 2019) and in the Arctic (Burgess, 2017; Box et al., 2019; Derksen et al., 2019). Lake ice in Canada, south of the Arctic region delineated in Figure 14.1, has declined (Alexeev et al., 2016; Derksen et al., 2019).

There is limited evidence of trends in meteorological or hydrological droughts over the historical record (see Douville et al. (2021) and Seneviratne et al. (2021) for multiple perspectives on drought; Wehner et al., 2017), but there is *medium confidence* in increasing atmospheric evaporative demand acting to intensify surface aridity during recent droughts (e.g., US-SW) (Seneviratne et al., 2021; Williams et al., 2020). The ongoing multi-decadal dry period in the Colorado River basin is as extreme as any drought in the past 1000 years (Murphy and Ellis, 2019; Williams et al., 2020).

The proportion of hurricanes in stronger categories has *likely* increased globally over the past 40 years, with *medium confidence* that the onshore propagation speed of hurricanes making landfall in the USA has slowed detectably since 1900 (Seneviratne et al., 2021; Kossin, 2018), contributing to detectable increases in local rainfall and coastal flooding associated with these storms. There is *high confidence* (Seneviratne et al., 2021) that anthropogenic climate change has contributed to extreme precipitation associated with recent intense hurricanes, such as Harvey in 2017.

North American sea ice extent and volume (thickness) have declined up to 10% per decade since 1981 (Fox-Kemper et al., 2021; Ding et al., 2017; Mudryk et al., 2018; Derksen et al., 2019; IPCC, 2019b), with changes accelerating during this time (*robust evidence, high agreement*) (Schweiger et al., 2019), resulting in longer and larger periods of open water (Wang et al., 2018a). Recent (2018) sea ice extent in the Bering Sea was the lowest in a 5500-year record and appears to lag atmospheric CO_2 by about two decades (Jones et al. 2021). High Arctic sea ice retreat since 1971 and increases in open-water duration in the most recent decade are unprecedented (Box et al., 2019) and most pronounced in the Chukchi, Bering and Beaufort seas (US-AK, CA-NW) (*high confidence*) (Wang and Overland, 2015; Jones et al., 2020).

Warming of North American offshore waters is significant and attributable to human activities, particularly along the Atlantic coast, contributing to sea level rise (SLR) through thermal expansion (*very high confidence*) (Fox-Kemper et al., 2021; IPCC, 2019b). Rates of SLR have accelerated along most North American coasts during the past

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

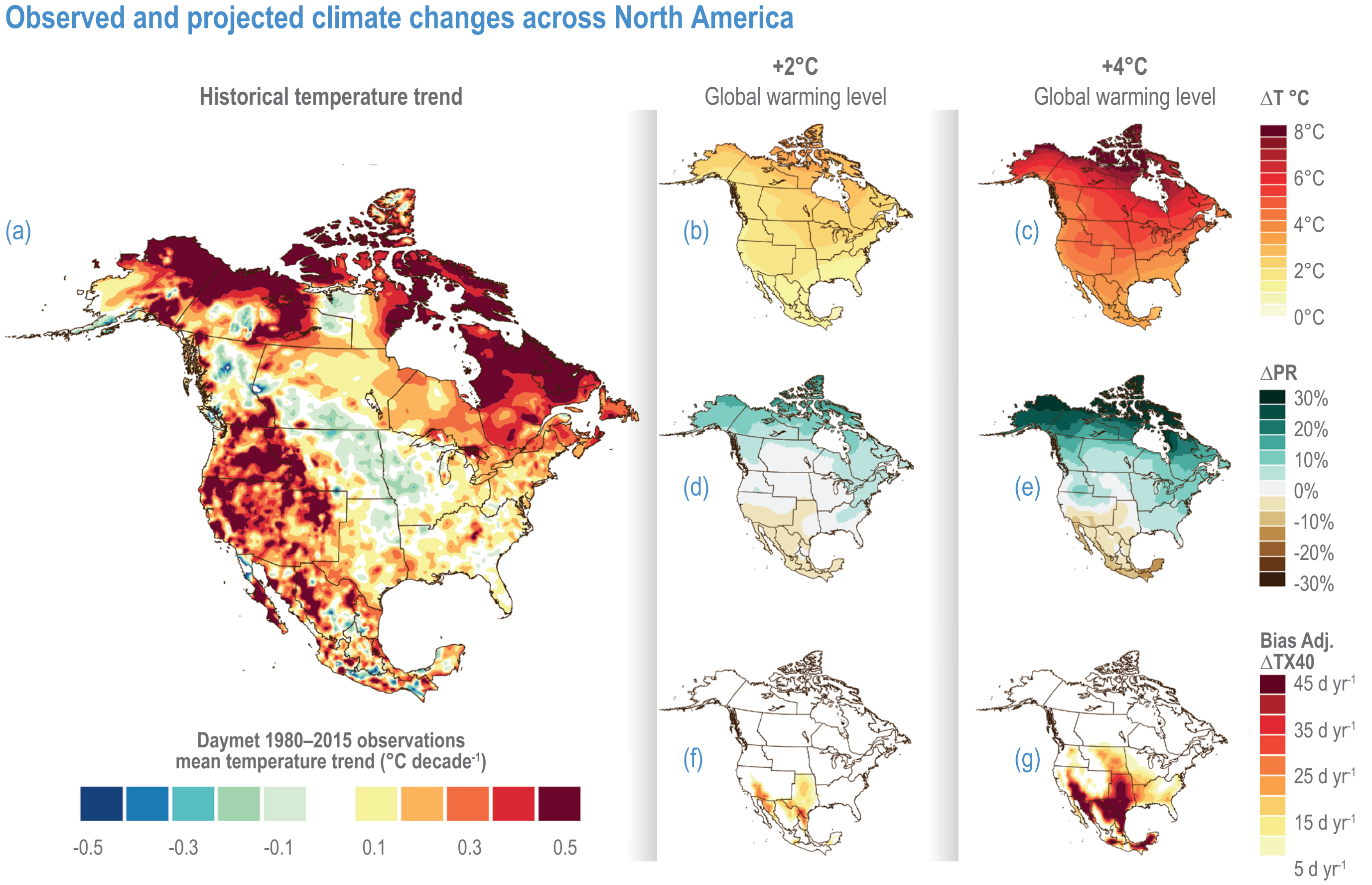

Figure 14.2 | Observed and projected climate changes across North America. Black boundary lines delineate North American sub-regions (Figure 14.1). Data were extracted from Gutiérrezet al. 2021a via http://interactive-atlas.ipcc.ch/ (WGI Interactive Atlas) (Gutiérrez et al., 2021b), where dataset details can be found. (A) Recent observations; (B) to (G) are from an ensemble of CMIP6 projections.

(A) Observed annual mean temperature trend over land for 1980–2015.

(B,C) Projected change in annual mean temperature over land relative to the 1986–2005 average, associated with 2°C or 4°C global warming.

(D,E) Like (B,C) but for projected percentage change in annual precipitation.

(F,G) Like (B,C) but for projected change in number of days per year with maximum temperature >40°C ('TX40').

three decades, excepting coastlines in southern Alaska (US-AK) and northeastern Canada (CA-QC, CA-NE) where land is rising (Ranasinghe et al., 2021; Greenan et al., 2018). Tidal flooding frequency has increased in the North Pacific from once every 1–3 years to every 6–12 months (Sweet et al., 2014).

Acidification of North American coastal waters has occurred in conjunction with increased atmospheric CO_2 concentration (Mathis et al., 2015; Jewett and Romanou, 2017; Claret et al., 2018) combined with other local acidifying inputs such as nitrogen and sulphur deposition (Doney et al., 2007) and freshwater nutrient input (*very high confidence*) (Strong et al., 2014; IPCC, 2019b). Oxygen minimum zones, particularly in the North Pacific south of US-AK, have expanded in volume and O_2 has declined since 1970 (IPCC, 2019b).

14.2.2 Projected Changes in North American Climate

Climate changes related to warming temperature, including more intense heatwaves over land and in the ocean, diminished snowpack, sea ice reduction and SLR, are projected with *high confidence* and are strongly sensitive to future GHG concentrations (Figure 14.2). Climatic hazards affected by hydrological change, including humidity-inclusive heat stress, extreme precipitation and more intense storms, are projected to intensify.

Pronounced amplification of warming across the Arctic and continental intensification of warming (Figure 14.2B,C) is projected with *high confidence* (Doney et al., 2007; Vose et al., 2017). Extreme heatwaves are projected to intensify, particularly in MX-NW, MX-N, MX-NE, US-SW, US-NP and US-SP (Figure 14.2F,G) and become more frequent and longer in duration as average temperature rises across North America (Seneviratne et al., 2021). Extreme cold events are projected to decrease in severity (Ranasinghe et al., 2021; Wuebbles et al., 2014).

Total precipitation is projected to increase across the northern half of North America (*very high confidence*) and decrease in southwest North America (MX-SW, MX-NW, US-SW) (*medium confidence*) (Figure 14.2D,E; Gutiérrez et al., 2021b). Further increases in the intensity of locally heavy precipitation are *very likely* across the continent, as a greater fraction of precipitation falls in intense events (Easterling et al., 2017; Prein et al., 2017a; Zhang et al., 2019a).

High-humidity hazards are projected to increase (*medium confidence*) in regions around the Gulf of Mexico and southeast North America (US-SE, US-SP, MX-NE, MX-SE) (Zhao et al., 2015). In subtropical regions that are less influenced by moisture from the Gulf of Mexico (including US-SW, US-SP, MX-NW and MX-N), the combination of higher temperature and less total precipitation leads to projections of increased aridity: drier surface conditions, higher evaporative demand by plants and more intense droughts (Ranasinghe et al., 2021; Jones and Gutzler, 2016; Easterling et al., 2017; Escalante-Sandoval and Nuñez-Garcia, 2017).

As temperatures rise, snow extent, duration of snow cover and accumulated snowpack are *virtually certain* to decline in subarctic regions of North America (Gutierrez et al., 2021a; McCrary and Mearns, 2019; Mudryk et al., 2021), with corresponding effects on snow-related hydrological changes (*high confidence*). These changes include declines in snowmelt runoff (Li et al., 2017), increased evaporative losses during snow ablation (Foster et al., 2016; Milly and Dunne, 2020), as well as increases in the frequency of rain-on-snow events (Jeong and Sushama, 2018a) and consecutive snow drought years in western North America (Marshall et al., 2019a).

Climate change is projected to magnify the impact of tropical cyclones in US-NE, MX-NE, US-SP, and US-SE by increasing rainfall (Patricola and Wehner, 2018) and extreme wind speed (*high confidence*) and slowing the speed of land-falling storms (*limited evidence, low confidence*) (Seneviratne et al., 2021; Kossin, 2018). The coastal region at severe risk from tropical storms is projected to expand northward within US-NE (*medium confidence*) (Kossin et al., 2017).

Additional reduction in polar sea ice is *virtually certain* (Ranasinghe et al., 2021; Mudryk et al., 2021), with the North American Arctic projected to be seasonally ice free at least once per decade under 2°C of global warming (*high confidence*) (IPCC, 2019b; Mioduszewski et al., 2019; Mudryk et al., 2018). Duration of freshwater lake ice across the northern USA and southern Canada is projected to diminish (*high confidence*) (Ranasinghe et al., 2021; Dibike et al., 2012; Mudryk et al., 2018; Sharma et al., 2019).

Ocean surface temperature is *very likely* to increase in future decades in waters around North America (Jewett and Romanou, 2017; Greenan et al., 2018), but at a slower rate than air temperature over the continent. Rates of change are projected to be relatively higher in northern latitudes, with most rapid warming in summer in the Arctic and Bering Sea (US-AK, CA-NW) (Wang and Overland, 2015; Wang et al., 2018a; Hermann et al., 2019).

Sea level rise is *virtually certain* to continue along North American coastlines except for parts of US-AK and around Hudson Bay (HB) with geographically variable rates of rise (Fox-Kemper et al., 2021; Ranasinghe et al., 2021; see Box 14.4). Relatively greater SLR is projected along the US-SE and MX-SW coastlines and relatively less along CA-BC and US-NW (Fox-Kemper et al., 2021; Ranasinghe et al., 2021; see Box 14.4) (Fasullo and Nerem, 2018; Greenan et al., 2018 IPCC, 2019b).

Ocean acidification (OA) along North American coastlines is projected to increase (*very high confidence*) (Jewett and Romanou, 2017). The frequency and extent of oxygen minimum and hypoxic zones are

Frequently Asked Questions

FAQ 14.1 | How has climate change contributed to recent extreme events in North America and their impacts?

Multiple lines of evidence indicate that climate change is already contributing to more intense and more frequent extreme events across North America. The impacts resulting from extreme events represent a huge challenge for adapting to future climate change.

Extreme events are a fundamental part of how we experience weather and climate. Exceptionally hot days, torrential rainfall and other extreme weather events have a direct impact on people, communities and ecosystems. Extreme weather can lead to other impactful events such as droughts, floods or wildfires. In a changing climate, people frequently ask whether extreme events are generally becoming more severe or more frequent, and whether an actual extreme event was caused by climate change.

Because really extreme events occur rarely (by definition), it can be very difficult to assess whether the overall severity or frequency of such events has been affected by changing climate. Nevertheless, careful statistical analysis shows that record-setting hot temperatures in North America are occurring more often than record-setting cold temperatures as the overall climate has gotten warmer in recent decades. The area burned by large wildfires in the western USA has increased in recent decades. Observed trends in extreme precipitation events are more difficult to detect with confidence, because the natural variability of precipitation is so large and the observational database is limited.

Our understanding of how individual extreme weather events have been influenced by climate change has improved greatly in recent years. Climate scientists have developed a formal technique (‘event attribution’, described in WGI FAQ 11.3) for assessing how climate change affects the severity or frequency of a particular extreme event, such as a record-breaking rainfall event or a marine heatwave. This is a challenging task, because any particular event can be caused by a combination of natural variability and climate change. Event attribution is typically carried out using models to compare the probability of a specific event occurring in today’s climatic environment relative to

Box FAQ 14.1 (continued)

the probability that the same event might have occurred in a modelled climate in which atmospheric GHGs have not risen due to human activities. Using this strategy, multiple studies have estimated that the historically extreme rainfall amount that fell across the Houston area from Hurricane Harvey (2017) was three to ten times more *likely* as the result of climate change.

The *impacts* from extreme events depend not just on physical climate system hazards (temperature, precipitation, wind, etc.), but also on the exposure and vulnerability of humans or ecosystems to these events. For example, damage from land-falling hurricanes along the coast of the Gulf of Mexico is expected to increase as very strong hurricanes become more frequent and intense due to climate change. But damage would also increase with additional construction along the shoreline, because coastal development increases *exposure* to hurricanes. And if some structures are constructed to poor building standards, as was the case when hurricane Andrew made landfall in Florida in 1992, then *vulnerability* to hurricane-caused impacts is increased.

Climate change also contributes to impacts from extreme events by making some building codes and zoning restrictions inadequate or obsolete. Many North American communities limit development in areas known to be flood-prone, to minimise exposure to flooding. But as climate change expands the areas at risk of exposure to flooding beyond historical floodplains, the impacts of potential flooding are increased, as Hurricane Harvey demonstrated. Adapting to climate change may require retrofits for existing structures and revised zoning for new construction. Some structures and neighbourhoods may need to be abandoned altogether to accommodate expanded flooding risk.

Climate change can be an *added stress* that increases impacts from extreme events, combined with other non-climatic stressors. For example, climate change in western North America has contributed to more extreme fire weather. The devastating impacts of recent wildfire outbreaks, such as occurred across western Canada in 2016 and 2017, the western United States in 2018 and 2020, and both countries in 2021, are to some extent associated with expanded development and forest management practices (such as policies to suppress low-intensity fires, allowing fuel to accumulate). The effects of development and forest management have dramatically increased the exposure and vulnerability of communities to intense wildfires. Climate change has added to these stressors: warming temperature leads to more extreme weather conditions that are conducive to increasingly severe wildfires.

Biodiversity is affected by climate change in this way too. For example, numerous bird populations across North America are estimated to have declined by up to 30% over the past half-century. Multiple human-related factors, including habitat loss and agricultural intensification, contribute to these declines, with climate change as an added stressor. Increasingly extreme events, such as severe storms and wildfires, can decimate local populations of birds, adding to existing ecological threats.

projected to increase, with less confidence, exacerbated by climate-driven eutrophication and increasing stratification (Altieri and Gedan, 2015; IPCC, 2019b).

14.3 Perception of Climate-Change Hazards, Risks and Adaptation in North America

14.3.1 Climate Change as a Salient Issue

The majority of the climate science community has reached consensus that mean global temperature has increased and human activity is a major cause (Oreskes, 2004; Anderegg et al., 2010; Cook et al., 2013; Cook et al., 2016; IPCC, 2021), setting the context for public policy action. Despite expert scientific consensus on anthropogenic climate change, there is polarisation and an ongoing debate over the reality of anthropogenic climate change in the public and policy domains, with attendant risks to society (*high confidence*) (Doran and Zimmerman, 2009; Ballew et al., 2019; Druckman and McGrath, 2019; Hornsey and Fielding, 2020; Wong-Parodi and Feygina, 2020). Public perception of consensus regarding anthropogenic climate change can be an important gateway belief, which establishes a crucial precondition for public policy action (van der Linden et al., 2015; van der Linden et al., 2019) by influencing the assessment of climate-change risks and opportunities, and formulation of appropriate mitigation and adaptation responses (Ding et al., 2011; Bolsen et al., 2015; Drews and Van den Bergh, 2016; Doll et al., 2017; Mase et al., 2017; Morton et al., 2017). Trust in experts, institutions and environmental groups is also important (Cologna and Siegrist, 2020; Termini and Kalafatis, 2021).

Rhetoric and misinformation on climate change and the deliberate undermining of science have contributed to misperceptions of the scientific consensus, uncertainty, disregarded risk and urgency, and dissent (*high confidence*) (Ding et al., 2011; Oreskes and Conway, 2011; Aklin and Urpelainen, 2014; Cook et al., 2017; van der Linden et al., 2017). Additionally, strong party affiliation and partisan opinion polarisation contribute to delayed mitigation and adaptation action, most notably in the USA (*high confidence*) (van der Linden et al., 2015; Cook and Lewandowsky, 2016; Bolsen and Druckman, 2018; Chinn et al., 2020) but with similar patterns in Canada (*medium confidence*) (Lachapelle et al., 2012; Kevins and Soroka, 2018). Vocal groups can affect public discourse and weaken public support for climate mitigation and adaptation policies (*medium confidence*) (Aklin and Urpelainen, 2014; Lewandowsky et al., 2019). Vested economic and political interests have organised and financed misinformation and 'contrarian' climate-change communication (Brulle, 2014; Farrell, 2016a; Farrell, 2016b; Supran and Oreskes, 2017; Bolsen and Druckman, 2018; Brulle, 2018). Traditional media–print and broadcast–frame and transmit climate-change information and play a crucial role in shaping public perceptions, understanding and willingness to act (Happer and Philo, 2013; Schmidt et al., 2013; Hmielowski et al., 2014; Bolsen and Shapiro, 2018; King et al., 2019; Chinn et al., 2020). The journalistic norm of 'balance' (giving equal weight to climate scientists and contrarians in climate-change reporting) biases coverage by unevenly amplifying certain messages that are not supported by science, contributing to politicisation of science, spreading of misinformation and reducing public consensus on action (Boykoff and Boykoff, 2004; Boykoff and Boykoff, 2007; Cook et al., 2017). Much online social media discussion of climate change takes place in 'echo chambers'–a social network among like-minded people in communities dominated by a single view that contributes to polarisation (Williams et al., 2015; Pearce et al., 2019) and the spread of misinformation (Treen et al., 2020).

14.3.2 Public Perceptions, Opinions and Understanding of Climate Change

In a 2018 survey across 26 nations, people in Canada and Mexico ranked climate change as the top global threat, whereas in the USA climate change ranked third (Poushter and Huang, 2019). The public's responses to the causes of climate change and risk perceptions in Canada (Mildenberger et al., 2016) and the USA (Howe et al., 2015) have revealed variations among regions (Figure 14.3) and less acceptance of climate change in rural regions than in urban areas. Canadian regions have higher acceptance of climate change (e.g., recognise it is happening and attributable to human activity) than the most liberal areas in the USA (Lachapelle et al., 2012; Mildenberger et al., 2016). Western Canadian regions with high carbon intensity economies had lower acceptance of climate change than the rest of Canada, whereas in the USA perceptions were more stable across regions (Lachapelle et al., 2012). A recent survey in Mexico found that for 73% of respondents climate change represents a major economic, environmental and social threat, and in the most vulnerable states (MX-SE), the perception is that climate-change impacts and extreme events have considerable implications for the way of life in communities (Zamora Saenz, 2018). In a 2017 survey, Azócar et al. (2021) found that 85% of respondents from Mexico acknowledged anthropogenic climate change. Peoples' experience with extreme events (e.g., hurricanes, high temperatures), socio-demographic characteristics, level of marginalisation and economic and social exclusion, as well as education levels, were important factors influencing perception of climate change in Mexico (Corona-Jimenez, 2018; Alfie and Cruz-Bello, 2021; Azócar et al., 2021). Drawing upon Indigenous knowledge (see Box 14.1) as well as lived experience of recent changes in ice, weather patterns, and species' phenology and distribution, Indigenous Peoples recognise that change is occurring in their communities and have effective solutions that are grounded in Indigenous world views (Harrington, 2006; Turner and Clifton, 2009; Norton-Smith et al., 2016a; Savo et al., 2016; Maldonado et al., 2017; Chisholm Hatfield et al., 2018).

14.3.3 Building Consensus on Climate Change

Building consensus for action on climate change is influenced by individual factors (e.g., ideology, world view, trust, partisan identity, religion, education, age) and the broader societal context (e.g., culture, media coverage and content, political climate, economic conditions) (*high confidence*) (McCright and Dunlap, 2011; Brulle et al., 2012; Hornsey et al., 2016; Arbuckle, 2017; Pearson et al., 2017; Bolsen and Shapiro, 2018; Ballew et al., 2020; Cologna and Siegrist, 2020; Goldberg et al., 2020). In a multi-country assessment of acceptance of global warming influenced by ideology (e.g., conspiratorial ideation, individualism, hierarchy, and left–right and liberal–conservative political orientation), the USA uniquely had the strongest link to doubt out of 25 countries for all factors, while Canada's dominant influence on non-acceptance was conservative political ideology, and for Mexico, there were no ideological effects (Hornsey et al., 2018).

Political affiliation and partisan group identity contribute to polarisation on the causes and state of climate change, most notably in the USA (*medium confidence*). Fewer US republicans hold the belief that human activity causes climate change than democrats (Bolsen and Druckman, 2018; Druckman and McGrath, 2019). Partisanship in the USA with respect to climate change has evolved over the period 1997–2016; initially, it was limited, but since 2008, there has been a widening, more entrenched partisan 'divide' (Dunlap et al., 2016). The millennial generation (born in the 1980s and 1990s), emerging as the largest US population cohort, has a potentially important political influence–reduction in polarisation–as they show relatively higher levels of concern and acceptance of climate-change science than older age groups. Political affiliation does not have as strong an effect on their climate change beliefs (Corner et al., 2015; Ross et al., 2019).

Communicating to educate or enhance knowledge on climate-change science or consensus can, but does not necessarily lead individuals to revise their beliefs (*medium confidence*) (Bolsen et al., 2015; Druckman and McGrath, 2019). People may reject new information that conflicts with their beliefs or not consider it credible, as political ideology and partisan affiliation are strong influences (Arbuckle, 2017). The climate-change issue may create resistance from individuals with conservative political ideologies and hierarchical, individualistic world views because it ascribes responsibility to developed, industrialised countries for emissions and brings about more environmental regulation (Stevenson et al., 2015). Lack of trust in scientific consensus on climate change may actually originate from opposition by US conservatives to the perceived advocacy for different climate-change policy approaches that challenge their world views (Bolsen and Druckman, 2018).

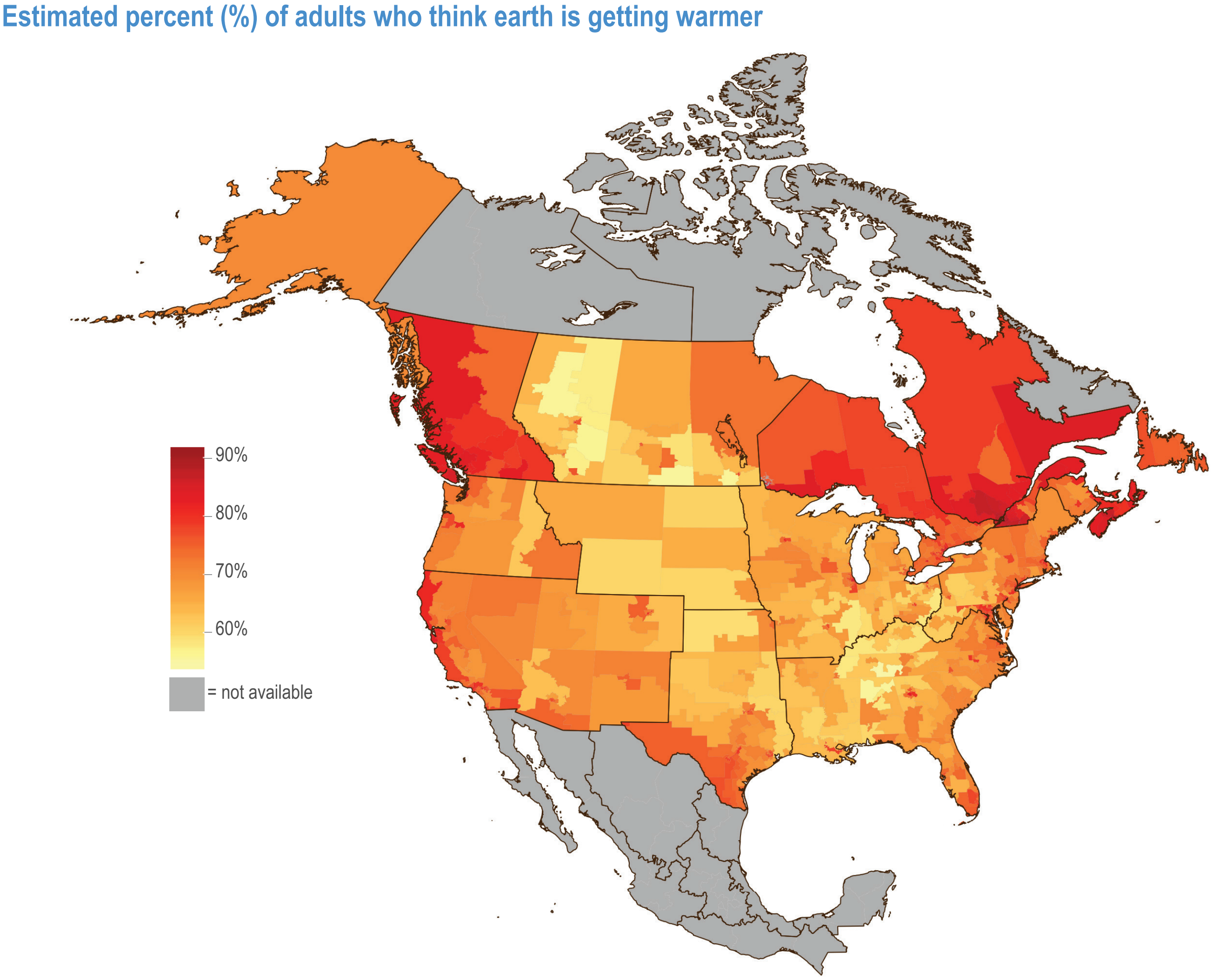

Figure 14.3 | Regional distribution of public perception that 'the Earth is getting warmer' as a surrogate for public acceptance that climate change is happening (percent of population). Scale is the Canadian federal electoral district or riding level and US congressional district. The three northern territories and Labrador, in Canada, did not meet population thresholds for modelling. The figure updates Mildenberger et al. (2016) and is based on equivalent public surveys in both countries: Canadian 'Earth is getting warmer' and US 'global warming is happening' undertaken in 2019. Equivalent surveys and modelling for Mexico are not available at the time of writing.

14.3.4 Factors Influencing Perceptions of Climate-Change Risks and Adaptation Action

Projected climate-change risk, urgency and necessary adaptations are perceived and understood differently by the public, communities, professional groups, climate scientists and public policy makers (*high confidence*) (Bolsen et al., 2015; Drews and Van den Bergh, 2016; Morton et al., 2017; Treuer et al., 2018). People can engage with climate change across three dimensions: cognitive (knowledge), affective (feelings) and behavioural (responses and actions) (Galway, 2019; Brosch, 2021). Risk assessment can be influenced by values regarding the subject under evaluation (Allison and Bassett, 2015; Stevenson et al., 2015) and can interact with other risks and change over time (Mach et al., 2016). Communities and practitioners (e.g., farmers, foresters, water managers) are influenced in their willingness to modify current practices and adopt new measures based on how they perceive, understand and experience climate-change uncertainty, risk and urgency as well as political and social norms (van Putten et al., 2015; Doll et al., 2017; Mase et al., 2017; Morton et al., 2017; Zanocco et al., 2018). Place-based and local-focused assessments allow individuals to more readily assess and adapt to risks as well as identify roles and responsibilities in the face of multiple, interacting and often unequally distributed climate-change impacts (Khan et al., 2018; Galway, 2019). Interest in preserving local archaeological sites threatened by SLR initiated collaboration and co-production of knowledge among disparate US communities: citizens, archaeologists, preservationists, planners, land managers and Indigenous Peoples (Fatorić and Seekamp, 2019; Dawson et al., 2020).

Psychological distancing–the perception that the greatest impacts occur sometime in the distant future and to people and places far away–can lead to discounting of risk and the need for adaptation (*medium confidence*) (Leviston et al., 2014; Mildenberger et al., 2019). Communication directed at local and personal framing of climate-change impact and risk information is one option for addressing low salience (Bolsen et al., 2019) particularly related to established risks such as SLR, flooding and wildfires in North America (Mildenberger et al., 2019). 'Personalised' risk communications have had mixed results creating behavioural change and policy support, and even caused resistance (Schoenefeld and McCauley, 2016). Communication focused extensively on risks and dangers of climate change can produce fear or dread, lessen agency and create fatalism that hinders action (Giddens, 2015; Mayer and Smith, 2019); it also can be labelled alarmist (Leiserowitz, 2005). Detailed SLR flooding maps for the San Francisco Bay area did not increase climate risk assessment but lessened personal risk perception of those with a strong belief in climate change, although policy preferences and support for adaptation did not change (Mildenberger et al., 2019). Defining coherent groups based on variations in beliefs, risk perceptions and policy preferences offers opportunities for effectively engaging with segments of the population instead of using the same approach for everyone (*low confidence*) (Maibach et al., 2011; Chryst et al., 2018). As an example, the US population was segmented into a continuum ranging from the 'Alarmed', the dominant group who were 'Concerned', then the Cautious, Disengaged, Doubtful, and least prevalent, the Dismissive (Chryst et al., 2018).

14.4 Indigenous Peoples and Climate Change

Indigenous knowledge and science are resources for understanding climate-change impacts and adaptive strategies (*very high confidence*) (SM14.1; Table SM14.1). The Indigenous Peoples of North America have contributed substantially to, and *continue* to contribute to, the growing literature, scholarship and research on climate change (Barreiro, 1999; Houser et al., 2001; Mustonen, 2005; Bennett et al., 2014; Maynard, 2014; Merculieff et al., 2017; FAQI, 2019; Ijaz, 2019; BIA, 2021). For thousands of years, Indigenous Peoples have developed and relied on their own knowledge systems for sustaining their health, cultures and arts, livelihoods and political security (Battiste and Henderson, 2000; Colombi, 2012; Nelson and Shilling, 2018). Diverse IK systems in North America consider weather and climate as major dimensions of understanding the relationship between society and the environment. Indigenous Peoples have distinct knowledge of climate change, over extensive temporal measures (Trosper, 2002; Barrera-Bassols and Toledo, 2005; Gearheard et al., 2013). The basis of this knowledge is often Indigenous Peoples' long and profound relationships with the environment, that is, to the ecosystems, waters, ice, lands, territories and resources in their homelands. The relationships have been forged by adaptation to a particular environment and involve systematic activities. Indigenous harvesters, including hunters, fishers, agriculturalists and plant gatherers, observe and monitor environmental change, and engage in systematic reflection with one another about trends over short- and long-term periods (Sakakibara, 2010; Sánchez-Cortés and Chavero, 2011; Kermoal and Altamirano-Jiménez, 2016; Metcalfe et al., 2020b). The holistic perspective of the interrelated and interdependent nature of ecosystems is a distinct characteristic of IK and often contrasts with findings and results of science alone. Indigenous harvesters, agriculturalists, leaders, culture bearers, educators and government employees develop theoretical and practical knowledge of seasonal and climate change that seeks to furnish the best available knowledge and information to inform climate-change policy and decisions (Barrera-Bassols and Toledo, 2005; McNeeley and Shulski, 2011). Examples of theoretical knowledge systems include Indigenous calendars of seasonal change and systems of laws and protocols for environmental stewardship (see Box 14.1) (Kootenai Culture Committee, 2015; Donatuto et al., 2020).

The practice and use of IK systems is recognised and affirmed by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (UNGA, 2007), and consistent with reports and guidance from UN bodies including the High Commissioner for Human Rights (Bachelet, 2019), Expert Mechanism on the Rights of Indigenous Peoples (UNGA, 2015; UNGA, 2018), the Permanent Forum of Indigenous Issues (Dodson, 2007; Cunningham Kain et al., 2013; Sena and UNPFII, 2013; Sena, 2014; Quispe and UNPFII, 2015) and the Special Rapporteur on the Rights of Indigenous Peoples (Cross-Chapter Box INDIG in Chapter 18; Toledo, 2013; UNGA, 2017). The right to self-determination, control over territorial development and cultural integrity make it important that climate scientists practise equitable engagement of IK and IK holders. There is a growing literature of success and lessons learned from co-production of knowledge between IK systems and diverse scientific traditions relating to climate change (Behe et al., 2018; Latulippe and Klenk, 2020; Camacho-Villa et al., 2021).

Current and projected climate-change impacts disproportionately harm Indigenous Peoples' livelihoods and economies (*very high confidence*). Indigenous Peoples' livelihoods in North America include a range of activities closely tied to traditional lands, waters and territories. These activities support a core economic base and an array of sustenance, including financial stability, food security, health and nutrition, safety, and adequate provisions and reserves of important supplies and resources, as well as the passing down of traditional knowledge. Indigenous lives and livelihoods are at risk in the following ways: Indigenous persons are more at risk of losing their lives due to factors that are exacerbated by climate-change impacts (Ford et al., 2006; Barbaras, 2014; Khalafzai et al., 2019). Indigenous Peoples' livelihood practices are being distressed, interrupted and, in some cases, made entirely inaccessible. Livelihood activities known and anticipated to be impacted by climate change are food security (Meakin and Kurtvits, 2009; Wesche and Chan, 2010; Nyland et al., 2017), harvesting of fish, plants and wildlife (Dittmer, 2013; Parlee et al., 2014; Jantarasami et al., 2018b; ICC Alaska, 2020), agriculture (St Regis Mohawk Tribe, 2013; Shinbrot et al., 2019; Settee, 2020), transportation (Swinomish Indian Tribe Community, 2010; Hori et al., 2018a; Hori et al., 2018b), and tourism and recreation (ICC Canada, 2008). Indigenous Peoples have been active in gathering to assess the impacts of climate change on their livelihoods, one example being the Bering Sea Elders Advisory Group (Bering Sea Elders Advisory Group and Alaska Marine Conservation Council, 2011; Bering Sea Elders Group, 2016).

Climate-change impacts have harmful effects on Indigenous Peoples' public health, physical health and mental health, including harmful effects connected to the cultural and community foundations of health (*very high confidence*). Health and climate change is a major issue for Indigenous Peoples (Section 14.5.6; Ford, 2012; Ford et al., 2014; Gamble et al., 2016; Jantarasami et al., 2018b; Middleton et al., 2020a; Donatuto et al., 2021). Climate-change impacts and risks affect Indigenous Peoples' health negatively in different ways. Indigenous health, as tied to nutrition and exercise, is threatened when local foods

Box 14.1 | Integrating Indigenous 'Responsibility-Based Thinking' into Climate-Change Adaptation and Mitigation Strategies

Indigenous Peoples throughout North America have experienced five centuries of territorial expropriation, loss of access to natural resources and, in many cases, barriers to the use of their sacred sites (Gabbert, 2004; Louis, 2007). The history of Indigenous struggles to preserve distinct cultural knowledge and assert autonomy in the face of colonialism has shaped land-use patterns and relationships with traditional territories (Cross-Chapter Box INDIG in Chapter 18; Alfred and Corntassel, 2005; Tuhiwai Smith, 2021). Climate change is now creating additional challenges for Indigenous Peoples. For example, increased water scarcity due to higher temperatures and diminished precipitation have led to reduced crop yields for Maya farmers in Yucatan (Sioui, 2019). Thawing permafrost in subarctic Canada (Quinton et al., 2019) has interfered with the land-based livelihoods of the Indigenous Dene Peoples (CCP6).

Recent climate-related changes represent cultural threats similar to the ones that occurred when European settlement began in the Americas over 500 years ago (Whyte, 2016; Whyte, 2017). Thus, for Indigenous Peoples, who often disproportionately bear the impacts of climate change, such changes are not novel, but seen as *déjà vu* (Whyte, 2016). Since livelihoods and subsistence are often directly dependent on the land and water, Indigenous Peoples have direct insights into the localised impacts of global environmental change. Indeed, Indigenous Peoples consider themselves stewards of the land (and water), and have a spiritual duty to care for the land and its flora, fauna and aquatic community, or 'Circle' of beings. Indigenous knowledge (IK) has gained recognition for its potential to bolster Western scientific research about climate change. Many recent examples demonstrate the scientific value of IK for resource management in climate-change adaptation and mitigation (e.g., Kronik and Verner, 2010; Maldonado et al., 2013; Wildcat, 2013; Etchart, 2017; Nursey-Bray et al., 2019). For example, Indigenous practices have not only contributed to the present understanding of North American forest fires, but also that the practice of frequent small-scale anthropogenic fires, also called cultural burns, is a key method to prevent large-scale destructive fires (Section 14.7.1). The growing interest and recognised value in these practices, particularly in California, has led to formal agreements with state and federal agencies (Long et al., 2020a; Lake, 2021).

Indigenous relationships with the land are commonly informed and guided by a cultural ethic of 'responsibility-based thinking' (Sioui and McLeman, 2014). The Indigenous cultural ethic informs and mediates personal and collective conduct with a sense of duty or responsibility towards human and other-than-human relations (see Sioui, 2020). The Indigenous responsibility-based outlook stems from a cultural paradigm that understands that it is human beings who must learn to live *with* the land (Cajete, 1999; Pierotti and Wildcat, 2000; McGregor et al., 2010a; McGregor, 2014). This way of thinking instils in its adherents an inherent awareness that the other-than-human realm is capable of existing and thriving without humans. Thus, it is for our own sake (as humans) that we learn to live according to certain ever-shifting parameters, requiring us to remain acutely attuned to our physical surroundings. This Indigenous cultural precept is perhaps among the most significant contributions of Indigenous Peoples to the rest of humanity in the face of climate change.

Indigenous relationships with natural systems continue to be mediated by cultural orders of governance and legal systems that pre-date, by several millennia, European traditions in North America. Napolean (2012) describes Indigenous legal orders as dynamic and encompassing knowledge that is simultaneously legal, religious, philosophical, social and scientific. Customary Indigenous legal orders (e.g., Borrows, 2002; Napolean, 2012) stand in contrast to Eurocentric understandings of law, which are closely related to, and founded on, the Western principles of rights. Indigenous legal orders are based on duties, obligations and responsibilities to the land and all beings, including humans, animals, plants, future generations and the departed/ancestors (Borrows, 2002; Borrows, 2010a; Borrows, 2010b; Borrows, 2016). Indigenous spiritual laws are centred on the values of responsibility and accountability to the land, and how these differ, in theory and in practice, from Western law, which is based on 'universal' principles, with little consideration for the local environmental context (Craft, 2014). Research has elucidated these Indigenous understandings about how their land-based responsibilities act as the foundation of how humans must operate according to the land on which they live and depend.

With increasing climate-change threats to land-based subsistence and cultural practices, Indigenous Peoples are increasingly taking their rightful leadership roles in resource co-management arrangements and other stewardship activities (Section 14.5.2.2). Indeed, Indigenous Peoples are increasingly assuming leadership positions with regard to land governance and climate-change action, as the stewards of their traditional territories since time immemorial. Therefore, it is imperative for Indigenous scholars, Elders and knowledge holders to occupy leadership roles in climate-change adaptation and mitigation, especially when *their* territories are concerned (Section 14.7; CCP6). For instance, Indigenous 'resurgence' paradigms draw on the strengths of traditional land-based culture and knowledge with regard to Indigenous leadership in land governance and stewardship (Alfred and Corntassel, 2005; Alfred, 2009; Simpson, 2011; Corntassel and Bryce, 2012; Coulthard, 2014; Alfred, 2015). Indigenous leadership in climate-change policy, therefore, can ensure that Indigenous right to self-determination is respected and upheld to allow Indigenous Peoples to continue to carry out their cultural responsibilities to the land, for the benefit of all North Americans (Powless, 2012; Etchart, 2017).

Box 14.1 (continued)

In northern Canada, a fusion of leading-edge Western science and IK on permafrost informed the co-development of predictive decision-support tools and risk management strategies to inventory and manage permafrost and adapt to permafrost thaw (CCP6). Permafrost thaw in the Dehcho region of Canada is widespread and occurring at unprecedented rates (WGI). The *Dehcho Collaborative on Permafrost* (DCoP) aims to improve the understanding of and ability to predict and adapt to permafrost thaw[3]. DCoP's collaborative approach, which places Indigenous Peoples in leadership positions, generates the new knowledge, predictive capacity and decision-support tools to manage natural resources that support Indigenous Dene Peoples' ways of life. Indigenous–academic partnerships can enhance climate-change adaptation and mitigation capacity, and provide openings for more holistic co-management approaches that recognise and affirm the central role of Indigenous Peoples as stewards of their ancestral territories, especially as they face accelerating climate-change impacts. Academic researchers and their Indigenous partners can support climate-change resilience via mobilising IK in stewardship and adaptation; researching governance arrangements, economic relationships and other factors that hinder Indigenous efforts in these areas; proposing evidence-based policy solutions at international and national scales; and outlining culturally relevant tools for assessing vulnerability and building capacity will also support climate-change resilience. Such IK underpins successful climate-change adaptation and mitigation (*very high confidence*) (see Green and Raygorodetsky, 2010; Kronik and Verner, 2010; Alexander et al., 2011; Powless, 2012; Ford et al., 2016; Nakashima et al., 2018). The inclusion of IK in adaptation and mitigation not only supports Indigenous cultural survival but also enables governments to recognise the territorial sovereignty of Indigenous Peoples.

Responsibility-based philosophies of Indigenous Peoples from across the continent support the development of climate-change adaptation and mitigation strategies that promote responsible and respectful relationships with the environment over the long term. Adapting to change, in all its forms, has since time immemorial been one of the defining characteristics of Indigenous cultures on Turtle Island (the American continent). In Yucatan, one Elder explained that with regards to climate-change impacts in the region, the Maya have always dealt with *k'ech*, or change, and that accepting and responding to change is part of the Maya identity and responsibility (Sioui, 2020). Given successive failures in adequately and effectively responding to climate change, it has become urgent for the rest of the human collective to (re)learn from Indigenous cultures to (re)consider our responsibility/ies to the land—the world over—and to reorient our societal imperatives to better respond and react to *change*. Such a process of learning from IK could foster the development of climate-change policies that promote responsible and respectful relationships with the environment over the long term, and prove to be more effective and holistic. Although most inhabitants of North America are non-Indigenous, it is possible and beneficial for our societies to learn to think and act in a more responsibility-based way about our relations to the land, and, by extension, about climate-change policy. A collective commitment to protecting and advancing Indigenous territorial rights, so Indigenous Peoples can continue to reassert their spiritual duty and role as stewards of their traditional territories, benefits all human and other-than-human 'Peoples'.

are less available and harvesting activities are less possible to practise (Norton-Smith et al., 2016b; Rosol et al., 2016; Gonzalez et al., 2018). Indigenous Peoples experience widespread public health concerns from severe droughts (Stewart et al., 2020; Schlinger et al., 2021; Wiecks et al., 2021), extreme heat (Doyle et al., 2013; Campo Caap, 2018; Kloesel et al., 2018a; Meadow et al., 2018; ITK, 2019; Ute Mountain Ute Tribe and Wood Environment Infrastructure Solutions Inc, 2019; Whyte et al., 2021), unpredictable precipitation patterns (Chavarria and Gutzler, 2018; Tom et al., 2018; Tlingit and Haida, 2019; Schlinger et al., 2021), flooding and coastal erosion (Jamestown S'klallam Tribe, 2016; Norton-Smith et al., 2016b; Puyallup Tribe of Indians, 2016; Marks-Marino, 2019; Ristroph, 2019; Marks-Marino, 2020b; Schlinger et al., 2021), wildfires and wildfire smoke (Edwin and Mölders, 2018; USEPA, 2018; Christianson et al., 2019a; ITK, 2019; Marks-Marino, 2020a; Mottershead et al., 2020; Woo et al., 2020; Wiecks et al., 2021), algal blooms (Peacock et al., 2018; Gobler, 2020; Donatuto et al., 2021; Preece et al., 2021; Schlinger et al., 2021), storms and hurricanes (Rioja-Rodríguez et al., 2018), influxes of invasive species (Pfeiffer and Huerta Ortiz, 2007; Pfeiffer and Voeks, 2008; Voggesser et al., 2013; Bad River Band of Lake Superior Tribe of Chippewa Indians and Abt Associates Inc., 2016; Scott et al., 2017; Reo and Ogden, 2018; Middleton et al., 2020a) and changing production systems (Rioja-Rodríguez et al., 2018). Indigenous Peoples' mental health is at risk and has already been affected negatively by climate change (Donatuto et al., 2021). Water security is one of the most serious concerns to Indigenous Peoples' health and well-being (Vanderslice, 2011; Cozzetto et al., 2013a; Redsteer et al., 2013; Hanrahan et al., 2014; Chief et al., 2016; Gamble et al., 2016; Jantarasami et al., 2018b; Kloesel et al., 2018a; Tom et al., 2018; Martin et al., 2020a; Arsenault, 2021). When some people are less able to practise traditional, cultural, social and family activities, they can become alienated, compounding the negative effects of traumas Indigenous persons already experience. Traumas include historic and continuing land dispossession, assimilation, social marginalisation and discrimination, and food and financial insecurities. The practise of cultural traditions are associated with education, harvesting and agriculture, exercise, positive social relationships and family life, which play foundational roles in the achievement of physical, public and mental health (Bell et al., 2010; Cunsolo Willox et al., 2015; Jantarasami et al., 2018b; Norgaard and Tripp, 2019; Billiot et al., 2020b; Adams et al., 2021; Donatuto et al., 2021).

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[3] See http://scottycreek.com/DCoP

Indigenous Peoples are affected dramatically by climate-related disasters and other climate-related extreme environmental events (*very high confidence*). Indigenous Peoples face numerous threats and have already been harmed by, and are planning for, extreme weather events with associations to climate change, including hurricanes and tornadoes (Oneida Nation Pre-Disaster Mitigation Plan Steering Committee and Bay-Lake Regional Planning Commission, 2016; Emanuel, 2019; Cooley, 2021; Marks-Marino, 2021; Zambrano et al., 2021), heatwaves (Confederated Tribes of the Umatilla Indian Reservation, 2016; Wall, 2017; La Jolla Band of Luiseno Indians, 2019; Mashpee Wampanoag, 2019; Wiecks et al., 2021), ocean warming and MHWs (Hoh Indian Tribe, 2016; Port Gamble S'klallam Tribe, 2016; Port Gamble S'klallam Tribe, 2020; State of Alaska, 2020; Muckleshoot Tribal Council, 2021; Port Gamble S'klallam Tribe, 2021), wildfires (Voggesser et al., 2013; Billiot et al., 2020a; Cozzetto et al., 2021b; Gaughen et al., 2021; Morales et al., 2021; National Tribal Air Association, 2021; Zambrano et al., 2021), permafrost thaw (Haynes et al., 2018; Low, 2020), flooding (Riley et al., 2011; Ballard and Thompson, 2013; Brubaker et al., 2014; Thompson et al., 2014; Burkett et al., 2017; Quinault Indian Nation, 2017; Ristroph, 2019; Sharp, 2019; Thistlethwaite et al., 2020) and drought (Knutson et al., 2007; Chief et al., 2016; Redsteer et al., 2018; Sioui, 2019; Bamford et al., 2020; Sauchyn et al., 2020). Some Indigenous Peoples are facing climate-change impacts that generate community-led permanent relocation and resettlement as an adaptation option (Maldonado et al., 2021). Coastal erosion is one climate-change issue that is often connected to Indigenous Peoples planning to resettle, including vulnerability connected to higher sea levels and storm surges (Quinault Indian Nation, 2017; Bronen et al., 2018; Affiliated Tribes of Northwest Indians, 2020). Adapting to new settlement areas threatens the continuity of communities. In a number of cases, Indigenous Peoples' having less access to adequate infrastructure is a driver of vulnerability to climate-related disasters and extreme weather events (Doyle et al., 2018; Patrick, 2018; Cozzetto et al., 2021a; Indigenous Climate Action et al., 2021). Disasters and extreme events are particularly severe when their impacts are compounded by inadequate infrastructure. Lack of flood protection infrastructure on Indigenous reserve communities leads to displacement, loss of homes and perpetuates disproportionate levels of risk to extreme weather events (Cunsolo et al., 2020; Fayazi et al., 2020; Yellow Old Woman-Munro et al., 2021).

Indigenous self-determination and self-governance are the foundations of adaptive strategies that improve understanding and research on climate change, develop actionable community plans and policies on climate change, and have demonstrable influence in improving the design and allocation of national, regional and international programmes relating to climate change (*very high confidence*). Historical and contemporary developments have crystallised international norms recognising the distinct status, role and rights of Indigenous Peoples in the form of significant international human rights instruments. Premier among them is the UNDRIP (UNGA A/RES/61/295), which has received universal consensus since its adoption by the UN General Assembly. The UN member States have affirmed the right of self-determination (Article 3, UNDRIP) regarded as the prerequisite to the exercise and enjoyment of all other human rights.

The integrity of the environment is impacting all of humanity, including Indigenous Peoples, their lands, territories, resources and their communities. Through self-determination, durable, sustainable and robust contributions from those with close, symbiotic relationships with the environment can be revealed in favour of all humanity. Indigenous Peoples of North America have been engaged in wide-ranging activities to address climate change (Doolittle, 2010; Parker and Grossman, 2012; Abate and Kronk, 2013; STACCWG, 2021). They include actions in the spheres of education (Donatuto et al., 2020; McClain, 2021; Morales et al., 2021), development of IK and science (Maldonado et al., 2016; AFN, 2020; Ferguson and Weaselboy, 2020; Huntington et al., 2021a; Jones et al., 2021; Sawatzky et al., 2021), adaptation planning and implementation (Angel et al., 2018a; Tribal Climate Adaptation Guidebook Writing Team et al., 2018; Hepler and Kronk Warner, 2019; Tribal Adaptation Menu Team, 2019; Metcalfe et al., 2020b), and political action and diplomacy (including treaty-based diplomacy) (Grossman, 2008; Kronk Warner and Abate, 2013; Callison, 2015).

14.5 Observed Impacts, Projected Risks and Adaptation by Sector

14.5.1 Terrestrial and Freshwater Ecosystems and Communities

14.5.1.1 Terrestrial Ecosystems: Observed Impacts and Projected Risks

Evidence continues to mount about the impacts of recent climate change on species and ecosystems (*very high confidence*) (Table 14.2; Weiskopf et al., 2020). Ranges and abundances of species continue to shift in response to warming throughout North America (*very high confidence*) (Cross-Chapter Box MOVING PLATE in Chapter 5; Cavanaugh et al., 2014; Molina-Martínez et al., 2016; Tape et al., 2016; Miller et al., 2017; Pecl et al., 2017; Zhang et al., 2018a). Future climate change will continue to affect species and ecosystems (*high confidence*) (IPBES, 2018), with differential responses related to species characteristics and ecology (D'Orangeville et al., 2016; Weiskopf et al., 2019). Climate change is projected to adversely affect the range, migration and habitat of caribou, an important food and cultural resource in the Arctic (CCP6; Leblond et al., 2016; Masood et al., 2017; Barber et al., 2018b; Borish, 2022).

Climate-induced shifts in the timing of biological events (phenology) continue to be a well-documented ecological response (*very high confidence*) (Table 14.2; Vose et al., 2017; Lipton et al., 2018; Vose et al., 2018; Molnar et al., 2021). Reduced snow season length may potentially lead to adverse camouflage effects on animals that change coat colour (Mills et al., 2013; Mills et al., 2018). Human conflicts with bears are expected to increase in response to shifts in hibernation patterns (Johnson et al., 2018) and food resources (Wilder et al., 2017; Wilson et al., 2017).

Severe ecosystem consequences of warming and drying are well documented (*very high confidence*) (Table 14.2). Significant ecosystem changes are expected from projected climate change (*high confidence*), such as in Mexican cloud forests (Helmer et al., 2019), North American rangelands (Polley et al., 2013; Reeves et al., 2014) and montane forests (Stewart et al., 2021; Wright et al., 2021). Permafrost thaw is projected to increase in Alaska and Canada (DeBeer et al., 2016; see also Ranasinghe et al., 2021), accelerating carbon release (CCP6, see also Canadell et al., 2021) and affecting hydrology. Predicting which species or ecosystems are vulnerable is challenging (Stephenson et al., 2019), although palaeoecological data (e.g., pollen, tree rings) provide context from past events to better understand current and future transformations (Nolan et al., 2018).

Climate-change impacts on natural disturbances have affected ecosystems (*very high confidence*) (Table 14.2; see Box 14.2), and these impacts will increase with future climate change (*medium confidence*). Facilitated by warm, dry conditions, 'mega-disturbances' and synergies between disturbances that include wildfires, insect and disease outbreaks, and drought-induced tree mortality continue to affect large areas of North America (Cohen et al., 2016; Young et al., 2017a; Hicke et al., 2020), overwhelming adaptive capacities of species and degrading ecosystem services (Millar and Stephenson, 2015; Stewart et al., 2021). This era of mega-disturbances is expected to become more widespread and severe in coming decades (Cook et al., 2015; Seidl et al., 2017; Buotte et al., 2019), with potentially significant impacts on ecosystems (Allen et al., 2015; Crausbay et al., 2017; Schwalm et al., 2017; Coop et al., 2020; Dove et al., 2020 Thompson et al. 2020, Stewart et al. 2021). Effects include widespread tree mortality (Allen et al., 2015; Kane et al., 2017; van Mantgem et al., 2018) and accelerated ecosystem transformation (*medium confidence*) (Guiterman et al., 2018; Crausbay et al., 2020; Munson et al., 2020).

14.5.1.2 Freshwater Ecosystems: Observed Impacts and Projected Risks

Climate change, either directly (warming water) or indirectly (glacier and snow inputs), has affected biogeochemical cycling and species composition in North American aquatic ecosystems (*very high confidence*) (Table 14.2; Moser et al., 2005; Saros et al., 2010; Preston et al., 2016), possibly amplifying other human-caused stresses on these systems (Richter et al., 2016). Excess nutrients associated with high farm animal density can be transported during intense rainfall events (expected to increase with climate change) causing algal blooms, fish kills and other detrimental ecological effects (Huisman et al., 2017; Coffey et al., 2019).

Projected climate change will cause habitat loss, alter physical and biological processes, and decrease water quality in freshwater ecosystems (*high confidence*) (Poesch et al., 2016; Crozier et al., 2019). Projected river warming of 1°C–3°C is expected to reduce thermal habitat for important salmon and trout species in the northwest USA by 5–31% (Isaak et al., 2018) and in Mexico (Meza-Matty et al., 2021), and for multiple fish species in Canada (Poesch et al., 2016). Cold-water streams at higher elevations will warm less and therefore may become climate refugia (Isaak et al., 2016). Projected warming of mountain lake ecosystems (Roberts et al., 2017b; Redmond, 2018) will affect ecosystem processes (Preston et al., 2016; Redmond, 2018; Moser et al., 2019). Loss of cold-water inputs from retreating glaciers are expected to adversely affect alpine stream ecosystems (Fell et al., 2017; Giersch et al., 2017). For anadromous fish species (e.g., Chinook salmon), future warming will reduce habitat suitability from river headwaters to oceans (Crozier et al., 2021).

Freshwater ecosystems across North America are increasingly at risk from extreme drought, compounded by human demands for water (Section 14.5.3; Kovach et al., 2019). Implications for aquatic and riparian species can vary, but it is widely agreed that these systems are highly sensitive to fluctuations in the hydrological cycle, which can increase competition by invasive species and compromise connectivity between potential cold-water refugia (Melis et al., 2016; Poff, 2019).

14.5.1.3 Adaptation in Terrestrial and Freshwater Ecosystems

Adaptation efforts to assess vulnerability of species and ecosystems, predict adaptive capacity and identify conservation-oriented options have increased markedly across North America (e.g., Hagerman and Pelai, 2018; Keeley et al., 2018; Thurman et al., 2020; Peterson St-Laurent et al., 2021; Thompson et al., 2021). Scenario-based planning, an approach for addressing uncertainty, continues to gain traction and is regularly applied by the US National Park Service (Star et al., 2016). Nonetheless, barriers to implementation of specific actions often exist (e.g., inflexible policies, lack of resources and stakeholder buy-in, political will), hampering progress (Stein et al., 2013; Shi and Moser, 2021). Efforts to evaluate the efficacy of implemented adaptation actions are also lacking (Prober et al., 2019), but some cases show progress. For example, ongoing efforts are quantifying how variable water releases from the Colorado River's Glen Canyon Dam affect endangered fish species (Melis et al., 2016). Nature-based Solutions (NbS) for adaptation (see Box 14.7) are increasingly being evaluated, especially at larger scales.

Effective climate-informed ecosystem management requires a well-coordinated suite of adaptation efforts (e.g., assessment, planning, funding, implementation and evaluation) that is co-produced among stakeholders, Indigenous Peoples and across sectors (*high confidence*) (Millar and Stephenson, 2015; Dilling et al., 2019). New applications of conventional strategies can be modified to achieve conservation goals under climate change (USGCRP, 2019). For example, mechanical thinning and prescribed burning (to reduce fuel loads and benefit ecosystems) could be used in combination with planting species better suited to new conditions to build resilience in western US forests to longer and hotter drought conditions (Bradford and Bell, 2017; Vernon et al., 2018). Protection of buffer areas, such as riparian strips in arid regions and boreal ecosystems, reduces water temperature, builds resistance to invasive species, increases suitable habitat (Johnson and Almlof, 2016) and facilitates protection of freshwater systems from runoff during and after intense rain events (National Research Council, 2002).

Innovative approaches may facilitate species' responses to climate change, particularly when vulnerability is exacerbated by habitat loss and fragmentation. Strategies include improved landscape connectivity for species dispersal (Carroll et al., 2018; Littlefield et al., 2019; Lawler et al., 2020; Thomas, 2020) or assisted migration (also called managed relocation) to climatically suitable locations (Schwartz et al., 2012; Dobrowski et al., 2015). Examples include translocation of salmon in the Columbia River (Holsman et al., 2012), genetic rescue (i.e., assisted gene flow increases genetic diversity to address local maladaptation) (Aitken and Whitlock, 2013) and locating and conserving climate refugia, such as in alpine meadows of the Sierra Nevada (Javeline et al.,

Table 14.2 | Examples of observed climate-change impacts on terrestrial and freshwater ecosystems

Impact	References
Local extinctions	Pomara et al. (2014); Wiens (2016)
Greening and increased productivity of North American vegetation from CO_2 fertilisation	Smith et al. (2016b); Zhu et al. (2016); Huang et al. (2018)
Changes in phenology, including migration as well as mismatches between species and with human visitation	Mayor et al. (2017); Zaifman et al. (2017); Breckheimer et al. (2020)
Vegetation conversions, including	
– shifts to denser forests with smaller trees	McIntyre et al. (2015)
– trees to savannas and grasslands	Bendixsen et al. (2015)
– woody plant encroachment into grasslands	Archer et al. (2017)
– changes in tundra plant phenology and abundance	Myers-Smith et al. (2019)
– expansion of boreal and subalpine forests into tundra, meadows	Juday et al. (2015); Lubetkin et al. (2017)
– reduced or lack of recovery following severe fire	Coop et al. (2020); O'Connor et al. (2020); see Box 14.2
Warmer droughts reducing plant productivity and carbon sequestration	Mekonnen et al. (2017); Gampe et al. (2021)
Slowing ecosystem function recovery of vegetation to pre-disturbance conditions following droughts	Schwalm et al. (2017); Crausbay et al. (2020)
Warming streams and lakes, and changes in seasonal flows that have affected freshwater fish distributions and populations	O'Reilly et al. (2015); Lynch et al. (2016); Poesch et al. (2016); Roberts et al. (2017b); Isaak et al. (2018); Christianson et al. (2019b); Zhong et al. (2019)
Upstream expansion of human-mediated invasive hybridisation and enhanced risk of extinction of native salmonid species	Muhlfeld et al. (2014)
Declining wetlands in western North America important for bird migrations	Donnelly et al. (2020)
Increases in harmful freshwater algal blooms	See Section 14.5.3

2015; Morelli et al., 2016). Maintaining diverse spawning habitats and salmon runs can increase resilience of salmonid populations to climate change (Schoen et al., 2017; Crozier et al., 2021). Newer modelling approaches can facilitate the visualisation of future management scenarios, per a recent study of fires in the southwest USA (Loehman et al., 2018), in addition to technologies in genomics for monitoring species and modifying adaptive traits (Phelps, 2019).

Adaptation actions have important limitations (Dow et al., 2013), particularly in the context of biodiversity conservation goals. 'Hard' limits include species extinctions and vegetation mortality events, despite conservation action (i.e., besides significant emissions reductions to mitigate warming, few if any interventions could have prevented these losses). In contrast, 'soft' adaptation limits exist primarily as a function of the social–ecological value systems of local communities and government entities that are reflected as goals and objectives in their management plans for ecosystems and species across North America. Soft limits are often mutable or can be removed altogether (Dow et al., 2013). In contrast, human modifications of landscapes that change or irreparably damage can limit adaptation by reducing connectivity and therefore range shifts (Parks and Abatzoglou, 2020).

14.5.2 Ocean and Coastal Social–Ecological Systems

14.5.2.1 Observed Impacts and Projected Risks of Climate Change

Warming of surface and subsurface ocean waters has been broadly observed across all North American marine ecosystems from the polar Arctic to the subtropics of Mexico (*virtually certain*) (Hobday et al., 2016; Jewett and Romanou, 2017; Pershing et al., 2018; Smale et al., 2019). Higher ocean temperatures have directly affected food-web structure (Gibert, 2019) and altered physiological rates, distribution, phenology and behaviour of marine species with cascading effects on food-web dynamics (*very high confidence*) (Gattuso et al., 2015; Pinsky and Byler, 2015; Sydeman et al., 2015; Poloczanska et al., 2016; Frölicher et al., 2018; Le Bris et al., 2018; Free et al., 2019; Stevenson and Lauth, 2019; Barbeaux et al., 2020; Dahlke et al., 2020). Pacific coastal waters from Mexico to Canada and US mid-Atlantic coastal waters have a high proportion of species (>5% of all marine species) near their upper thermal limit, representing hotspots of risk from MHWs (*medium confidence*) (Smale et al., 2019; Dahlke et al., 2020). Kelp, a macroalgae, forms important habitat for other marine species, and its biomass has decreased 85–99% in the past 40–60 years off Nova Scotia, Canada, replaced by invasive and turf algae; this is associated directly with warming waters (Filbee-Dexter et al., 2016).

Climate change has induced phenological and spatial shifts in primary productivity with cascading impacts on food webs (*high confidence*) (Siddon et al., 2013; Stortini et al., 2015; Sydeman et al., 2015; Stanley et al., 2018). This includes widespread starvation events of fish, birds (e.g., tufted puffins in Bering Sea in 2016–2017 and Cassin's Auklets in British Columbia in 2014–2015) and marine mammals (grey whales along both coasts of North America) (Sydeman et al., 2015; Duffy-Anderson et al., 2019; Jones et al., 2019b; Cheung and Frölicher, 2020; Piatt et al., 2020), which challenge protected species and fisheries management (Section 14.5.4; Chasco et al., 2017; Wilson et al., 2018; Barbeaux et al., 2020; Free et al., 2020; Fisher et al., 2021; Cheung and Frölicher, 2020). Climate change has altered foraging behaviour and distribution of North Atlantic right whales and their target copepod prey (Record et al., 2019) increasing entanglement rates in lobster and snow crab fishing gear on the east coast of the USA and Canada as lobster and crab distributions also shift due to changing water

Box 14.2 | Wildfire in North America

Recent Observations, Attribution to Climate Change and Projections

Anthropogenic climate change has led to warmer and drier conditions (i.e., fire weather) that favour wildland fires in North America (*high confidence*) (see AR6, WGI, Chapter 12, Ranasinghe et al., 2021). In response, increased burned area in recent decades in western North America has been facilitated by anthropogenic climate change (*medium confidence*). Annual numbers of large wildland fires and area burned have risen in the past several decades in the western USA (USGCRP, 2017; USGCRP, 2018), and area burned has increased in Canada (although the number of large fires has declined slightly recently) (Gauthier et al., 2014; Natural Resources Canada, 2018; Hanes et al., 2019). Attribution studies have reported that climate change increased burned area in Canada (1959–1999) (Gillett et al., 2004) as well as the western USA (1984–2015) (Abatzoglou and Williams, 2016) and California (1972–2018) (Williams et al., 2019a). Decreased precipitation was the primary climate-change cause of increased burned area in the western USA, with warming a secondary influence (Holden et al. 2018), whereas warming (through aridity) was most important in a California study (Williams et al., 2019a). A drier atmosphere (including reduced precipitation) has been linked to climate change through altered large-scale atmospheric circulation, which then facilitated greater burned area in the western USA (Zhang et al., 2019c). Through anomalous warm and dry conditions, anthropogenic climate change contributed to the extreme fires of 2016 (Kirchmeier-Young et al., 2019; Tan et al., 2019) in western Canada and the extreme fire season in 2015 in Alaska (Partain et al., 2017). These studies did not include human activities that influence fire–climate relationships (Syphard et al., 2017).

Warming has led to longer fire seasons (Westerling, 2016) and drier fuels (Williams et al., 2019a). Warmer and drier fire seasons in the western USA during 1985–2017 have contributed to greater burned area of severe fires (Parks and Abatzoglou, 2020). Simultaneity in fires increased during 1984–2015 (Podschwit and Cullen, 2020), challenging firefighting effectiveness and resource sharing. In Mexico, fires have been correlated with dry conditions (Kent et al., 2017; Marin et al., 2018; Zuniga-Vasquez et al., 2019). Wildland fire activity in the grasslands of the US Great Plains has increased during the past several decades (Donovan et al., 2017) related to antecedent precipitation or aridity that affected fuel quantity (Littell et al., 2009).

Climate change is projected to increase fire activity in many places in North America during the coming decades (see also AR6, WGI, Chapter 12, Ranasinghe et al., 2021) (Boulanger et al., 2014; Williams et al., 2016; Halofsky et al., 2020), via longer fire seasons (Wotton and Flannigan, 1993; USGCRP, 2017), long-term warming (Villarreal et al., 2019; Wahl et al., 2019) and increased lightning frequency in some areas of the USA and Canada (*medium confidence*) (Romps et al., 2014; Finney et al., 2018; Chen et al., 2021). Unusually extensive and severe fires have occurred in the Arctic tundra during recent extremely warm and dry years, suggesting that continued warming may increase the probability of such fires in the future (Hu et al., 2015). In drier non-forest ecosystems in the western USA, fires are limited by fuel availability and vegetation productivity; warming will decrease productivity, leading to lower burned area (Littell et al., 2018).

Impacts on Natural Systems

Although fire is a natural process in many North American ecosystems, increases in burned area and severity of wildland fires have had significant impacts on natural ecosystems (*medium confidence*). The length of streams and rivers impacted by fire has increased in the USA along with burned area (Ball et al. 2021). Mega-fires can cause major changes in the structure and composition of ecosystems, particularly where human alterations are significant (Stephens et al., 2014; Loehman et al., 2020). Unusually severe fires may have led to the conversion of forest to grassland in the southwest USA (Haffey et al., 2018). Recent warming and drying have limited post-fire tree seedling and shrub establishment, limiting ecosystem recovery (Davis et al., 2019; O'Connor et al., 2020; Rodman et al., 2020). In boreal forests, soil carbon is being lost through increasingly severe or frequent fires (Walker et al., 2019).

Projected future fire activity will continue to affect ecosystems and alter their structure and function (*medium confidence*) (Coop et al., 2020; Loehman et al., 2020). Increased fire activity (Stevens-Rumann et al., 2018; Stevens-Rumann and Morgan, 2019; Turner et al., 2019a; Cadieux et al., 2020), further warming and drying that stresses tree seedlings, and model projections of stand-replacing fires at the forest–non-forest boundary in the western USA (Parks et al., 2019) have raised the possibility of shifts in species composition or vegetation type (Halofsky et al., 2020). These projections suggest high variability in ecosystem responses depending on interactions between vegetation type, moisture stress, disturbances regimes and human alterations (Hurteau et al., 2008; Kitzberger et al., 2017; Littell et al., 2018; Hurteau et al., 2019; Loehman et al., 2020; O'Connor et al., 2020).

Impacts on Human Systems

Increased fire activity, partly attributable to anthropogenic climate change, has had direct and indirect effects on mortality and morbidity, economic losses and costs, key infrastructure, cultural resources and water resources (*medium confidence*), although other factors, such as increasing populations in the wildland–urban interface, have also contributed. During 2000–2018, significant fire events claimed 315 lives in the USA (NOAA, 2019); the economic impacts (e.g., capital, health, indirect losses from economic disruption) from the 2018

Box 14.2 (continued)

California fires were 149 billion USD (Wang et al., 2021). Poor air quality from fires caused increased respiratory distress (*very high confidence*); exposure extends long distances from the fire source (Section 14.5.6.3). In addition to public and private property damage and loss, fires have caused irretrievable losses from archaeological and historical sites (Ryan et al., 2012). Post-fire conditions have created unanticipated challenges for communities' water supply operations (Bladon et al., 2014; Návar, 2015; Martin, 2016) by altering water quality and availability (Smith et al., 2011; Bladon et al., 2014; Robinne et al., 2020) or public safety by increasing exposure to mass wasting events after extreme rainfall events (Cui et al., 2019; Kean et al., 2019). California utilities have proactively shut down parts of their electricity grid to reduce risk of fire during extreme weather, and substantial numbers of people will be increasingly vulnerable to this action in the coming decades (Abatzoglou et al., 2020).

In the USA, annual costs of federal wildland fire suppression have increased by a factor of 4 since 1985 (USGCRP, 2018) and were 1.5–3 billion USD during 2016–2020 (NIFC, 2021). Annual costs of fire protection in Canada have risen two- to threefold from 1970 to 2017, to $1.0–1.4 billion CAD during 2015–2017 (considering the 2017 CAD value) (Natural Resources Canada, 2021). In one of its worst fire seasons, British Columbia expended over 500 million CAD in 2017 for fire suppression (Natural Resources Canada, 2018). The number of days of synchronous fire danger is expected to double in the western USA by 2051–2080, thereby increasing demands on fire suppression resources (Abatzoglou et al., 2021).

The 2016 Fort McMurray fire ranks as the costliest natural disaster in Canada to date (3 billion CAD in insured damages) (Mamuji and Rozdilsky, 2018; IBC, 2020). More than 88,000 people were evacuated; many were not aware of the high pre-existing fire risk and had limited warning to prepare and leave (McGee, 2019). The community subsequently required extensive social support and experienced mental health challenges (Government of Alberta, 2016; Cherry and Haynes, 2017; Mamuji and Rozdilsky, 2018; Brown et al., 2019a; McGee, 2019). Although a broad recovery plan was developed (Regional Municipality of Wood Buffalo, 2016), reconstruction and economic recovery has been slow (Mamuji and Rozdilsky, 2018).

Wildland fire was identified as a top climate-change risk facing Canada (Council of Canadian Academies, 2019) and poses a challenge to communities and fire management (Coogan et al., 2019). Projected area burned in Canada using RCP2.6 will increase annual fire suppression costs to 1 billion CAD the by end of century (60% increase relative to 1980–2009) and to 1.4 billion CAD using RCP8.5 (119% increase) (Hope et al., 2016). In the USA, cumulative costs of fire response through 2100 are projected to be 23 billion USD (considering the 2015 USD value) yr^{-1} under RCP8.5 (EPA, 2017). Lower-emissions scenarios reduce these future cumulative costs by 55 million USD (EPA, 2017) to 7–9 billion USD (considering the 2005 USD value) (Mills et al., 2015a). Fire increases from future warming will reduce timber supply in eastern Canada (Gauthier et al., 2015; Chaste et al., 2019) and increase post-fire sedimentation in watersheds of the western USA (Sankey et al., 2017).

Adaptation

Wildland fire risks are not equitably distributed as they intersect with exposure and socioeconomic attributes (e.g., age, income, ethnicity) to influence vulnerability and adaptive capacity (*medium confidence*) (Wigtil et al., 2016; Davies et al., 2018; Palaiologou et al., 2019). Individuals in rural areas, low-income neighbourhoods and immigrant communities, as well as renters in California, had less capacity to prepare for and recover from fire (Davies et al., 2018). In the USA, 29 million people live in areas with significant potential for wildfires and 12 million are socially vulnerable (Davies et al., 2018). In Canada, there are 117 million ha (14% of total land area) of wildland–human interface, and 96% of populated places have some wildland–urban interface within 5 km (Johnston and Flannigan, 2018).

There is growing recognition of the need to shift fire management and suppression activities to co-exist with more fire on the landscape. This includes widespread use of prescribed fire across landscapes to increase ecological and community-based resilience (*high agreement, medium evidence*) (Schoennagel et al., 2017; McWethy et al., 2019; Tymstra et al., 2020). Otherwise, the unprecedented combination of increased human exposure and size of recent mega-fires creates community risks that may exceed conventional operational and forest management response capacity and budgets (Podur and Wotton, 2010; Wotton et al., 2017; Loehman et al., 2020; Moreira et al., 2020; Parisien et al., 2020) particularly with ongoing population and infrastructure expansion into the wildland–urban interface (Canadian Council of Forest Ministers, 2016; Coogan et al., 2019).

Climate-informed post-fire ecosystem recovery measures (e.g., strategic seeding, planting, natural regeneration), restoration of habitat connectivity and managing for carbon sequestration (e.g., soil conservation through erosion control, preservation of old growth forests, sustainable agroforestry) are critical to maximise long-term adaptation potential and reduces future risk through co-benefits with carbon mitigation (Davis et al., 2019; Hurteau et al., 2019; Coop et al., 2020; Stewart et al., 2021). Innovation in and scaling up the use of prescribed fire and thinning approaches are contributing to pre- and post-fire resilience goals, including use of Indigenous Peoples burning practices that are receiving a new level of awareness (see Box 14.1; Kolden, 2019; Marks-Block et al., 2019; Long et al., 2020b).

Box 14.2 (continued)

The tools FireSmart Canada[1], Firewise USA[2] and Think-Hazard Mexico[3] were devised to reduce fire risks and create fire-resilient communities. They provide design guidance at building, lot, subdivision and community scales, and instruct citizens on creating defensible space (National Fire Protection Association, 2013; Firesmart Canada, 2018). Implementation has been fragmented and variable as it depends on voluntary uptake by individuals, businesses and communities across a range of adaptive capacities and fire-exposed landscapes (Smith et al., 2016a). Many vulnerable groups do not have access to financial or physical resources to reduce fire risk (Collins and Bolin, 2009; Palaiologou et al., 2019).

Although innovative, holistic approaches to wildland fire management are becoming more common across North America, broader application is necessary to address the growing risks (*medium confidence*). A social–ecological perspective blends ecosystem complexity, scale and processes into land-use planning along with community values, perception and capacities as well as institutional arrangements (Smith et al., 2016a; Spies et al., 2018). A risk assessment perspective expands from short-term, reactive fire response to landscape-scale, long-term prevention, mitigation, and preparedness with community and practitioner engagement (Coogan et al., 2019; Sherry et al., 2019; Johnston et al., 2020; Tymstra et al., 2020).

temperatures (Meyer-Gutbrod et al., 2018; Davies and Brillant, 2019). Similarly, whale entanglements in fishing gear along the Pacific coast has increased twentyfold (Hazen et al., 2018). Projected shifts in the North Pacific Transition Zone by up to 1000 km northward (by the end of the century under RCP8.5) combined with changes in coastal upwelling (Polovina et al., 2011; Hazen et al., 2013; Rykaczewski et al., 2015) could alter up to 35% of elephant seal and bluefin tuna foraging habitat (Robinson et al., 2009; Kappes et al., 2010).

In North American Arctic marine systems, rapid warming is significant, with cascading impacts beyond polar regions (CCP6), and presents limited opportunities (tourism, shipping, extractive) but high risks (shipping, fishing industries, Indigenous subsistence and cultural activities) (*high confidence*) (Sections 14.5.4, 14.5.9, 14.5.11; CCP6 Gaines et al., 2018; IPCC, 2019b; Samhouri et al., 2019; Free et al., 2020; Holsman et al., 2020). Both direct hazards and indirect food-web alterations from sea ice loss have imperilled seabirds, marine mammals, small-boat operators, subsistence hunters and coastal communities (CCP6; Sigler et al., 2014; Allison and Bassett, 2015; Huntington et al., 2015; Hauser et al., 2018; Raymond-Yakoubian and Daniel, 2018; Dezutter et al., 2019). Increasingly favourable environmental conditions due to warming combined with shipping and other activities has raised the rate of invasive species movement into the Arctic (Mueter et al., 2011). Sea ice loss due to climate change is expected to accelerate over the next century (Section 14.2, Fox-Kemper et al., 2021).

Coral reefs in the Gulf of Mexico and along the coasts of Florida and the Yucatan Peninsula are facing increasing risk of bleaching and mortality from warming ocean waters interacting with non-climate stressors (*very high confidence*) (Cinner et al., 2016; Hughes et al., 2018; Sully et al., 2019; Williams et al., 2019b). Coral reefs are contracting in equatorial regions and expanding poleward (Lluch-Cota et al., 2010; Jones et al., 2019a). Loss of coral habitat leads to loss of ecosystem structure, fish habitat, food for coastal communities and impacts tourism opportunities (Section 14.5.7; Weijerman et al., 2015a; Weijerman et al., 2015b). Without mitigation to keep surface temperatures below a 2°C increase by the end of the century, up to 99% of coral reefs will be lost; however, 95% of reefs will still be lost even if warming is kept below 1.5°C (*high confidence*) (Hoegh-Guldberg et al., 2018; Hoegh-Guldberg et al., 2018). In Florida, by 2100, an estimated 24–55 billion USD may be lost in recreational use and value derived by people knowing the reef exists and is healthy (Lane et al., 2013; Hoegh-Guldberg et al., 2019b) as coral reefs decline (Section 14.5.9).

Sea level rise has led to flooding, erosion and damage to infrastructure along the western Gulf of Mexico, the southeast US coasts and the southern coast of the Gulf of St Lawrence (*very high confidence*) (Section 14.2; Daigle, 2006; Lemmen et al., 2016; Frederikse et al., 2020). Mangroves, important nurseries for fish and climate refugia for corals (Yates et al., 2014), are under threat from climate change along the east coast of Mexico (Pedrozo Acuña, 2012). This SLR, storm surge and attendant erosion of coastlines and barrier habitats are projected to have large impacts on coastal ecosystems, maritime industries (Section 14.5.9), urban centres and cities (Section 14.5.5) along the Gulf of Mexico, Caribbean Sea, southeast USA, southern Gulf of St Lawrence and Pacific Coast of Mexico (see Box 14.4; Semarnat, 2014; Sweet et al., 2017; Vousdoukas et al., 2020). Coastal archaeological and historical sites are especially vulnerable to SLR (Anderson et al., 2017; Hestetune et al., 2018; Hollesen et al., 2018).

Future seawater CO_2 levels have been shown in laboratory studies to negatively impact Pacific and Atlantic squid, bivalve, crab and fish species (Pacific cod), and indirectly alter food-web dynamics (*high confidence*) (Kaplan et al., 2013; Long et al., 2013b; Gledhill et al., 2015; Seung et al., 2015; Punt et al., 2016; Swiney et al., 2017; Hurst et al., 2019; Wilson et al., 2020). Long-term exposure to CO_2 has reduced growth of Atlantic halibut (Gräns et al., 2014), whereas some cultured oysters (Fitzer et al., 2019) and key Alaskan commercial fish species

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4 See www.firesmartcanada.ca

5 See www.nfpa.org

6 See https://thinkhazard.org

https://doi.org/10.1017/9781009325844.016

show tolerance for high CO_2 waters (i.e., juvenile walleye pollock) (Hurst et al., 2012). Ocean acidification has already caused shellfish growers in the USA and Canada to modify hatchery procedures and farming locations to protect the most vulnerable life stages (Cross et al., 2016) and is projected to increasingly impact shellfish resources in the central and northeast Pacific and Atlantic coasts (Section 14.5.4; Seung et al., 2015; Punt et al., 2016).

Open ocean oxygen minimum zones (OMZ) are expanding in the North Atlantic, the North Pacific California Current and tropical oceans due to warming waters, stratification and changes in precipitation (*medium confidence*) (WGI Section 3.6.2; Deutsch et al., 2015b; Breitburg et al., 2018; Claret et al., 2018; Ito et al., 2019). Hypoxic events along coasts, which are partially influenced by climate change, have been documented for all three countries, with events more prevalent on the east coast and around the Gulf of Mexico due to a regional oceanography dominated by rivers and estuaries carrying land-based nutrients (Breitburg et al., 2018). Hypoxia has directly caused large mortality events for fish and crabs in US estuaries in the Northwest Atlantic (Chesapeake Bay), Northeast Pacific (Puget Sound) and the Gulf of Mexico (Froehlich et al., 2015; Rakocinski and Menke, 2016; Sato et al., 2016; Kolesar et al., 2017). The OMZs and hypoxic events are projected to increase over the next century and may limit where fish can move (*medium confidence*) (Deutsch et al., 2015b; Stortini et al., 2015; Bianucci et al., 2016; Li et al., 2016).

Favourable conditions for harmful algal blooms (HABs) have expanded due to warming, more frequent extreme weather events (Gobler et al., 2017; Pershing et al., 2018; Trainer et al., 2019) and increased stratification, CO_2 concentration and nutrient inputs (*high confidence*) (Wells et al., 2015; Gobler et al., 2017; Griffith and Gobler, 2019). Increased occurrence of HABs (McCabe et al., 2016; Yang et al., 2016; Gobler et al., 2017; USGCRP, 2018) has induced ecological impacts and societal costs (see Section 14.5.4 for fishery closures). During the 2013–2016 Pacific MHW (see Box 14.3), a *Pseudo-nitzschia* diatom bloom off the west coast of the USA caused extensive closures of crab and razor clam fisheries (Fisher et al. 2021), with economic and sociocultural impacts beyond those in the fisheries sector (Ritzman et al., 2018).

Beaching of massive *Sargassum* seaweed mats (*Sargassum natans* and *S. fluitans*) have been reported across the Caribbean and Gulf of Mexico from 2011 to the present, affecting US and Mexico nearshore ecosystems, human health and the tourism industry (Franks et al., 2016; Resiere et al., 2018; Wang et al., 2019). Costs of beach clean-up is high, with Texas spending over 2.9 million USD annually (Webster and Linton, 2013). Attribution of *Sargassum* blooms to climate change is still tenuous and complicated by multiple drivers and few observational data sources (*low confidence*) (Wang et al., 2019).

14.5.2.2 Adaptation: Current State, Barriers and Opportunities

Emerging technologies and cooperative marine management are approaches to facilitate adaptation but require coordination and investment for implementation (*high confidence*) (Gattuso et al., 2018; Miller et al., 2018; Holsman et al., 2019; Karp et al., 2019). Advancements in oceanographic and ecological nowcasting and forecasting tools (i.e., O_2, pH, temperature, aragonite saturation state,

Box 14.3 | Marine Heatwaves

Marine heatwaves are periods of discrete anomalously high (compared with a 30-year history) sea surface temperatures that persist for a minimum 5 d but up to several months (Hobday et al., 2016; Frölicher et al., 2018; Holbrook et al., 2019; Laufkötter et al., 2020). There have been MHWs attributed to climate change in every marine system of North America including large areas of the Northwest Atlantic (2012), Caribbean Sea (2015), Bering Sea (2016–2018) and central through Northeast Pacific (2013–2016) (NOAA, 2018; Holbrook et al., 2019; Smale et al., 2019). Such MHW events have affected kelp forests (Arafeh-Dalmau et al., 2019), corals (Eakin et al., 2018), seagrasses, bottom-dwelling organisms, marine birds (Loredo et al., 2019; Smale et al., 2019), mammals (Suryan et al., 2021), fish and shellfish, and marine-dependent human communities (Huntington et al., 2020; Fisher et al., 2021; Suryan et al., 2021). Increased sea temperatures directly increase metabolic demand and change productivity and behaviour of fish species (Stock et al., 2017; Free et al., 2019) as well as induce rapid redistribution of species poleward and to deeper, colder waters (Pecl et al., 2017; Rheuban et al., 2017; Crozier et al., 2019; Stevenson and Lauth, 2019; Yang et al., 2019; Barbeaux et al., 2020; Cheung and Frölicher, 2020). In the Pacific, from the Baja Peninsula to the Bering Sea, there is evidence of widespread shifts in coastal biota and multi-trophic-level starvation of seabirds and whales from combined metabolic demand and reduced prey quality associated with protracted MHWs across multiple regions ((CCP6); Sydeman et al., 2015; Duffy-Anderson et al., 2019; Sanford et al., 2019; Smale et al., 2019; Suryan et al. 2021). The distribution of two economically important North American species, Bering Sea Pacific cod (Pinsky et al., 2013b; Stevenson and Lauth, 2019; Barbeaux et al., 2020; Spies et al., 2020) and American lobster (Rheuban et al., 2017), have shifted north. The MHW-induced loss of coral reefs across tropical North American waters has varied in severity regionally. For instance, in 2015 and 2016, extensive, severe bleaching affected more than 30% of corals off the southeast USA and a large proportion of US Hawaiian Islands, but had moderate to no impact off the Mexican Yucatan Peninsula (Frieler et al., 2013; Weijerman et al., 2015a; Weijerman et al., 2015b; Cinner et al., 2016; van Hooidonk et al., 2016; Hughes et al., 2018; Sully et al., 2019; Williams et al., 2019b). Some reefs are exhibiting recovery following efforts focused at reducing non-climate stressors (e.g., overfishing, nutrient pollution and tourism use). Such MHWs are increasing in intensity and frequency (Hobday et al., 2016; Smale et al., 2019) with the largest increases in frequency and spatial coverage projected for the Gulf of Mexico, US southern east coast and US Pacific Northwest (Ranasinghe et al., 2021) and pose a key risk to marine systems in North America (Section 14.5.2; Chapters 3, 16).

sea ice conditions) can reduce climate impacts by supporting fisheries and aquaculture adaptation along US coasts (Section 14.5.4; Cooley et al., 2015; Irby et al., 2015; Siedlecki et al., 2015; Siedlecki et al., 2016; Siddon and Zador, 2017). Forecasts and warnings reduce human exposure to HAB toxins in the Great Lakes, the west coast of Florida, east coast of Texas and the Gulf of Maine (Anderson et al., 2019).

Ocean management that utilises a portfolio of nested, multi-scale, climate-informed and ecosystem-based management approaches in North American waters can increase the resilience of marine ecosystems by addressing multiple stressors simultaneously (*high confidence*) (Marshall et al., 2018; Holsman et al., 2019; Smale et al., 2019; Holsman et al., 2020). Integrated ecosystem assessments (Foley et al., 2013; Levin et al., 2014) are increasingly used to provide strategic advice and context for harvest allocations and bycatch avoidance (Zador et al., 2017) as well as early warnings of ecosystem-wide change (e.g., sentinel species, ecological indicators) (Cavole et al., 2016; Hazen et al., 2019; Moore and Kuletz, 2019). Dynamic ocean management policies may improve resilience of marine species and ecosystems to climate (*medium confidence*) (Hyrenbach et al., 2000; Maxwell et al., 2015; Dunn et al., 2016; Tommasi et al., 2017a; Tommasi et al., 2017b; Hazen et al., 2018; Wilson et al., 2018; Holsman et al., 2019; Karp et al., 2019). New proactive and rapid management approaches have been developed to minimise impacts of increasingly frequent entanglements of protected species, caused by climate-driven changes in prey and fishery activities (Corkeron et al., 2018; Meyer-Gutbrod et al., 2018). Dynamic closure areas are being used to address these issues and reduce loggerhead turtle bycatch in Hawaiian shallow-set longline fisheries (Howell et al., 2015; Lewison et al., 2015), blue whale ship-strike risk in near-real time (Hazen et al., 2017; Abrahms et al., 2019b) and bycatch of multiple top predator species in a west coast drift gillnet fishery (Hazen et al., 2018).

Improved coordination and planning at multiple scales will be important for marine species conservation and recovery as species redistribute across fishery areas, marine protected zones, and international and jurisdictional boundaries (Section 14.5.4; Cross-Chapter Box MOVING PLATE in Chapter 5; Pinsky et al., 2018; Karp et al., 2019). Indigenous Peoples' co-management with federal and state partners of marine resources and protected species is an important approach (Section 14.5.4; Chapters 5 and 6; CCP6; Galappaththi et al., 2019).

Securing broodstocks for rebuilding and supplementation can be challenging for marine populations already in decline (e.g., blue king crab in Alaska, steelhead salmon in Puget Sound, white abalone in California, groundfish in the northeast USA and Canada) (Section 14.5.4; Table SM14.8). Marine protected areas can attenuate climate impacts through trophic redundancy, preserving ecological processes, biodiversity and climate refugia (Roberts et al., 2017a; Schoen et al., 2017), although benefits decrease after mid-century (or sooner for high-latitude marine protected areas) as species reach their thermal limit, unless coupled with GHG mitigation (Bruno et al., 2018). Transport, relocation and cultivation of resistant breeds of salmon, oysters, corals, marine mammals and other keystone species, as well as hatchery supplementation of impaired populations of fish and shellfish, are species conservation and recovery methods that will be in greater demand under climate change, although unintended environmental impacts must be considered. Options for protecting and restoring coral reefs to prevent loss of ecosystem function are under development with Florida reef species (Gattuso et al., 2018; National Academies of Sciences, 2019). An emerging approach for financing the protection of reefs involves re-categorising reefs as 'natural infrastructure' which has allowed for use of insurance to rebuild lost reefs (Storlazzi et al., 2019).

14.5.3 Water Resources

Climate change poses increasing threats to North American aquatic ecology, water quality, water availability for human uses, and flood exposure, through reductions in snow and ice, increases in extreme precipitation and hotter droughts. Adaptation will be impeded in cases where there are conflicts over competing interests or unintended consequences of uncoordinated efforts, heightening the importance of cooperative, scenario-based water resource planning and governance (*high confidence*).

14.5.3.1 Observed Impacts

North American water resources continue to be affected by ongoing warming, with impacts driven by reductions in snow and ice, increases in extreme precipitation and hotter droughts (*high confidence*) (Section 14.2; Fleming and Dahlke, 2014; Mortsch et al., 2015; Dudley et al., 2017; Fyfe et al., 2017; McCabe et al., 2017; Chavarria and Gutzler, 2018; Lall et al., 2018; Bonsal et al., 2019; USGCRP, 2019). The cascading effects of severe droughts, floods, sediment mobilisation, HABs and pathogen contamination episodes have revealed the vulnerability and exposure of large numbers of people and economic activities to those hazards.

North America's dams, levees, wastewater-management and water conveyance facilities have improved water supply safety and have reduced flood and drought risks, but a substantial portion of that infrastructure is ageing and inadequate for modern conditions (Ho et al., 2017; Tellman et al., 2018; Carlisle et al., 2019; FEMA, 2019; ASCE, 2021). Increasingly heavy precipitation from a variety of storm types has affected parts of North America (Feng et al., 2016; Prein et al., 2017a; Kunkel and Champion, 2019; Kunkel et al., 2020), contributing to contamination from combined sewer overflows (Olds et al., 2018) and increased flood damages that are partially attributed to anthropogenic climate change (van der Wiel et al., 2017; Davenport, 2021). Extreme precipitation events have overwhelmed water control infrastructure, imperilling public safety and contributing to extensive damages in parts of North America (Kytomaa et al., 2019; Vano et al., 2019; White et al., 2019). Damages stem from extremity of the event and prior land-use and infrastructure decisions (*high confidence*).

In South Carolina, 5 days of heavy rainfall in October 2015 caused the failure of more than 50 dams and some levees, significantly magnifying destruction from the floodwaters (FEMA, 2016). Slow-moving, destructive storms like hurricanes Harvey (2017) and Florence (2018) have caused significant flooding (van Oldenborgh et al., 2017; Paul et al., 2019b). In those cases, urban sprawl may have altered storm dynamics (Zhang et al., 2018b), while increased asset exposure to the flood hazard amplified the multi-billion-dollar losses (Klotzbach et al., 2018; Trenberth et al., 2018). A substantial fraction of the damage from hurricane Harvey's extreme rainfall has been attributed to anthropogenic climate change (see Box 14.5; Emanuel, 2017; Risser and Wehner, 2017). A near disaster at California's Oroville dam in 2017 was caused by inadequate infrastructure design and maintenance together with an unusually large number of atmospheric river (AR) storms. The event required emergency reservoir spills while the state was beginning recovery from the extreme 2012–2016 drought (Vano et al., 2019; White et al., 2019).

In Mexico, some poor neighbourhoods and informal settlements are located in areas exposed to recurrent flooding. Residents often lack access to public services and technical resources for risk reduction, which heightens their vulnerability (Castro and De Robles, 2019).

Population growth and urban development have increased the exposure and vulnerability of Canadian communities to flood damages, with cumulative damages (including uninsured losses) exceeding 10 billion USD in the past decade (The Geneva Association et al., 2020). Recurring floods are particularly costly (e.g., New Brunswick) (Beltaos and Burrell, 2015; Kovachis et al., 2017). Floods in High River, AB (2013) and Gatineau, QC (2017, 2019) initiated considerations of building flood resilience including planned retreat (Saunders-Hastings et al., 2020).

Extended and severe droughts in the western USA, northern Mexico and Canadian Prairies, exacerbated by higher temperatures, have caused economic and environmental damage (Williams et al., 2013; Agha Kouchak et al., 2015; Diaz et al., 2016; Bain and Acker, 2018; Lopez-Perez et al., 2018; Ortega-Gaucin et al., 2018; Xiao et al., 2018; Martinez-Austria et al., 2019; Bonsal et al., 2020; Martin et al., 2020b; Milly and Dunne, 2020; Overpeck and Udall, 2020). Droughts have intensified tensions among competing water-use interests and accelerated depletion of groundwater resources (*high confidence*) (Section 14.5.4; Pauloo et al., 2020).

Climate trends are affecting riverine, lake and reservoir water quality (*medium confidence*). Droughts and increased evapotranspiration have impaired water quality by concentrating pollutants in diminished water volumes (Paul et al., 2019a). Cyanobacterial blooms and pathogen exposure events are increasing in frequency, intensity and duration in North America (Taranu et al., 2015). They are closely associated with observed changes in precipitation intensity and associated nutrient loading (e.g., agricultural runoff, sanitary sewer overflows), elevated water temperatures and eutrophication (Michalak et al., 2013; Michalak, 2016; Trtanj et al., 2016; Chapra et al., 2017; IBWC, 2017; Williamson et al., 2017; Olds et al., 2018; Coffey et al., 2019). These events endanger human and animal health, recreational and drinking water uses and aquatic ecosystem functioning, and cause economic losses (Michalak et al., 2013; Bullerjahn et al., 2016; Chapra et al., 2017; Huisman et al., 2018). Households and communities dependent on substandard wells, unimproved water sources or deficient water provision systems are more exposed than others to experience climate-related impairment of drinking water quality (Section 14.5.6.5; Allaire et al., 2018; Baeza et al., 2018; California State Water Resources Control Board, 2021; Navarro-Espinoza et al., 2021; Water and Tribes Initiative, 2021).

14.5.3.2 Projected Impacts and Risks

Climate change is projected to amplify current trends in water resource impacts, potentially reducing water supply security, impairing water quality and increasing flood hazards to varying degrees across North America (*high confidence*). Examples are presented in Table 14.3.

Projected long-term reduction in water availability in the southwest US and northern Mexico (e.g., from the Colorado and Rio Grande rivers) will have substantial ecological and economic impacts given the region's heavy water demands (*high confidence*) (Lall et al., 2018; Paredes-Tavares et al., 2018; Martinez-Austria et al., 2019; Milly and Dunne, 2020; Williams et al., 2020). Increased water scarcity will intensify the need to address competing interests across state and national boundaries, including honouring commitments to Indigenous Peoples who have long struggled with inadequate access to their water entitlements and marginalisation in water resource planning (Mumme, 1999; Cozzetto et al., 2013b; Mumme, 2016; McNeeley, 2017; Radonic, 2017; Robison et al., 2018; Curley, 2019; Water and Tribes Initiative, 2020; Wilder et al., 2020).

Increased scarcity of renewable water relative to legally allocated or desired uses may develop in many parts of North America. A detailed analysis of projected water demands (consumptive uses) and availability found increasingly frequent shortages in several watersheds across the USA (Brown et al., 2019b). This might lead to maladaptive increased groundwater mining, or alternatively to policies promoting sustainable balancing of water consumption with renewable supplies, for example, by facilitating voluntary water transfers or improving enforcement of groundwater rights (Colorado River Basin Stakeholders, 2015; California Natural Resources Agency et al., 2020; Colorado Water Conservation Board, 2020; Pauloo et al., 2020).

Climate change is projected to reduce groundwater recharge in major southwest US aquifers (e.g., Southern High Plains, San Pedro and Wasatch Front), exacerbating their ongoing depletion due to unsustainable pumping. Other aquifers, especially those farther north, face uncertain or possibly increasing recharge (*medium confidence*) (Meixner et al., 2016).

Projected changes in temperature and precipitation present direct risks to North American water quality, varying with regional and watershed contexts (Chapra et al., 2017; Coffey et al., 2019; Paul et al., 2019a), and related to streamflow, population growth (Duran-Encalada et al., 2017) and land-use practices (*medium confidence*) (Mehdi et al., 2015). Harmful algal blooms increase in frequency across the USA (Wells et al., 2015) with the highest risk projected for the Great Plains and Northeast USA, and greatest economic impacts from lost recreation value in the southeast USA (Chapra et al., 2017).

The diversity of climate regimes across North America results in regional differences in water-related climate-change risks (Figure 14.4).

14.5.3.3 Adaptation

North American water planners and policy makers have abandoned stationarity assumptions (Milly et al., 2015) to address climate change.

Table 14.3 | Selected projected water resource impacts in North America

Climate drivers and processes	Examples of future risks and impacts	Location (see Figure 14.1)	References
Warming-induced reductions in mountain snow and glacial mass	Projected decreases in annual and late-summer streamflow from high-elevation reaches of snow-fed rivers, affecting stream ecology and water supplies (*high confidence*)	US-NW, US-SW, CA-BC, CA-PR	Jost et al. (2012); Solander et al. (2018); Bonsal et al. (2019); Milly and Dunne (2020)
Earlier seasonal snowmelt runoff	Greater winter/early spring flooding risks and reduced summer surface water availability, intensifying seasonal mismatch with water demands (*high confidence*); increased challenges for balancing multi-purpose reservoir objectives (e.g., flood management, water supply, ecological protection and hydropower) (*high confidence*)	US-NW, US-SW, CA-BC, CA-PR	Cohen et al. (2015); Dettinger et al. (2015); Bonsal et al. (2019); Bonsal et al. (2020); RMJOC (2020); Bureau of Reclamation (2021d)
Earlier seasonal snowmelt runoff	Possible reductions in water supply security (*medium confidence*); reduced viability of some small-scale irrigation systems (*medium confidence*)	US-SW	Medellin-Azuara et al. (2015); Ullrich et al. (2018); Bai et al. (2019); Milly and Dunne (2020); Ray et al. (2020); Bureau of Reclamation (2021b); Bureau of Reclamation (2021a); Bureau of Reclamation (2021c)
Changes in seasonal timing and/or total annual runoff	Impacts on electric power generation (*medium confidence*) varying by location and type of generation	US-SW, US-NW, CA-QC	Haguma et al. (2014); Bartos and Chester (2015); Guay et al. (2015); Turner et al. (2019b); RMJOC (2020); Bureau of Reclamation (2021d)
Changes in seasonal timing and/or total annual runoff	Impacts on urban water supplies	CA-QC	Foulon and Rousseau (2019)
Warming-related increased imbalance between renewable surface water supplies and consumptive water demands	Greater pressures on groundwater resources, possible increased aquifer depletion, reduced baseflow into surface streams and reduced long-term water supply sustainability (*medium confidence*)	US-SW, US-SP, US-SE, MX-N, MX-NW	Bauer et al. (2015); Molina-Navarro et al. (2016); Russo and Lall (2017); Brown et al. (2019b); Nielsen-Gammon et al. (2020); Bureau of Reclamation (2021b)
Warming-related drought amplification	Reduced water availability for human uses and ecological functioning (*medium* to *high confidence*) varying by location; increased evaporative losses from reservoirs	Widespread especially: US-SW, US-NP, US-SP, CA-PR, MX-NW, MX-N	Prein et al. (2016); Dibike et al. (2017); Lall et al. (2018); Paredes-Tavares et al. (2018); Martinez-Austria et al. (2019); Tam et al. (2019); Martin et al. (2020b); Milly and Dunne (2020); Overpeck and Udall (2020); Williams et al. (2020); Bureau of Reclamation (2021b)
Heavier and/or prolonged rainfall events	Flooding, infrastructure and property damage (*medium* to *high confidence*) varying by location; increased erosion and debris flows with impacts on public safety, reservoir sedimentation and stream ecology (hazards amplified in watersheds affected by wildfires)	Widespread especially: US-SE, US-NE, US-NP, US-SP, US-SW, CA-BC, MX-CE, MX-NE, MX-SE	Feng et al. (2016); Emanuel (2017); Prein et al. (2017a); Prein et al. (2017b); Haer et al. (2018); Kossin (2018); Mahoney et al. (2018); Thistlethwaite et al. (2018); Curry et al. (2019); Larrauri and Lall (2019); Wobus et al. (2019); Ball et al. (2021)
Heavier and/or prolonged rainfall events	Water quality impairment, increasing HAB events due to increased sediment and nutrient loading together with warming; greatest impacts in humid areas with extensive agriculture (*medium to high confidence*) varying by location	US-MW, US-NE, US-SE, US-NP, US-SP, CA-ON, CA-AT, MX-NE, MX-NW	Alam et al. (2017); Chapra et al. (2017); Sinha et al. (2017); Ballard et al. (2019)
Increasingly variable precipitation	Highly variable precipitation poses challenges for water management, worsening water supply and flooding risks; atmospheric river events are projected to increase variability by dominating future North American west coast precipitation (*medium confidence*)	US-SW, US-NW, CA-BC	Gershunov et al. (2019); Huang et al. (2020)
Hotter summer season	Evaporative losses from reservoirs are projected to increase significantly (*very high confidence*)	US-SW, US-NW, US-NP	Bureau of Reclamation (2021b)

Transboundary institutions, government agencies and professional organisations are taking the lead on adaptation planning and implementation (ASCE, 2018b; Clamen and Macfarlane, 2018; International Joint Commission, 2018). Major water agencies are using climate scenarios to identify vulnerabilities and evaluate adaptation options (Yates et al., 2015; Vogel et al., 2016; California Department of Water Resources, 2019; Ray et al., 2020; Bureau of Reclamation, 2021d).

The Water Utility Climate Alliance advises municipal water providers to address uncertainty by considering a wide range of plausible future climate conditions (WUCA, 2010). In some areas, the impacts of wildfires on water supply resiliency are being considered (Martin, 2016). Many North American Indigenous Peoples are engaged in climate-change adaptation planning, although these efforts may be hampered by the complicated legal and administrative setting in which they must operate (Norton-Smith et al., 2016a; McNeeley, 2017).

Recent climate extremes have heightened governmental attention to climate-change impacts (e.g., California Natural Resources Agency et al., 2020). Droughts have exposed shortcomings in water management and governance (Gray et al., 2015; Xiao et al., 2017b; Lopez-Perez et al., 2018) spurring legislation and administrative

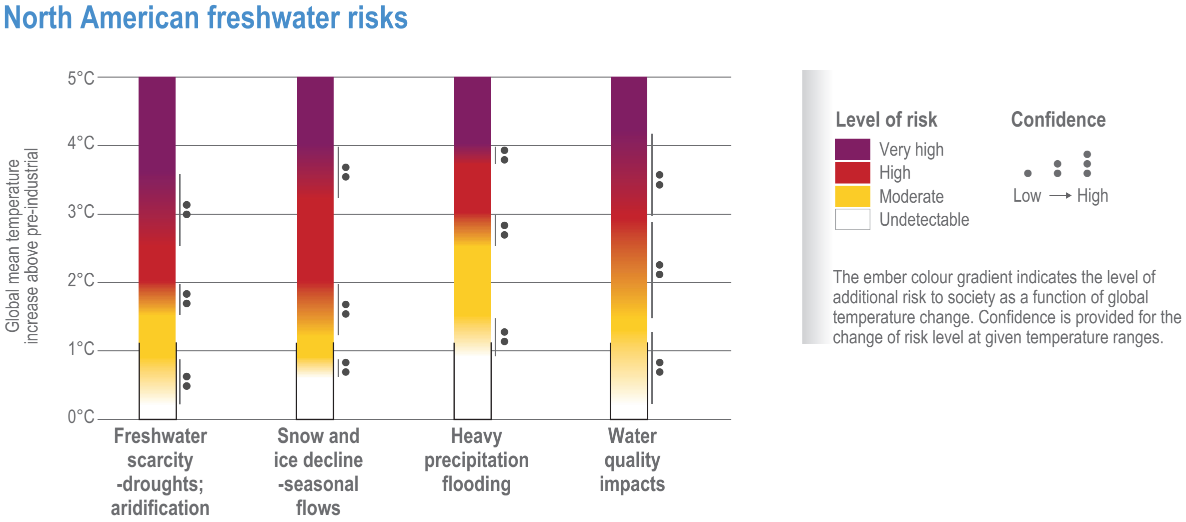


Figure 14.4 | Freshwater resource risks as a function of global mean surface temperature increase relative to pre-industrial (1850–1900) levels. Estimated sensitivities are based on references cited in Table 14.3 (SM14.4).

changes to improve groundwater regulation and documentation of water rights (California Department of Food and Agriculture, 2017; Miller, 2017; Lund et al., 2018; Hanak et al., 2019). Water allocation policies are being reassessed to enhance equity, sustainability and flexibility through shortage sharing agreements, improved groundwater regulation and voluntary water transfers. Developments include an interstate drought management agreement for the Colorado River (US Law, 2019), and agreements between the USA and Mexico to provide pulse flows to benefit the ecology of the Colorado River Delta (Pitt and Kendy, 2017). Statewide water planning in Colorado has emphasised building drought resilience (e.g., by facilitating temporary water transfers) (Colorado State Government, 2015; Yates et al., 2015). At local scales, there have been innovations in cooperative watershed protection and water resource planning (Cantú, 2016). Indigenous Peoples are playing an increasing role in identifying equitable and resilient options for adaptation by contributing their knowledge and voicing their perspectives on the importance of healthy water bodies for human and environmental well-being (Norton-Smith et al., 2016a; Water and Tribes Initiative, 2020). Collaboration between stakeholders, policymakers and scientists is increasingly common in water resources adaptation planning and assessment.

Examples of adaptation include increasing adoption of water-saving irrigation methods in California (Cooley, 2016), experimentation with using flood waters to enhance groundwater recharge (Kocis and Dahlke, 2017; California Department of Water Resources, 2018) and agricultural land management programmes, including developing riparian buffers to protect water quality (Section 14.5.4; Mehdi et al., 2015; Schoeneberger et al., 2017). Indigenous Peoples are building upon traditional practices to adapt to the effects of climate change, for example, by working jointly to recharge local aquifers (Basel et al., 2020).

Water-right laws, interstate compacts and international treaties regarding transboundary water shape the context for climate-change adaptation, but the possibility of long-term climate change typically was not contemplated at their inception. Gaps in coverage and vaguely defined terms can lead to tensions and disputes, especially in areas facing increased aridity, creating difficulties for adaptation. For example, unregulated pumping of groundwater for irrigation during short-term droughts can serve as an adaptation to acute conditions (Section 14.5.4), but if persisting in the long term, it can deplete finite groundwater resources and de-water hydrologically connected rivers. Such outcomes have engendered bitter and costly interstate conflicts in the USA, some even reaching the US Supreme Court including *Texas v. New Mexico* (Rio Grande) and *Florida v. Georgia* (Apalachicola-Chattahoochee-Flint).

Transboundary rivers that exemplify the need to address climate impacts include the Colorado (Gerlak et al., 2013), Columbia (Cosens et al., 2016) and Rio Grande/Rio Bravo (Mumme, 1999; Mumme, 2016; Garrick et al., 2018; Payne, 2020). Drought emergencies can open opportunities for progress on collaborative adaptive governance, but such windows may quickly close when wetter conditions return (Sullivan, (2019).

Water serves a wide variety of environmental functions and human uses as it moves through North America's river basins, so the impacts of climate change are expected to be widespread and multifaceted. This increases the importance of collaborative adaptation efforts that are equitable, transparent and give voice to differing values, perspectives and entitlements across a broad socioeconomic spectrum of urban and rural, Indigenous and non-Indigenous participants (Miller et al., 2016; Cosens et al., 2018). Adaptation planning may be hampered by conflicting interests, jurisdictional boundaries and inherent interconnections between actions and impacts at different points throughout a watershed or river basin. Differential power relationships, decision-making authority and access to information also can interfere with effective adaptive governance, while equitable processes for decision making bolstered by reliable shared information can help to overcome those impediments (Cosens et al., 2016; Arnold et al., 2017; Cosens et al., 2018; Porter and Birdi, 2018).

Across North America, there are growing signs of progress towards adaptive water governance and implementation of climate-resilient, and ecosystem-based, water management solutions (Colorado River Basin Stakeholders, 2015). California's approach to groundwater sustainability regulation intends to foster such collaborative problem-solving by giving local Groundwater Sustainability Agencies the authority to design locally appropriate plans to meet state-defined sustainability goals (State of California, 2014; Miller, 2017). As evidenced by the US interstate disputes, the greatest difficulties arise in cases where stark upstream–downstream differences in interests leave little room for mutual benefit. Severe aridification may test the limits of adaptive capacity.

Research on water diplomacy recommends broadening negotiations beyond a narrow focus on zero-sum issues, like rigid water allocations, to embrace a more diverse set of shared interests including the need for flexibility to respond to changing conditions. A process for ongoing inclusive engagement of a watershed's stakeholders in mutual social, policy and science learning is important. Such mutual learning can build trust and establish a common platform of credible information for co-creation of adaptation solutions. In addition, better understanding of the policy positions and constraints of others can help stakeholders to identify workable solutions to contentious water management issues (Payne, 2020; Wilder et al., 2020). Cooperation between Mexico and the USA on mapping and assessment of transboundary aquifers is a product of such ongoing engagement (Callegary et al., 2018; Sanchez et al., 2018). Other examples of the benefits of sustained engagement are provided by a set of co-management arrangements between state, federal and Indigenous authorities on water management for fishery restoration in the US Pacific Northwest (Tsatsaros et al., 2018) and Indigenous involvement in multi-level co-management of water resources in Canada's Northwest Territories (Latta, 2018).

14.5.4 Food, Fibre and Other Ecosystem Products

14.5.4.1 Observed Impacts and Projected Risks: Agriculture, livestock and forestry

Climate change has affected crops across North America through changes in growing seasons and regions, extreme heat, precipitation, water stress and soil quality (Table 14.1; Figure 14.5; Section 5.4.1; Figure 5.3) (Mann and Gleick, 2015; Galloza et al., 2017; Otkin et al., 2018). These changes directly influence crop productivity, quality and market price (*high confidence*) (Kistner et al., 2018; Reyes and Elias, 2019). Effects of historical climate change on maize, soybean, barley and wheat crop yields vary from strong increases to strong decreases (e.g., > –0.5 to > +0.5 t ha^{-1} yr^{-1} for maize) within North America's agroecological regions, even for the same crop (Ray et al., 2019). Across North America, climate change has generally reduced agricultural productivity by 12.5% since 1961, with progressively greater losses moving south from Canada to Mexico (Ortiz-Bobea et al., 2021), yet responses are highly differential across regions and crops. Some crop loss events are partially attributed to climate change (*high confidence*) such as the 2012 Midwest and Great Plains drought, which cost agriculture 30 billion USD (Smith and Matthews, 2015; Rupp et al., 2017). Aridity is extending northward, altering crop suitability ranges (Figure 14.4); up to 50% of distributional shifts in growing regions for US crops between 1970 and 2010 may be related to climate change (Lant et al., 2016; Cho and McCarl, 2017). Irrigation is expanding to areas formerly largely dependent on rainfall (Wang et al., 2018b).

Without adaptation, climate change is projected to reduce overall yields of important North American crops (e.g., wheat, maize, soybeans) (*high confidence*) (Tables SM14.3, SM14.4; Chen et al., 2017; Levis et al., 2018). For example, projected heat stress (RCP8.5) reduced mid-century (2040–2069) maize and cotton yields by 12–15% of historical yields (1950–2005), with the US-SW suffering the largest impacts (Table SM14.5; Elias et al., 2018). Warming and heat extremes will delay or prevent chill accumulation, affecting perennial crop development (e.g., fruit set failure), yield (e.g., walnuts, pistachios, stone fruit) and quality (e.g., grapes) (*medium confidence*) (Parker et al., 2020). Warming will alter the length of growing seasons of cold-season crops (e.g., broccoli, lettuce) and will shift suitability ranges of warm-season California crops (e.g., tomatoes) (*medium confidence*) (Marklein et al., 2020). Increasing atmospheric CO_2 will enhance yields yet reduce nutrient content of many crops (*high confidence*); a CO_2 concentration of 541 ppm (seen by 2050 in RCP8.5) would reduce per-capita nutrient availability in North American diets by 2.5–4.0% (Beach et al., 2019). Crop pest and pathogen outbreaks are expected to worsen under climate change (*high confidence*) (Deutsch et al., 2018; Wolfe et al., 2018; Zhang et al., 2019a).

Climate change is anticipated to cause declines in livestock production across North America (*high confidence*) (Table 14.4; SM14.6; Havstad et al., 2018; Murray-Tortarolo et al., 2018). Increases in extreme temperature raise the risk of livestock heat stress, disease and pest impacts (Rojas-Downing et al., 2017). Projected aridification reduces forage production in the southwest USA and northern Mexico (*high confidence*) (Polley et al., 2013; Reeves et al., 2014; Cooley, 2016; Bradford et al., 2020) and transforms grasslands into woody shrublands (Briske et al., 2015; Murray-Tortarolo et al., 2018), while warmer and wetter conditions in the northern regions (CA-PR, US-NW, US-NP) may enhance rangeland production by extending growing seasons (*high confidence*) (Hufkens et al., 2016; Derner et al., 2018; Zhang et al., 2019a). Increased CO_2 will enhance production (*medium confidence*) but reduce forage quality (*high confidence*) in US-NP and US-NW (Table SM14.6; Derner et al., 2018).

Climate-change impacts on forests (Section 14.5.1; see Box 14.2) may affect timber production by altering tree species distributions, productivity, and wildfire and insect disturbances (*medium confidence*). Southern or drier locations may shift from forests to other vegetation types, whereas higher-latitude areas may experience forest expansion (Brecka et al., 2018). Tree species composition is projected to change with climate change (Wang et al., 2015; Bose et al., 2017). Tree growth may increase or decrease from changes in temperature or moisture depending on location, with lower growth expected from warming in water-limited areas (Littell et al., 2010). Increased productivity associated with more favourable climate conditions is projected for boreal forests (Brecka et al., 2018), although in some regions, growth will reverse and decline with additional warming (D'Orangeville et al., 2018; Chaste et al., 2019). As a result of these changes, timber yields in North America either may increase in the future (Beach et al., 2015; EPA, 2015a) or decrease (Boulanger et al., 2014; McKenney et al., 2016;

D'Orangeville et al., 2018; Thorne et al., 2018; Chaste et al., 2019) depending on location and the mechanisms included. Wildfires and insect outbreaks are projected to increase with future climate change, thereby limiting biomass (Gauthier et al., 2015; Bentz et al., 2019; Chaste et al., 2019).

14.5.4.2 Observed Impacts and Projected Risks: Fisheries and Aquaculture

Climate impacts outlined in Section 14.5.2 have induced yield losses for multiple subsistence, recreational and commercial fisheries (*very high confidence*), and contributed to commercial fishery closures across North America (Sections 14.5.1, 14.5.3; Figure 14.6; Table SM14.7; Lynn et al., 2014; Barbeaux et al., 2020; Fisher et al., 2021). Climate-driven declines in productivity are widespread (*high confidence*) (Figure 14.6), although a few increases are observed in northern regions (*medium confidence*) (Cunningham et al., 2018; Crozier et al., 2019; Zhang et al., 2019b). Redistribution of species has increased travel distance to fishing grounds, shifted stocks across regulatory and international boundaries, and increased interactions with protected species (*very high confidence*) (Figure 14.6; Table SM14.7; Cross-Chapter Box MOVING PLATE in Chapter 5; Morley et al., 2018; Free et al., 2019; IPCC, 2019b; Rogers et al., 2019; Stevenson and Lauth, 2019; Young et al., 2019). Climate shocks have reduced yield and increased instability in fishery revenue (*high confidence*) (Fisher et al., 2021).

Declines in yield and poleward stock redistributions (an average of ~20.6 km per decade) are expected to continue under climate change and increase in magnitude with atmospheric carbon (*high confidence*) (Table 14.4; Hare et al., 2016; Pecl et al., 2017; Rheuban et al., 2017; Morley et al., 2018; Smale et al., 2019; Szuwalski et al., 2021). For example, without adaptation, end-of-century losses of Bering Sea pollock yield (relative to persistence scenarios) is *likely* to reach 50% under moderate (RCP4.5) and 80% under low (RCP8.5) mitigation scenarios, respectively (Holsman et al., 2020). Expanding HABs, pathogens and altered ocean chemistry (OA and dissolved oxygen) will reduce yields and increase closures of fisheries along all North American coasts (*medium confidence*) (Section 14.5.2; Deutsch et al., 2015a; Ekstrom et al., 2015; Seung et al., 2015; Punt et al., 2016; Howard et al., 2020). For fisheries that represent 56% of current US fishing revenue, projected annual net losses under high-emission scenarios (RCP8.5, 2021–2100) may reach double that of low-emission scenarios (RCP2.6) (Moore et al., 2021).

Warming waters and OA have impacted aquaculture production in North America (*high confidence*) (Figure 14.6; Clements and Chopin, 2017; Reid et al., 2019; Stewart-Sinclair et al., 2020). Under climate change

Crop responses to climate change will depend on existing mean climate, the type of climate change, and characteristics of crop types

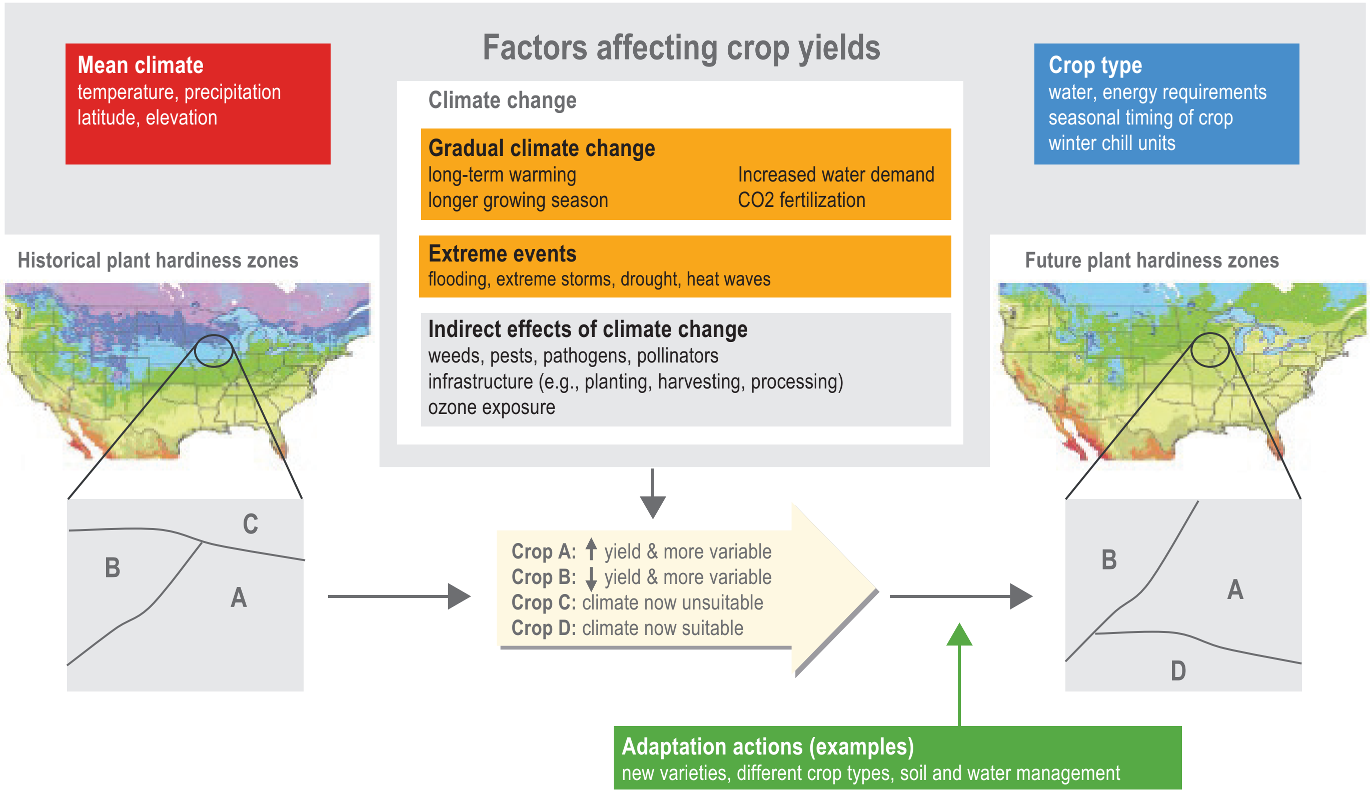
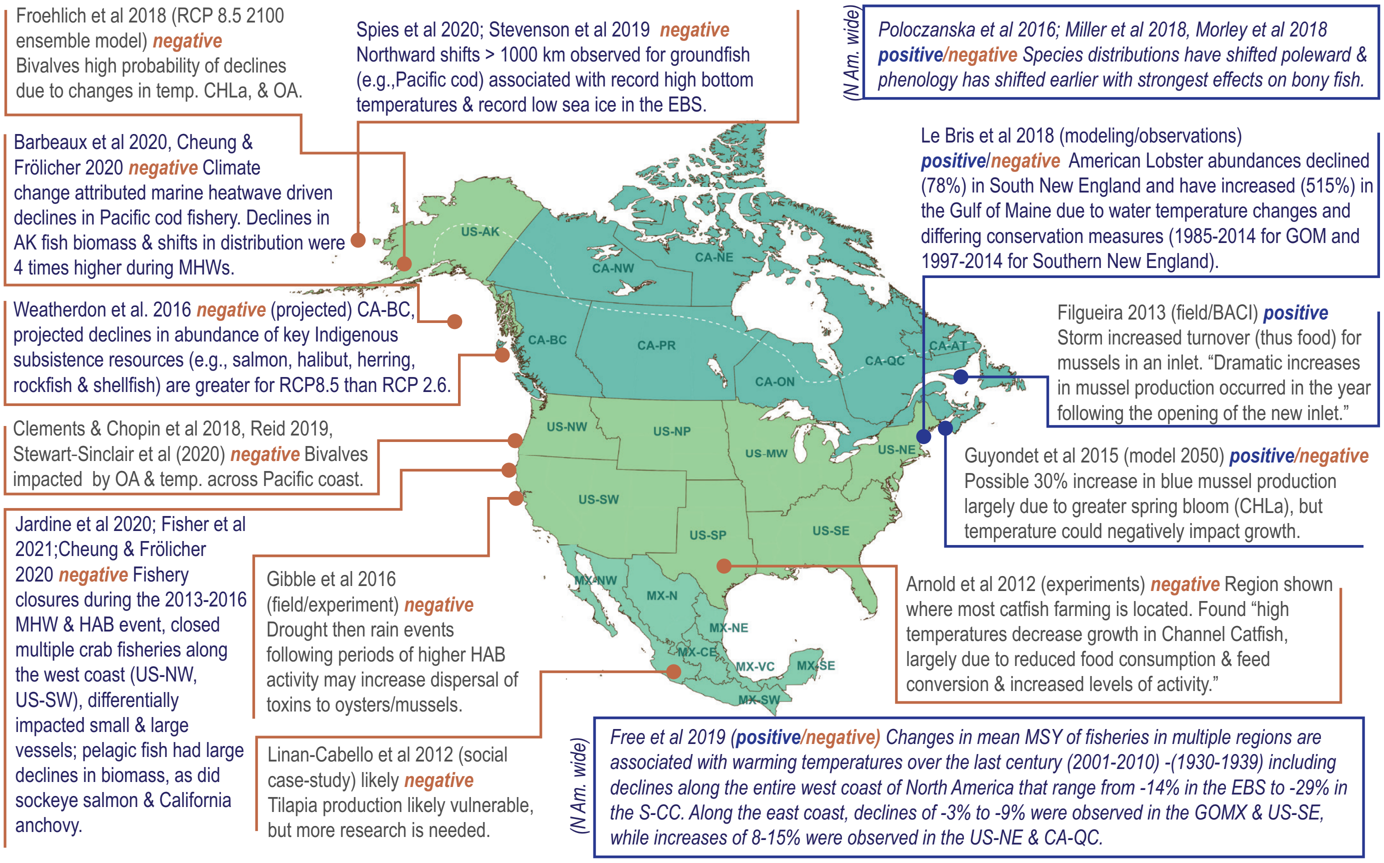


Figure 14.5 | Crop responses to climate change will depend on existing mean climate, type of climate change and characteristics of crop types. Hypothesised responses for Crop Types A, B, C and D include changing crop yields or changing crop area. Adaptation actions may alter hypothesised responses. (Maps from Matthews et al., 2019.)

Climate change impacts on North American fisheries and aquaculture



Froehlich et al 2018 (RCP 8.5 2100 ensemble model) ***negative*** Bivalves high probability of declines due to changes in temp. CHLa, & OA.

Spies et al 2020; Stevenson et al 2019 ***negative*** Northward shifts > 1000 km observed for groundfish (e.g.,Pacific cod) associated with record high bottom temperatures & record low sea ice in the EBS.

Poloczanska et al 2016; Miller et al 2018, Morley et al 2018 ***positive/negative*** *Species distributions have shifted poleward & phenology has shifted earlier with strongest effects on bony fish.*

Barbeaux et al 2020, Cheung & Frölicher 2020 ***negative*** Climate change attributed marine heatwave driven declines in Pacific cod fishery. Declines in AK fish biomass & shifts in distribution were 4 times higher during MHWs.

Le Bris et al 2018 (modeling/observations) ***positive/negative*** American Lobster abundances declined (78%) in South New England and have increased (515%) in the Gulf of Maine due to water temperature changes and differing conservation measures (1985-2014 for GOM and 1997-2014 for Southern New England).

Weatherdon et al. 2016 ***negative*** (projected) CA-BC, projected declines in abundance of key Indigenous subsistence resources (e.g., salmon, halibut, herring, rockfish & shellfish) are greater for RCP8.5 than RCP 2.6.

Filgueira 2013 (field/BACI) ***positive*** Storm increased turnover (thus food) for mussels in an inlet. “Dramatic increases in mussel production occurred in the year following the opening of the new inlet.”

Clements & Chopin et al 2018, Reid 2019, Stewart-Sinclair et al (2020) ***negative*** Bivalves impacted by OA & temp. across Pacific coast.

Guyondet et al 2015 (model 2050) ***positive/negative*** Possible 30% increase in blue mussel production largely due to greater spring bloom (CHLa), but temperature could negatively impact growth.

Jardine et al 2020; Fisher et al 2021;Cheung & Frölicher 2020 ***negative*** Fishery closures during the 2013-2016 MHW & HAB event, closed multiple crab fisheries along the west coast (US-NW, US-SW), differentially impacted small & large vessels; pelagic fish had large declines in biomass, as did sockeye salmon & California anchovy.

Gibble et al 2016 (field/experiment) ***negative*** Drought then rain events following periods of higher HAB activity may increase dispersal of toxins to oysters/mussels.

Arnold et al 2012 (experiments) ***negative*** Region shown where most catfish farming is located. Found “high temperatures decrease growth in Channel Catfish, largely due to reduced food consumption & feed conversion & increased levels of activity.”

Linan-Cabello et al 2012 (social case-study) likely ***negative*** Tilapia production likely vulnerable, but more research is needed.

*Free et al 2019 (**positive/negative**) Changes in mean MSY of fisheries in multiple regions are associated with warming temperatures over the last century (2001-2010) -(1930-1939) including declines along the entire west coast of North America that range from -14% in the EBS to -29% in the S-CC. Along the east coast, declines of -3% to -9% were observed in the GOMX & US-SE, while increases of 8-15% were observed in the US-NE & CA-QC.*

Figure 14.6 | Case studies of climate-change impacts on North American fisheries (blue text) and aquaculture (gray text).

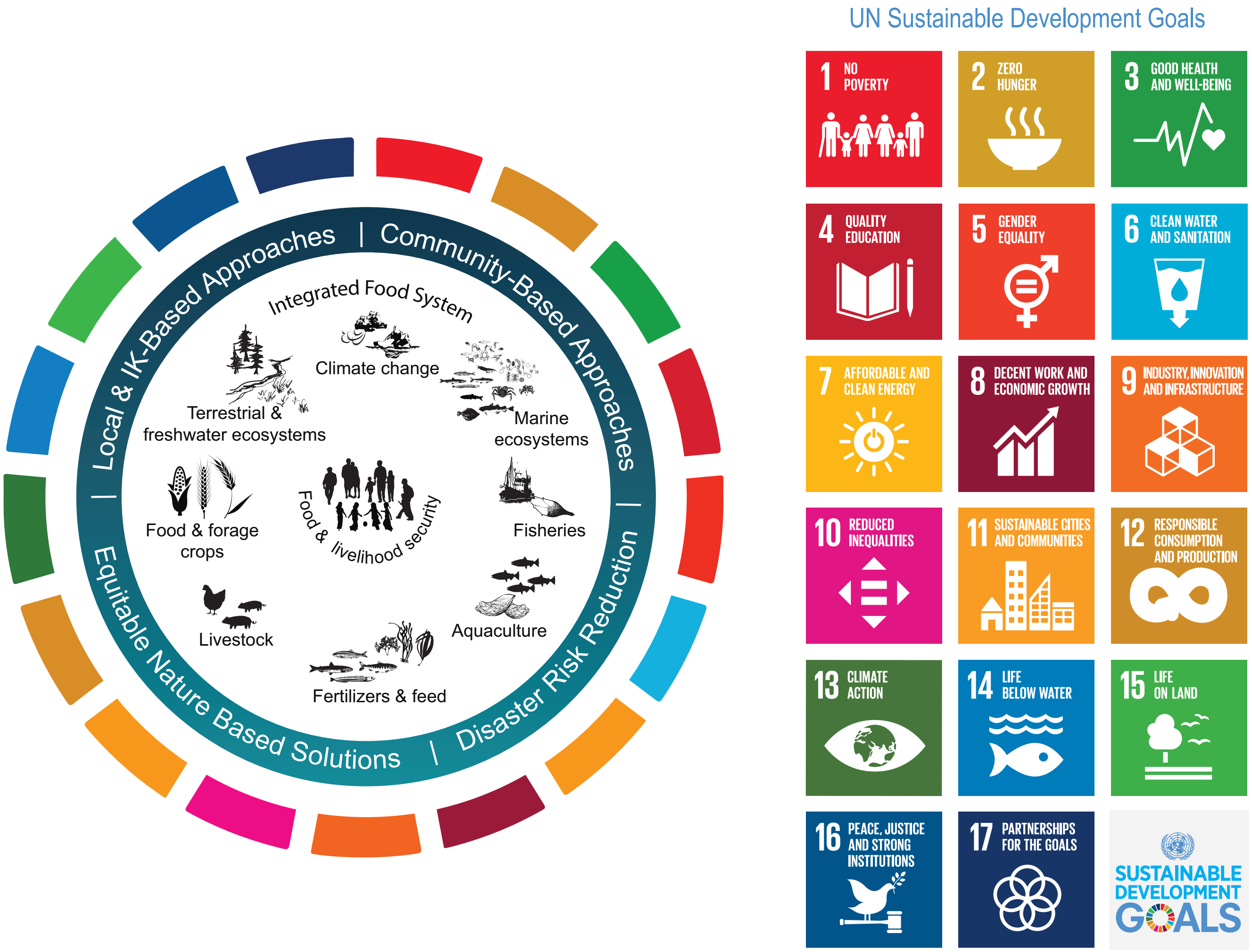
(RCP8.5), declines in marine finfish and bivalve aquaculture become *likely* by mid-century (Froehlich et al., 2018; Stewart-Sinclair et al., 2020). Adaptation is possible but uncertain (Bitter et al., 2019; Fitzer et al., 2019; Reid et al., 2019), especially with increasing extreme events. Nature-based aquaculture solutions (e.g., conservation aquaculture, restorative aquaculture) could aid carbon mitigation and local-level adaptation, especially for seaweed and bivalve culture (see Box 14.7; Froehlich et al., 2017; Froehlich et al., 2019; Reid et al., 2019; Theuerkauf et al., 2019).

14.5.4.3 Food and Fibre Adaptation: Cross-Cutting Themes

Across food and fibre systems, climate resilience is enhanced through diversifying income and harvest portfolios as well as increasing local biodiversity and functional redundancy (*high confidence*) (Messier et al., 2019; Rogers et al., 2019; Young et al., 2019; Aquilué et al., 2020; Fisher et al., 2021). Ecosystem-based practices and sustainable intensification (increasing yields while minimising resource demand and ecosystem impacts) (Cassman and Grassini, 2020; Rockström et al., 2021) will help the sector meet food production demands under climate change (*medium confidence*), but effectiveness generally declines and is less certain after 2050 in scenarios without carbon mitigation (*high confidence*) (Bermeo et al., 2014; Gaines et al., 2018; Costello et al., 2020; Free et al., 2020; Holsman et al., 2020). Across the sector, successful adaptation is underpinned by approaches that meaningfully consider the coupled social–ecological networks around food and fibre production and value IK (*very high confidence*) (see Box 14.1; FAO, 2018; Steele et al., 2018; Calliari et al., 2019). Integrated modelling, participatory planning and inclusive decision making promote effective and equitable adaptation responses (*very high confidence*) (Figure 14.7, Section 14.7) Toledo-Hernández et al., 2017; Eakin et al., 2018; Monterroso and Conde, 2018; Alexander et al., 2019; Hodgson and Halpern, 2019; Holsman et al., 2019; Samhouri et al., 2019; Barbeaux et al., 2020; Hollowed et al., 2020), while a paucity of high-resolution and locally tailored climate change information remains a barrier to adaptation (Ekstrom et al., 2015; Donatti et al., 2017; Young et al., 2019).

14.5.4.4 Food and Fibre Adaptation: Agriculture, Livestock and Forestry

Land management and horticulture approaches that preserve and improve soil structure and organic matter can reduce erosion (*high confidence*) (Sections 14.5.1, 14.5.3; Lal et al., 2011; Bisbis et al., 2018). Preserving biodiversity and water, changing planting dates and double cropping are also effective climate adaptation strategies (Bisbis et al., 2018; Hernandez-Ochoa et al., 2018; Monterroso-Rivas et al.,


Adaptation in North American food sectors

UN Sustainable Development Goals

Figure 14.7 | Adaptation in North American food sectors is shown, modified from Cottrell et al. (2019).

2018; Wolfe et al., 2018). Traditional agriculture inherently includes climate adaptive practices that enhance biodiversity, soil quality and agricultural production (e.g., multiple cultivars, heat-tolerant heritage cattle breeds) (Bermeo et al., 2014; Gomez-Aiza et al., 2017; Ortiz-Colón et al., 2018). Agroecology and agroforestry (see Box 14.7) in North America has expanded from (but not replaced) traditional and rural practices in Mexico (Metcalfe et al., 2020a) as a sustainable and climate-resilient alternative to industrial agriculture (Schoeneberger et al., 2017) that increases productivity (by 6–65% depending on the crop), enhances microclimates and provides co-benefits for GHG mitigation (Abbas et al., 2017; Cardinael et al., 2017; Schoeneberger et al., 2017; Snapp et al., 2021). Irrigation is an effective adaptation strategy in key agricultural areas (Miller, 2017; Lund et al., 2018) and could stabilise food security in rain-fed regions (e.g., southeast Mexico) (Spring, 2014); water allocation must balance multiple needs and rights (*medium confidence*) (Section 14.5.3; Brown et al., 2015b; Levis et al., 2018; Gomez Diaz et al., 2019). Heritage livestock breeds, changing species and precision-ranching technology may promote ranch and rangeland resilience (Zhao et al., 2013). In loblolly pine plantations in the southern USA, effective adaptation includes reducing tree density and, less effectively, shifting to slash pine (Susaeta et al., 2014). Salvage logging following forest disturbances (e.g., insect outbreaks) can increase timber harvest (Bogdanski et al., 2011; USDA Forst Service, 2011; Han et al., 2018; Morris et al., 2018a).

14.5.4.5 Food and Fibre Adaptation: Fisheries and Aquaculture

Proactive and ecosystem-based management increases climate resilience in fisheries (*high confidence*), but effectiveness after 2050 may be limited without global carbon mitigation (*medium confidence*) (Gaichas et al., 2017; Gaines et al., 2018; Kritzer et al., 2019; Barbeaux et al., 2020; Free et al., 2020; Holsman et al., 2020). Flexibility (e.g., mobility, diverse incomes or harvest portfolios) underpins climate resilience across regions, management policies and fisheries, although small-scale fisheries have less scope for adaptation (Aguilera et al., 2015; Young et al., 2019). Climate-informed and dynamic management

Table 14.4 | Observed and projected impacts to food and fibre resources

Climate driver	Observed change[a]	References	Projected change	References
Agriculture and livestock (Tables SM14.2–SM14.5)				
Extreme events	Estimates of yield reduction from heat stress for both maize and cotton indicate that historically, US-SW heat stress reduced cotton yield by 26% and maize yield by 18% compared with potential yield. Extreme heat was associated with increased crop failure in MX-CE, US-SW. Hailstorm increased frequency observed in MX coinciding with the most vulnerable stage or flowering period of maize. Extreme precipitation damages to soil, increased erosion, and reduced crop yields observed in Mexico and US-MW.	Altieri and Nicholls (2009); Mastachi-Loza et al. (2016); Elias et al. (2018); Kistner et al. (2018); Reyes and Elias (2019)	Heat stress (RCP8.5) reduces mid-century (2040–2069) maize and cotton yields by 12–15% of historical yields (1950–2005) with largest impacts in US-SW, and additional drought-related stress in US-MW could reduce maize and soybean yields by ~5 and ~10%, respectively, by late century under RCP4.5. Warming and extreme heat (>35%) will delay (or prevent) chill accumulation, impacting perennial crop development, yields and quality (US-SW). Increases in extreme temperature raise the risk of livestock heat stress, disease and pest impacts.	Jin et al. (2017); Rojas-Downing et al. (2017); Elias et al. (2018); Parker et al. (2020)
Mean growing season precipitation decline, mean temperature increase, drought	Across the US Great Plains (US-SP, US-NP) between 1968 and 2013 climate change induced 3.55, –0.55 and 0.94% change in yield for (irrigated and non-irrigated) maize, sorghum and soybeans, respectively. Droughts and increasing temperatures reduced soil fertility in Mexico and contributed to soil erosion and degradation, and suitability loss of 18–22%. Experimental and simulated reductions in water supply of 25–50% result in similar-magnitude declines in yield for multiple food and forage crops (e.g., wheat, maize).	Frisvold and Konyar (2012); Leskovar et al. (2012); Aladenola and Madramootoo (2014); Galloza et al. (2017); Havstad et al. (2018); Kukal and Irmak (2018)	Warming alters the length of growing seasons of cold-season crops and shifts suitability ranges of warm-season California crops. Aridification reduces forage production in US-SW and MX-N. Warming is associated with reduced livestock growth and fertility, increased pathogens in US-SE, US-SP, US-MW and US-NE, and reduced milk production in US-MW.	St-Pierre et al. (2003); Polley et al. (2013); Key and Sneeringer (2014); Reeves et al. (2014); Cooley (2016); Hufkens et al. (2016); Derner et al. (2018); Hristov et al. (2018); Ortiz-Colón et al. (2018); Zhang et al. (2019b); Bowling et al. (2020); Bradford et al. (2020); Marklein et al. (2020)
Multiple drivers	Climate change reduced total factor productivity of agriculture and livestock in North America by 12.5% (ranging from approximately –35 to 8%) between 2016 and 2015. Losses have been greatest in Mexico (–30 to –25%) (Figure 14.5), and lowest in Canada (>0%). Reduced yield in Mexico and the USA; increased weed and pest pressure in US-NE, US-MW, US-NP and US-NW.	Garruña-Hernández et al. (2012); Loreto et al. (2017); Wolfe et al. (2018); Torres Castillo et al. (2020; Ortiz-Bobea et al. (2021)	Declines in yield and changes in suitability ranges for maize (–18 to 5%), sorghum (–16 to 12%) and wheat (–38 to –15%) in Mexico (RCP4.5, 8.5; 2040–2099); northward shifts in the suitable area for six crops from the central USA (2100). Warming accompanied by increased CO_2 may benefit crop production of small grains in southern Canada up to 3°C global warming level (GWL), although benefits decline after 2.5°C GWL. Increased CO_2 enhances production but reduces forage quality in US-NP and US-NW. Without adaptation, 2°C GWL increases insect-caused production losses ~36 and ~44% for maize and wheat, respectively.	Calderón-García et al. (2015); Herrera-Pantoja and Hiscock (2015); Lant et al. (2016); Chen et al. (2017); Montiel-González et al. (2017); Reyer et al. (2017); Derner et al. (2018); Deutsch et al. (2018); Levis et al. (2018); López-Blanco et al. (2018); Murray-Tortarolo et al. (2018); Wolfe et al. (2018); Gomez Diaz et al. (2019); Qian et al. (2019); Zhang et al. (2019b); Arce Romero et al. (2020)
Aquaculture and fisheries (Tables SM14.6, SM14.8)				
Extreme events	MHW and HAB events of 2014–2016 resulted in multiple fishery closures along the west coast (US-NW, US-SW); disparate impacts observed between small and large vessels with greatest impacts on small vessel revenue and fishery participation; impacts highest for ports in the N-CC and least for fishing communities with diverse livelihoods and harvest portfolios. In the EBS, GOA and N-CC, declines in fish biomass and shifts in distribution were four times higher and greater during MHWs than that of general warming over the same period. Pelagic fish showed largest decrease in biomass (7%), as did Sockeye salmon and California anchovy; increased risk to hatcheries and low-lying pond systems from severe storms. Extreme heat is associated with reduced productivity of aquaculture species.	Handisyde et al. (2017); Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019); Reid et al. (2019); Bertrand et al. (2020); Cheung and Frölicher (2020); Jardine et al. (2020); Sippel et al. (2020); Fisher et al. (2021)	Doubling of MHW impact levels by 2050 among the most important fisheries species (over previous assessments that focus only on long-term climate change).	Cheung and Frölicher (2020)

Climate driver	Observed change^{a}	References	Projected change	References
Multiple drivers	Climate shocks reduce catch, revenue and county-level wages and employment among commercial harvesters in US-NE. Climate variability during 1996–2017 is responsible for a 16% (95% CI: 10–22%) decline in county-level fishing employment in New England; impacts mediated by local biology and institutions. Seafood is an important source of nutrients and protein for Indigenous Peoples in CA-BC. Polices that incorporate nutrition in fisheries management are limited in North America.	Marushka et al. (2019); Oremus (2019); also see Section 14.5.6	Declines in North American catch potential of flatfish under RCP8.5 for the EBS, GOA, GOMX, US-SE and US-NE; declines in productivity for multiple species in Mexico, with the largest declines in productivity (>35%) for abalone and Pacific sardine. Impacts are greatest for artisanal species; declines in fish community biomass for all North American coasts except US-SW and the Canadian Arctic; declines are greater under RCP8.5 than RCP2.6. Modest increases (up to 10%) in landings of CA-QC and CA-AT surf clams and shrimp are projected under RCP2.6 by 2100 and declines in snow crab up to 16% are expected (RCP2.6, 8.5). Mussel landings increase 21%, while declines in shellfish and lobster landings (2090) are twice as high under RCP8.5 (42–54%) as RCP2.6. Shellfish and snow crab landings decline in CA-QC and CA-QT; declines under RCP8.5 are double those of RCP2.6. Climate change reduces EBS blue king crab recovery in simulations. Relative to the USA and Canada, Mexico has the strongest benefits in net catch under RCP2.6 relative to RCP8.5 (>30% increase in catch); increases of 70% in catch potential projected for the Canadian Arctic (CA-NE, CA-NW) under RCP8.5 (versus minimal changes under RCP2.6). High-resolution and size-spectrum models project declines in groundfish catch and biomass in S-EBS. Shifting transboundary stocks may increase challenges.	Weatherdon et al. (2016); Cheung (2018); Carozza et al. (2019); Cisneros-Mata et al. (2019); Reum et al. (2019); Tai et al. (2019); Mendenhall et al. (2020); Wilson et al. (2020)
Ocean and lake acidification	Ocean acidification (OA) reduced maximum sustainable yield, catch and profits of EBS Tanner crab in simulations. Survival of larval and juvenile red king crab in the lab decreased 97–100% with decreasing pH; no appreciable effects of pH on larval growth of walleye pollock in the lab (Hurst, 2013); mixed evidence of impacts of changes in pH on freshwater or saltwater finfish aquaculture; OA reduced growth, calcification, attachment and increased mortality in calcifying molluscs and seaweeds in the USA and Canada; OA may benefit non-calcifying seaweeds.	Long et al. (2013a); Seung et al. (2015); Punt et al. (2016); Clements and Chopin (2017); Handisyde et al. (2017); Swiney et al. (2017); Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019); Reid et al. (2019); Stewart-Sinclair et al. (2020)	Declines for some shellfisheries and flatfish due to OA and temperature. OA conditions under RCP8.5 reach critical risk thresholds for mollusc harvests earlier in northern regions than southern areas. OA risk to shellfisheries is highest in N-CC. OA causes 1% additional decline in Arctic cod populations by 2100 under RCP8.5. OA influences management reference points of Northern Rock sole. OA and temperature reduce probability of recovery in simulations of EBS blue king crab.	Ekstrom et al. (2015); Reum et al. (2019); Steiner et al. (2019); Wilson et al. (2020); Punt et al. (2021)
Mean temperature increase	Species distributions have shifted poleward and phenology has shifted earlier with the strongest effects on bony fish. Warming over the past century (2001–2010 to 1930–1939) is associated with declines in maximum sustainable yield along the entire west coast of North America that range from –14% in the EBS to –29% in the CC-S. Along the east coast, declines of –3 to –9% were observed in the GOMX and US-SE, while increases of 8–15% were observed in the US-NE and CA-CQ; mixed positive and negative growth and mortality responses for aquaculture species in North America. Juvenile red king crab survival decreases as temperatures increase in lab experiments. American Lobster abundances declined (78%) in South New England and have increased (515%) in the Gulf of Maine due to water temperature changes and differing conservation measures (between 1985 and 2014 for the GOM, and 1997 and 2014 for southern New England).	Poloczanska et al. (2016); McCoy et al. (2017); Swiney et al. (2017); Le Bris et al. (2018); Miller et al. (2018); Food Agriculture Organization of the United Nations (2019); Free et al. (2019); Reid et al. (2019); Weiskerger et al. (2019); Bertrand et al. (2020); Le et al. (2020)	By end of century, North American fish biomass, catch potential and revenue are ~9% higher under RCP2.6 than RCP8.5 and differences are greatest for US fisheries (relative to Canada and Mexico; poleward redistributions (reported ranges of 10.3–39.1 km per decade) and to depth decrease access to shellfisheries in CA-QC and subsistence species in CA-BC (–28% by 2100), with impacts increasing north to south and under RCP8.5 as compared with RCP2.6. Climate change (RCP8.5) shifts the relative percentage of catch and profits for the USA–Canada transboundary stocks under RCP8.5 (but not RCP2.6); decreases in biomass of historically large fisheries in US-NA and CA-QC, and US-AK and important subsistence species in CA-WA and CA-BC, while some increases in the North Atlantic. Declines are greater under RCP8.5 relative to RCP2.6. In EBS (US-AK), community biomass, catches and mean body size decreases by 36, 61 and 38%, respectively, under RCP8.5 (2100). Climate change causes declines in global marine aquaculture production under RCP8.5 with impacts greater for bivalve than finfish and with significant disparities among regions in direction and magnitude of changes; greatest declines for finfish aquaculture expected in northern regions (GOA, CA-BC, CA-CQ), and large declines for bivalve production (declines of 20–100%) for Canada. Declines become more probable by 2050–2070.	Weatherdon et al. (2016); Cheung (2018); Froehlich et al. (2018); Morley et al. (2018); Greenan et al. (2018); Steiner et al. (2019); Sumaila et al. (2019); Bryndum-Buchholz et al. (2020); Holsman et al. (2020); Palacios-Abrantes et al. (2020); Reum et al. (2020); Sumaila and Zwaag (2020); Whitehouse and Aydin (2020); Wilson et al. (2020)

Notes: See Figure 14.1 for region acronym definitions. (a)

(Hazen et al., 2018) improves modelled fishery performance (*medium confidence*) (Section 14.5.2; Froehlich et al., 2017; Tommasi et al., 2017a; Tommasi et al., 2017b; Karp et al., 2019; Barbeaux et al., 2020), yet planning and policies that directly incorporate climate-change information remain limited (Skern-Mauritzen et al., 2015; Marshall et al., 2019b). Expanding aquaculture across North America will *likely* address deficits in nutritional and protein yields (Gentry et al., 2019; Costello et al., 2020), yet aquaculture initiatives have largely progressed without explicitly considering climate impacts (FAO, 2018; Froehlich et al., 2019), and critical elements for climate adaptation (e.g., climate-informed zoning, monitoring, insurance) are not widely implemented (Liñan-Cabello et al., 2016; FAO, 2018; Stewart-Sinclair et al., 2020). Climate-informed and standardised aquaculture governance, and increased coordination with fishery and coastal management, is needed for climate resilience (*high confidence*) (Brugère et al., 2019; Froehlich et al., 2019; Free et al., 2020; Galparsoro et al., 2020).

14.5.5 Cities, Settlements and Infrastructure

Cities are complex social–ecological systems with large populations, concentrated wealth, ageing infrastructure, reliance on extrinsic and increasingly stressed natural systems, social inequality, differential institutional capacities and impervious, heat-retaining surfaces (Maxwell et al., 2018a; Schell et al., 2020). These factors interact with location (e.g., proximity to coast, in a floodplain) to create city-specific vulnerabilities to climate change and requirements for resilience initiatives (Mercer Clarke et al., 2016). Cities are home to diverse cultural and social communities, including large Indigenous populations who can be uniquely affected by climate change yet who bring valuable IK and leadership to urban adaptation efforts (Statistics Canada, 2020; Brown et al., 2021). The rural and remote settlements of North America also experience similar hazards and risks; however, such challenges are due to different factors such as geographic isolation, dependence on local food resources and socioeconomic conditions (Kearney and Bell, 2019; Vodden and Cunsolo, 2021).

14.5.5.1 Observed Impacts

14.5.5.1.1 Rising temperatures and extreme heat

Extreme heat events are affecting natural assets and built infrastructure as well as individuals in cities and rural settlements across North America (*high confidence*) (Maria Raquel et al., 2016; Amec Foster Wheeler and Credit Valley Conservation, 2017; Howell and Brady, 2019; Martinich and Crimmins, 2019). Key urban infrastructure systems (e.g., services in buildings, energy distribution) are interdependent and susceptible to cascading impacts (e.g., electricity supply disruption during a heatwave compromising another system like water delivery, high-rise cooling) (Brown et al., 2021). Urban social inequality and systemic racism has led to disproportionately higher exposure to urban heat island effects in low-income and minority neighbourhoods in US cities, due in part, to less green space and tree cover to offset heat retained in the built environment (Hoffman et al., 2020; Schell et al., 2020; Hsu et al., 2021). In the rural context, extreme heat contributes to migration out of small communities; for example, see cases reported in Mexico (Nawrotzki et al., 2015a). Extreme heat events pose a significant risk to residents of small towns across North America due to limited resources to address heat impacts and attendant increased morbidity and mortality (Section 14.5.6.1; McDonald et al., 2016; Guo et al., 2018; D'ulisse, 2019).

Hot and dry conditions increase risk of wildfires close to human settlements through collateral impacts on properties, economic activity and human health (see Box 14.2; Section 14.5.6.3). These environmental conditions also stress natural assets (e.g., urban forests, wetlands, household gardens, green walls) and performance of green infrastructure leading to higher operation and maintenance costs (*high confidence*) (Kabisch et al., 2017; Terton, 2017).

14.5.5.1.2 Storms and flooding

Short-duration, high-intensity rainfall and other extreme events (e.g., hurricanes, atmospheric river events) create significant flooding risks and impacts for cities in North America and negatively affect the lives, livelihoods, economic activities, infrastructure and access to services (*high confidence*) (Amec Foster Wheeler and Credit Valley Conservation, 2017; Curry et al., 2019). In 2016, US flooding events caused 126 fatalities and 11 billion USD (considering the 2016 USD value) in damages (NOAA, 2019). In Canada, flooding accounts for 40% of the costs associated with weather-related disasters recorded since 1970 (Canadian Institute for Climate Choices, 2020); the most costly event was the 2013 Calgary flood (CA-PR) (1.8 billion CAD in catastrophic insurance losses and 6 billion CAD in direct costs such as uninsured losses) (Office of the Auditor General of Canada, 2016). Mexico City is seasonally impacted by high-intensity rainfall events that generate local flooding (de Alba and Castillo, 2014). Rural and remote settlements are also threatened by floods; Indigenous lands in Canada are disproportionately exposed to flooding, with almost 22% of residential properties at risk of a 1-in-100-year flood (Thistlethwaite et al., 2020; Yumagulova, 2020).

Wind storms and hurricanes are significant climate hazards for North American cities and settlements, affecting urban forests, electricity distribution and service delivery, and damaging buildings and transportation infrastructure (Amec Foster Wheeler Environment and Infrastructure, 2017; British Columbia Hydro, 2019; Smith, 2020), with enduring impacts on small villages due to lost livelihoods and limited recovery capacity (e.g., Rio Lagartos and Las Coloradas in MX-SE after Hurricane Isidore) (Audefroy and Cabrera Sánchez, 2017). The Pacific coast of Mexico is also experiencing hurricanes such as Patricia (category IV) in 2015 and Newton (category I) in 2016 (CONAGUA, 2015; CONAGUA, 2016); hurricane Patricia affected 56 municipalities in the states of Colima, Nayarit and Jalisco (MX-CE, MX-NW) (Calleja-Reina, 2016).

14.5.5.1.3 Sea level rise

Sea level rise interacts with shoreline erosion, storm surge and wave action, saline intrusion and coastal flooding to directly threaten coastal cities and small communities in North America with impacts to public and private buildings and infrastructure, port and transportation facilities, water resources (*high confidence*) (NOAA National Weather Service, 2017; Boretti, 2019) and cultural heritage sites (see Box 14.4; Dawson et al., 2020). Sea level rise is creating conditions where considerable financial investments are needed and, in many cases, are being raised to address adaptation needs (see Box 14.4; CCP6, Fatorić and Seekamp, 2017; Hinkel et al., 2018; Greenan et al., 2018). Across North America, high population density and concentrated development along the coast generates exposure to SLR impacts.

14.5.5.2 Projected Impacts and Risks

Evidence since the AR5 highlights increased risk to quality of life in cities and rural communities as a result of exposure to intensifying climate-change hazards, and the compounding and interacting effects of climate and non-climate factors (*medium confidence*).

14.5.5.2.1 Rising temperatures and extreme heat

Extreme heat events are projected to increase in frequency and intensity across North America in the coming decades (Section 14.2.2; Figure 14.2F,G). Inland urban areas in the southern and eastern USA are susceptible to urban heat island effects, particularly the Midwest/Great Lakes regions (Krayenhoff et al., 2018) and also Mexico City and many other cities in Mexico (Vargas and Magaña, 2020). Climate change (RCP8.5) interacting with urban form, development and systemic racism (Schell et al., 2020; Hsu et al., 2021) could worsen risks from extreme heat in North American cities, especially where there is limited adaptation (*high confidence*) (Krayenhoff et al., 2018). Impacts from extreme heat will be exacerbated when multiple hazards occur simultaneously (e.g., heatwaves concurrent with droughts) (Mora et al., 2018; Zscheischler et al., 2018). Extreme heat events increase energy demand for space cooling in buildings, especially during peak demand periods and heatwaves (IEA, 2018a). This can decrease cooling efficiency, increase emissions of GHG from electricity generation, increase refrigerant loads and associated emissions, and negatively affect air quality (IEA, 2018a). Major electrical grid failure (i.e., blackouts) have increased across the USA and will continue to be particularly dangerous for human health when they coincide with extreme heat events (Stone et al., 2021). Efforts to increase resilience of the infrastructure that cities rely on are increasing (Climate-Safe Infrastructure Working Group, 2018).

Warmer and/or drier conditions may reduce water supply reliability for cities and small communities that rely on surface water sources fed by rain or snowmelt runoff, for example, Victoria and Vancouver, Canada (CA-BC) (Metro Vancouver, 2016; Vadeboncoeur, 2016; Islam et al., 2017); San Pedro, Hermosillo and Los Pargas, Aguascalientes, México (MX-NW, MX-CE) (Vadeboncoeur, 2016; Soto-Montes-de-Oca and Alfie-Cohen, 2019); New York City (US-NE) (NYC Department of Environmental Protection, 2014); and Washington State (US-NW) (Section 14.5.3.2; Fosu et al., 2017).

14.5.5.2.2 Storms and flooding

Annual and winter precipitation is expected to increase for most of Canada (Section 14.2; Figure 14.2D,E) and will increase flooding in cities and settlements (*high confidence*) (Bonsal et al., 2019). Although there is more geographic variation across the continental USA (e.g., between high-latitude and subtropical zones), extreme precipitation events are projected to increase in frequency and intensity with impacts on flood hazards (Section 14.5.3.2; Easterling et al., 2017). Winter (snow and ice) storms are expected to increase in northern North America and decrease in southern North America under RCP8.5 (Jeong and Sushama, 2018b). Projected increases in wind-driven rain exposure is an emerging consideration for moisture-resilient design and management of buildings, especially in western and northern Canada (Jeong and Cannon, 2020).

14.5.5.2.3 Sea level rise

In the USA, many people are projected to be at risk of flooding from SLR (*high confidence*) (see Box 14.4). A projected SLR of 0.9 m by 2100 could place 4.2 million people at risk of inundation in US coastal counties, whereas a 1.8-m SLR exposes 13.1 million people (Hauer et al., 2016). In California, under an extreme 2-m SLR by 2100, 150 billion USD (2010) of property or more than 6% of the state's GDP and 600,000 people could be affected by flooding (Barnard et al., 2019). A 1-m SLR would inundate 42% of the Albemarle-Pamlico Peninsula in North Carolina and incur property losses of up to 14 billion USD (considering the 2016 USD value) (Bhattachan et al., 2018). In nine southeast US states, a 1-m SLR would result in the loss of more than13,000 recorded historical and archaeological sites with over 1000 eligible for inclusion in the National Register for Historic Places (Anderson et al., 2017). This SLR raises groundwater levels by impeding drainage and enhancing runoff during rain events (Hoover et al., 2017); coastal flooding enhances saltwater intrusion affecting drinking water supply in settlements (e.g., coast of Texas) (Anderson and Al-Thani, 2016).

In Canada, SLR is expected to increase the frequency and magnitude of extreme high-water-level events (Greenan et al., 2018) and to create widespread impacts on natural and human systems (*high confidence*) (see Box 14.4; Lemmen et al., 2016). Although coastal sensitivity is high in the Arctic, Canada's more populated regions are also sensitive to the impacts of SLR (Manson et al., 2019). The Mi'kmaq community of Lennox Island First Nation is exploring relocation options because of erosion from SLR (Savard et al., 2016).

In Mexico, crucial coastal tourism cities, such as Cancun, Isla Mujeres, Playa del Carmen, Puerto Morelos and Cozumel (MX-SE), are at risk of SLR with an estimated economic impact of 1.4–2.3 billion USD (Section 14.5.7; Ruiz-Ramírez et al., 2019). Negative effects of the 'coastal squeeze' phenomena (generated by SLR, land subsidence, sediment deficit and current urbanisation processes) have been documented on tourist destinations along the coasts of the Mexican Gulf of Mexico and Mexican Caribbean. Zoning, limiting urbanisation along the coastline and using NbS (see Box 14.7) are alternatives that could be applied to improve the adaptation of these destinations (Martínez et al., 2014; Salgado and Luisa Martinez, 2017; Lithgow et al., 2019).

Rural low-lying coastal areas are at risk from SLR where natural barriers or shoreline infrastructure are deteriorating and this interacts with remoteness, resource-dependent economies and socioeconomic challenges to adaptive capacity (Bhattachan et al., 2018; Manson et al., 2019). The Northeast Atlantic region of North America (CA-AT, US-NE) is exposed to high risk by combined effects of land subsidence and climate-driven SLR (see Box 14.4; Lemmen et al., 2016; Sweet et al., 2017; Fleming et al., 2018; Greenan et al., 2018).

14.5.5.3 Adaptation

In North American cities, present-day adaptation responses extend beyond the traditional focus on infrastructure to include measures aimed to protect people, property and ecosystems (*medium confidence*). Barriers to adaptation include challenges related to the local physical and environmental setting, effects of colonialism and racism, socioeconomic attributes of the population, institutional frameworks and competing interests of city stakeholders (*medium confidence*). The current scale of adaptation is generally not commensurate with reducing risks from projected climatic hazards, although resources exist that provide guidance and examples of effective adaptation (*medium confidence*). Some remote Canadian communities have demonstrated strengths (e.g., strong social networks) that support resilience to climate change (Kipp et al., 2020; Vodden and Cunsolo, 2021). In some US cities with political resistance to action on climate change, adaptation measures focused on addressing extreme events (rather than climate-change impacts) have been able to make progress (Hamin et al., 2014). Enhanced public awareness of the risks from extreme events associated with climate change is important for motivating adaptation (Section 14.3; Howe et al., 2019) and developing a climate-change agenda (Aragón-Durand, 2020).

Community-level planning tailors adaptation responses and disaster preparedness to the local context but misalignment of policies within and between levels of government can prevent implementation (Oulahen et al., 2018). Coordination, planning and national support are needed to provide sufficient financial resources to implement climate-resilient policies and infrastructure (Section 14.7.3; USGCRP, 2018).

Public health measures to address extreme heat events are more common across North America, with a focus on vulnerable populations (e.g., City of Toronto, 2019) and innovative approaches for reaching at-risk populations with an overarching intent of prevention (*medium confidence*) (Section 14.4.6.1; Guilbault et al., 2016). The heatwave plan for Montreal includes visits to vulnerable populations, cooling shelters, monitoring of heat-related illness and extended hours for public pools (Lesnikowski et al., 2017); efforts have reduced heatwave-related mortalities (Benmarhnia et al., 2016).

Other adaptation responses to reduce temperature effects include modifying structures (roofs, engineered materials) and the urban landscape through green infrastructure (e.g., urban trees, wetlands, green roofs), which increases climate resilience and quality of life by reducing urban heat island effects, while additionally improving air quality, capturing stormwater and delivering other co-benefits to the community (e.g., access to food, connection to nature, social connectivity) (*high confidence*) (see Box 14.7; Ballinas and Barradas, 2016; Emilsson and Sang, 2017; Kabisch et al., 2017; Krayenhoff et al., 2018; Petrovic et al., 2019; Schell et al., 2020). Green infrastructure can be flexible and cost-effective (Ballinas and Barradas, 2016; Emilsson and Sang, 2017; Kabisch et al., 2017). Initiatives can be 'bottom-up' community-led adaptation with support from municipal governments (e.g., East Harlem in New York City) (Petrovic et al., 2019). Valuing municipal natural assets (e.g., assigning economic value to cooling from urban forests or stormwater retention by urban wetlands) is becoming increasingly common in Canada and the USA (Wamsler, 2015; Roberts et al., 2017a; Municipal Natural Assets Initiative, 2018). Guidance assists municipalities to identify, value and account for natural assets in their financial planning and asset management programmes (O'Neil and Cairns, 2017) and consider future climate (Municipal Natural Assets Initiative, 2018).

Meeting increasing demand for indoor space cooling with equitable access requires new approaches to providing cooling (e.g., equipment efficiencies, refrigerants with lower global warming potential) and electricity production and transmission innovation (Shah et al., 2015; IEA, 2018a). While energy efficiency and building code standards are not directly established by local governments, they can encourage behaviour change via incentives (e.g., rebates on efficient equipment) or disincentives (e.g., more onerous permit approvals).

Experience with droughts, heatwaves and other weather extremes has led many municipal water managers to accept the importance of building resilience to the risks of future water shortages and costs posed by climate change (Metro Vancouver, 2016; Misra et al., 2021;

Box 14.4 | Sea Level Rise Risks and Adaptation Responses for Selected North American Cities and Settlements

Approximately 95 million Americans lived in coastal communities in 2017 (US Census Bureau, 2019) and in 2013, Canada had roughly 6.5 million coastal residents (Lemmen et al., 2016), while Mexico had 19 million people living in coastal municipalities in 2015 (Azuz-Adeath et al., 2018). Sea level rise around North American coastlines (Figure Box 14.4.1) is projected to be greatest along the coasts of Atlantic Canada, northern Gulf of Mexico for the USA and the Pacific coast of Mexico (IPCC, 2021). Sections 14.5.2.1, 14.5.5.1.3 and 14.5.5.2.3 describe SLR impacts. The status of adaptation to SLR by local governments is variable (see Table Box 14.4.1, where progress is indicated by colour coding) and ranges from financed implementation to preliminary, preparatory or scoping studies and workshops. Adaptation planning and implementation to address SLR and coastal flooding have been initiated across many cities and settlements in North America, but preparedness varies (*high confidence*).

Box 14.4 (continued)

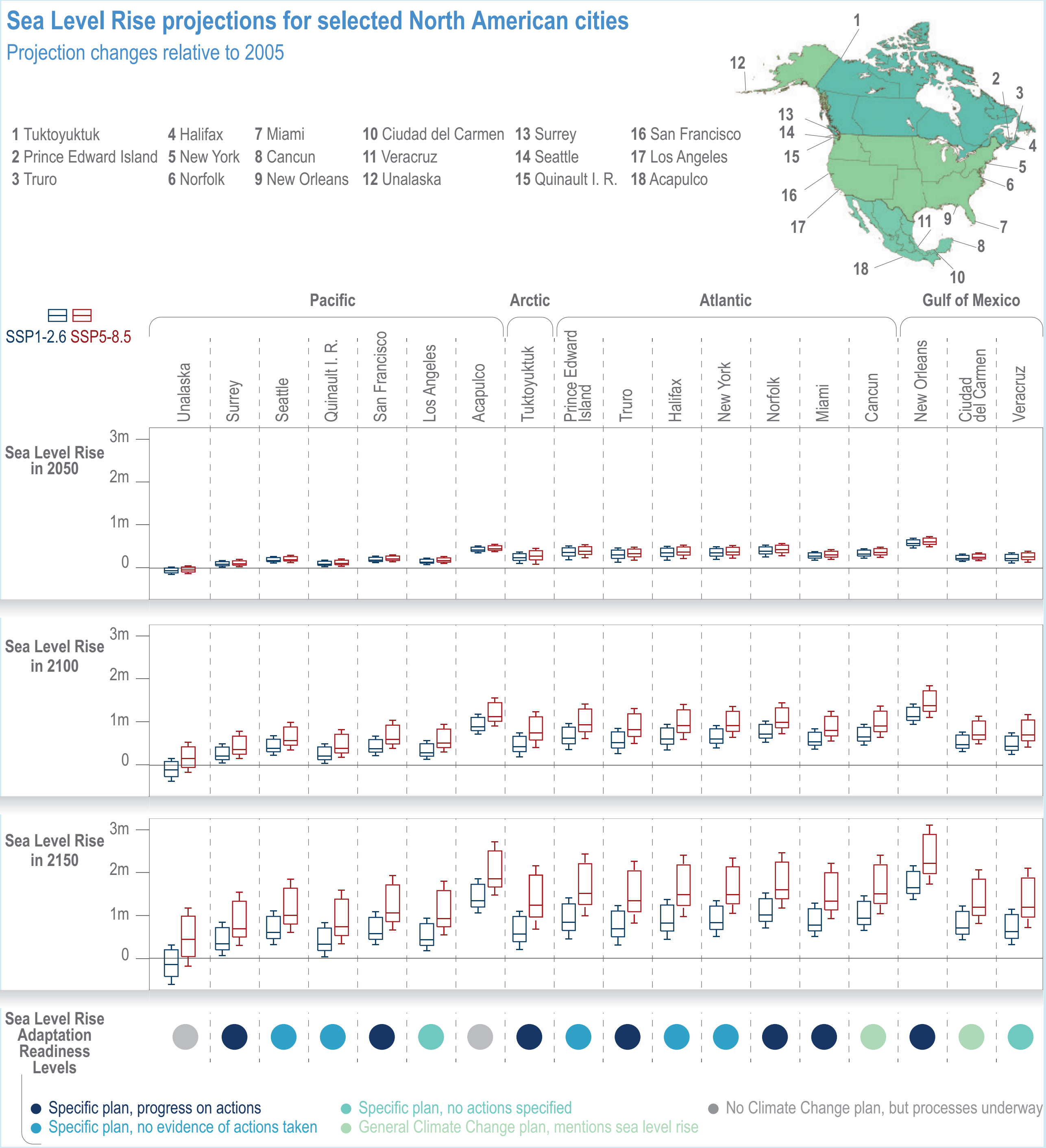


Figure Box 14.4.1 | Sea level rise projections for 2050, 2100 and 2150 for selected North American cities. Projections changes are relative to 2005, which is the central year for the 1994–2014 reference period. Horizontal lines in the boxes represent the median projection, boxes represent 25th to 75th percentile and whiskers the 10th to 90th percentile of SLR projections from all CMIP6 models as well as other lines of evidence (see Fox-Kemper et al., 2021 Table 9.7 for more details). Two SLR scenarios are provided for lower (SSP126) and higher emissions (SSP585), and are consistent with the WGI AR6 Interactive Atlas (Gutiérrez et al., 2021b. Numbers and colours (see Table Box 14.4.1 for detailed readiness definitions) on the map and in the projections represent the sites and status of SLR adaptation progress. Information supporting SLR adaptation status is summarised in Table Box 14.4.1.

Box 14.4 (continued)

Table Box 14.4.1 | Status of adaptation actions for locations on the SLR map above according to level of SLR preparedness through adaptation (as discoverable on government websites)

Ocean basin	Site no.	Area/city	Exposure (not exhaustive)	Adaptation readiness 1	Does the area/city have an adaptation plan for SLR? If so, are they taking actions to implement it? (Status)
Arctic	1	Tuktoyuktuk, CA	Infrastructure, municipal services, transportation, homes, 900 people	●	Tuktoyaktuk Coastal Erosion Study completed March 2019. Additional investments in both planning and actual adaptation measures have occurred. Limited financial resources remain a barrier (Government of Canada, 2020).
Atlantic	2	Prince Edward Island with Lennox Island, CA	PEI: residential, industrial and commercial infrastructure; Lennox Island: 10 of 79 homes, causeway to the island, sacred grounds, sewage treatment systems	🔵	Prince Edward Island government released a 5-year climate change action plan in 2018 which includes both adaptation and mitigation (Prince Edward Island Government, 2018). Biennial progress reports were issued (Prince Edward Island Government, 2019). The Mi'kmaq community of Lennox Island First Nation has explored relocation options (Daigle et al., 2015).
	3	Truro, CA	A regional centre of 12,000 residents, which has been vulnerable to repeated floods for decades	●	Town of Truro, County of Colchester and Millbrook First Nations, commissioned a flood risk study 2014–2017 (CBCL, 2017; Sherren et al., 2019) triggered by the 2012 flooding. The outcome was Truro-Onslow dyke project–a voluntary retreat with realignment of dyke infrastructure and habitat restoration by conversion of agricultural land into salt marsh habitat (Saunders-Hastings et al., 2020).
	4	Halifax, CA	Transportation causeways and bridges, marine facilities, municipal infrastructure	🔵	HalifACT 2050 is a comprehensive plan adopted as of 2020 by the Halifax regional council which includes reducing GHGs and adapting to climate change including a section on coastal preparedness (Halifax Regional Council, 2020).
	5	New York, USA	20 million people at risk by 2050; 40% of water treatment plans will be compromised by flooding, 60% of power plants will need to be relocated, transportation systems will need to be upgraded to avoid flooding	🔵	New York City has developed many adaptation plans for sustaining NYC in light of SLR and other climate hazards and impacts, especially since Hurricane Sandy affected the city in 2012. It is unclear how much of the planning has moved forward into implementation (NYC, 2013; New York City, 2015; NYC Mayor's Office of Resiliency, 2020).
	6	Norfolk, USA	Homes, massive US naval base, shipyards, active waterfront and deep-water ports	●	City of Norfolk published a very specific Coastal Resilience Strategy in 2014. Capital improvement projects highlighted in this strategy have been funded (City of Norfolk Virginia, 2014). A plan for protecting Naval base and shipyard is not evident.
	7	Miami, USA	Homes, port, transportation infrastructure, tourism (hotels, restaurants, beaches)	●	Miami Dade County released a specific SLR Strategy in 2021. Actions in the plan include elevating roads and other infrastructure, designing ways to accommodate more water in and around buildings, building on higher ground and expanding waterfront parks and canals. The plan includes a map with current and planned adaptation projects in the county (Miami-Dade County, 2021).
	8	Cancun, MX	Tourism infrastructure (hotels, restaurants, beaches), homes, markets, service industry, transportation	🟢	The 2013 Climate Change Plan assigns adaptation in general to different government levels. There is no evidence of specific adaptation plan for SLR (Government of Quintana Roo, 2013).
Gulf of Mexico	9	New Orleans, USA	Entire city, especially low-lying, low-income areas, vulnerable as evidenced by Hurricane Katrina in 2005	●	City of New Orleans adaptation is incorporated in the broader Louisiana coastal climate-change adaptation plan (CPRA, 2023). The process includes very specific projects with updates on risk-based implementation.
	10	Ciudad del Carmen, MX	Freshwater access, 11,000 homes, aquaculture	🟢	The Campeche State Climate Change Plan was released in 2013 (Government of Campeche, 2013). The plan does not include any specific recommended actions to adapt to SLR in Cuidad del Carmen. Flood-risk maps for Ciudad del Carmen were created in 2011 (Audefroy, 2019).
	11	Veracruz, MX	Freshwater access, sewage treatment systems, electrical and petrochemical industries	🟩	State of Veracruz published a climate-change plan in 2008 (Government of Veracruz, 2008). The plan includes specific tables of actions needed to monitor and adapt to SLR. The World Bank funded coastal adaptation in Veracruz focused on mangroves to dissipate storm surge but no investments in infrastructure to mitigate SLR.
Pacific	12	Unalaska, USA	Loss of cultural resources, salinisation of rivers and lakes	⚪	Climate Change Adaptation and Vulnerability Assessment workshops have been held with discussion of coastal erosion. SLR is not viewed to be as important as impacts from sea ice and permafrost loss (Poe et al., 2016).
	13	Surrey (Greater Vancouver Area), CA	Disruption in flow of goods in and out of Port of Vancouver, communication facilities, road, rail and air transportation infrastructure, businesses and agriculture	●	Surrey has a Coastal Flood Adaptation Strategy (CFAS) approved by the council (City of Surrey, 2019) with 46 actions (policy and programme, local area infrastructure). Some local area infrastructure improvements have received capital funding.

Box 14.2 (continued)

Ocean basin	Site no.	Area/city	Exposure (not exhaustive)	Adaptation readiness 1	Does the area/city have an adaptation plan for SLR? If so, are they taking actions to implement it? (Status)
	14	Seattle, USA	Low-lying areas, near-shore habitats, stormwater drains, roads, homes, businesses, socially vulnerable communities	●	Seattle released a Climate Change Response Plan in 2017 which includes general approaches including development of risk maps for SLR which are also available online (City of Seattle, 2017).
	15	Quinault Indian Reservation (Tahola), USA	650 residents and buildings	●	Quinault Indian Reservation has a plan to move Tahola to higher ground, 0.5 miles from the existing village (EPA, 2021).
	16	San Francisco, USA	37,200 residents, 17,200 businesses and 167,300 jobs vulnerable to inundation by 2100 at upper bounds of SLR, mostly along the bay side of the city	●	SF has an active, SLR planning process as well as an iterative Sea Level Rise Action Plan (City of San Francisco, 2016), planning tools and iterative assessment (City and County of San Francisco, 2020).The process specifically addresses wastewater, water, transportation, power, public safety, open space, port, neighbourhoods and changing shoreline.
	17	Los Angeles, USA	Power plants, wastewater treatment plants, Port of Los Angeles, beaches, tourism	●	Los Angeles has commissioned a projected SLR impact report but not an action plan. The Port of Los Angeles is particularly vulnerable and, as of 2019, has an SLR Adaptation Plan (Newbold et al., 2019).
	18	Acapulco, MX	Tourism infrastructure (hotels, restaurants beaches), homes, markets, service industry, transportation	●	No climate-change plan exists, although the Mexican Tourism Sector conducted a climate-change vulnerability assessment covering Acapulco (Guerrero, 2017).

Sea Level Rise Adaptation Readiness Levels

- ● Specific plan, progress on actions - specific plan for SLR with evidence of progress on taking actions including allocating funding for projects
- ● Specific plan, no evidence of actions taken - specific plan for SLR with concrete actions identified but no evidence of actions taken to date
- ● Specific plan, no actions specified - specific plan for SLR but does not include specific actions
- ● General Climate Change plan, mentions sea level rise - general climate-change adaptation action plan, which mentions SLR as a risk, issue or impact but no concrete actions, developed
- ● No Climate Change plan, but processes underway - No climate-change adaptation action plan but processes underway such as workshops, studies and vulnerability assessments

WUCA, 2021). In the southwest USA, water utilities have introduced demand-management programmes to encourage water conservation (e.g., tiered pricing, incentives for water-efficient appliances and fixtures, and rewards for replacing water-guzzling lawns with water-thrifty native vegetation) (Section 14.5.3.3; Luthy et al., 2020; Baker, 2021). Water providers also have increased their adaptive capacity by diversifying water sources (Hanak et al., 2015).

Adaptation to the risks of wildland–urban interface fire is underway (see Box 14.2; Kovacs et al., 2020), but the scope of adaptation required to sufficiently minimise wildfire risks for cities and settlements across North America has not been assessed (*medium confidence*). Leadership at the local level is increasingly supported by federal resources that provide guidance on hazard and exposure assessment, property protection, community resilience and emergency planning (National Research Council of Canada, 2021).

Cities and settlements in North America can be susceptible to multiple flooding hazards (i.e., coastal SLR, pluvial or fluvial flooding); each presents unique adaptation challenges that can be addressed through structural (e.g., armouring coastlines, reservoirs, levees, floodgates; New York City commuter tunnels) and non-structural approaches (e.g., land-use planning and zoning, expanding green infrastructure; Chetumal, Mexico) (*high confidence*) (Hardoy et al., 2014). Green infrastructure practices (e.g., open-space preservation, floodplain restoration, urban forestry, de-channelisation of streams) (see Box 14.7) can reduce urban flooding, erosion and harmful runoff (Kovacs et al., 2014; Angel et al., 2018b; Government of Canada, 2021c). Structural approaches have limitations and require trade-offs that could be addressed with a focus on social–ecological solutions and stronger institutional coordination (e.g., flood risk management in Mexico City) (Aragón-Durand, 2020). In response to high-intensity rainfall events, Mexico City invested in stormwater infrastructure, although additional benefits could have been realised if water supply needs had been incorporated (de Alba and Castillo, 2014). Some programmes exist to facilitate stormwater and wastewater infrastructure updating to accommodate increased precipitation across North America. The US federal Clean Water State Revolving Fund provides low-interest loans for states to upgrade infrastructure for climate change, with 42 billion USD provided since 1987 (ASCE, 2019). In Canada, local governments are important leaders in managing engineered and green infrastructure decisions, incentivising property-level flood protection and ensuring service delivery (Government of Canada, 2021c). The civil engineering profession is playing an active role in facilitating an understanding of risks and prioritisation of adaptation investments in communities (Tye and Giovannettone, 2021).The high concentration of valuable assets in cities requires mechanisms to facilitate replacement of assets including use of existing and proposed insurance mechanisms (*medium confidence*) (Section 14.7).

Adaptation planning and implementation to address SLR and coastal flooding has been initiated across cities and settlements in North America

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but varies in preparedness (*high confidence*) (see Box 14.4). Efforts are supported by SLR design guidelines. In Canada, the Government of British Columbia provided SLR projections for 2050 (i.e., +0.5 m) and 2100 (i.e., +1 m) in order to initiate community vulnerability and risk assessment, and adaptation planning (The Arlington Group Planning + Architecture Inc et al., 2013). Based on recent hurricane impacts in Yucatan, Mexico, recommendations to enhance the rules governing the Mexican Recovery Program included incorporating local knowledge and IK when rebuilding houses and other structures on coasts (Audefroy and Cabrera Sánchez, 2017). Where in-place adaptation is insufficient, planned retreat is being considered as a sustainable option for reducing future risks (Saunders-Hastings et al., 2020).

14.5.6 Health and Well-being

Research examining climate-change impacts on human health in North America has increased substantially since AR5 (Harper et al., 2021a). Using a systematic approach (Harper et al., 2021b), the assessment focused on advancements since AR5.

14.5.6.1 Heat-Related Mortality and Morbidity

High temperatures currently increase mortality and morbidity in North America (*very high confidence*), with impacts that vary by age, gender, location and socioeconomic factors (*very high confidence*). Observed increases in heat-related mortality have been attributed to climate change in North America (Vicedo-Cabrera et al., 2021). Temperature effects on health vary based on how unusual the temperature is for that time and location (*medium evidence, high agreement*), highlighting the important role that temperature extremes and variability play in mortality and morbidity (Li et al., 2013; Lee et al., 2014; Barreca et al., 2016; Allen and Sheridan, 2018). Adaptation has played an important role in reducing observed heat-related deaths (Vicedo-Cabrera et al., 2018b).

Rising temperatures are projected to increase heat-related mortality across emission scenarios this century in North America (*very high confidence*), although the magnitude of increase varies geographically (Isaksen et al., 2014; Petkova et al., 2014; Wu et al., 2014; Weinberger et al., 2017; Anderson et al., 2018a; Limaye et al., 2018; Marsha et al., 2018; Morefield et al., 2018). Elderly people (Isaksen et al., 2014; Limaye et al., 2018) and urban areas (Limaye et al., 2018) are projected to experience the greatest increase in heat-related mortality this century. Warming temperatures are also projected to increase heat-related morbidity (*medium confidence*). For instance, the incidence and treatment costs of asthma attributed to warmer temperatures are projected to increase in Texas by 2040–2050 (A1B) (McDonald et al., 2015).

While heat-related mortality is projected to increase across emissions scenarios and shared socioeconomic pathways, fewer deaths are projected under both lower-emissions scenarios and higher-adaptation scenarios in North America (*very high confidence*). Heat-related mortality was projected to be 50% less under RCP4.5 compared with RCP8.5 in the USA for SSP3 and SSP5 (Table 14.5; Wu et al., 2014; Marsha et al., 2018).

14.5.6.2 Cold-Related Mortality

Winter season mortality rates are generally high in high-income regions such as North America, with most of that mortality due to cardiovascular diseases (Ebi and Mills, 2013). It is important to differentiate between

Table 14.5 | A summary of adaptation options for different health outcomes in North America

Health outcome	Adaptation options
Heat-related mortality and morbidity	Future temperature-related health impacts can be reduced by adaptation measures (Petkova et al., 2014; Wu et al., 2014; Mills et al., 2015b; Kingsley et al., 2016; Anderson et al., 2018b; Marsha et al., 2018; Morefield et al., 2018), including more effective warning and response systems and building designs, enhanced pollution controls, urban planning strategies and resilient health infrastructure (*very high confidence*) (Figure Box 14.7.1).
Wildfire-related mortality	Air quality indices are correlated with many respiratory conditions (Yao et al., 2013; Hutchinson et al., 2018), suggesting that providing air quality information to the public could reduce smoke-related health impacts (Yao et al., 2013; Rappold et al., 2017). Enhanced coordination between the health sector and fire suppression agencies can also reduce the health impacts of wildfire smoke via improving communication, weather forecasting, mapping, fire shelters and coordinated decision making (Withen, 2015), including transnational and cross-jurisdictional actions.
Vector-borne disease	Prevention of vector-borne disease currently involves surveillance, reducing environmental risks and promoting individual behaviours to reduce human–vector contact. Top-ranked Canadian West Nile interventions include individual protection (i.e., window screens, wearing lightly coloured clothing), and regional management and mosquito-targeting interventions (i.e., larvicides, vaccination of animal reservoirs, modification of human-made larval sites) (Hongoh et al., 2016).
Water-borne disease	Climate change is projected to increase water-borne disease risks (*medium confidence*), particularly in areas with ageing water and wastewater infrastructure in North America (*high confidence*). In Wisconsin, USA, precipitation changes are projected to increase gastrointestinal illness in children this century (A1B, A2, B1) (Uejio et al., 2017). Slight reductions in precipitation-associated gastrointestinal illness is projected if water treatment infrastructure is upgraded slowly over time; however, if water treatment infrastructure is installed more rapidly, large decreases in precipitation-associated gastrointestinal illness incidence are projected (Uejio et al., 2017), highlighting the benefits of rapidly implementing adaptation actions.
Food-borne disease	Food safety programmes play important roles in reducing the risk of climate-related food-borne disease (*high confidence*). Integrated health surveillance, more stringent refrigeration temperature controls to limit pathogen growth, targeted communication to the public and food sector, and enhanced coordination between the health and food sectors can reduce risk (Hueffer et al., 2013; Jones et al., 2013; Fillion et al., 2014; Doyle et al., 2015). In Mexico, the projected risk of *Vibrio parahaemolyticus* in oysters was 11 times higher in a high-emissions scenario compared with a low-emissions scenario by the end of the century; however, this risk could be substantially lowered with adaptation measures, including improving temperature control (Ortiz-Jiménez, 2018).
Mental health	Effectiveness of individual and/or group therapy, and place-specific mental health infrastructure, to treat mental health challenges is well proven; yet, there is limited evidence evaluating these interventions within the context of climate change (e.g., Tschakert et al., 2017; Young et al., 2017b; Cunsolo and Ellis, 2018).

mortality related to cold temperatures and mortality due to other factors that vary with season (Ebi and Mills, 2013; Ebi, 2015). Warmer temperatures do not always equate to lower winter mortality: many cold-related deaths do not occur during the coldest times of year or in the coldest places (*high confidence*) but occur during the beginning or end of the winter season (Barnett et al., 2012; Lee et al., 2014; Schwartz et al., 2015; Sarofim et al., 2016b; Smith and Sheridan, 2019). Warmer US cities generally experience more mortality from extreme cold events and cold temperatures than colder cities in the USA and Canada (Lee et al., 2014; Gasparrini et al., 2015; Schwartz et al., 2015; Wang et al., 2016; Smith and Sheridan, 2019). While mortality rates linked to direct cold exposure (e.g., hypothermia, falls and fractures) is generally low, the relatively higher mortality during milder temperatures is thought to be largely due to respiratory infections and cardiovascular impacts (Lee et al., 2014; Gasparrini et al., 2015), which, although correlated with temperature, may not be caused by cold temperatures (Ebi and Mills, 2013; Ebi, 2015; Sarofim et al., 2016a). When separating the effects of cold temperatures from the effects of the winter season, one study found that cold temperature did not drive mortality and suggested that winter season excess mortality was due to seasonal factors other than temperature (e.g., influenza, seasonal gatherings) (Kinney et al., 2015).

Mortality attributed to cold temperatures has increased in the USA and remained stable in Canada from 1985 to 2012 despite increasing winter temperatures (Vicedo-Cabrera et al., 2018b). Some attenuation in cold-related mortality in Mexico and warmer US states is projected under climate change, but less so in colder climates in northeast USA and Canada, with statistically insignificant trends in some regions and increasing cold-related mortality in other regions (Li et al., 2013; Mills et al., 2015b; Schwartz et al., 2015; Sarofim et al., 2016a; Wang et al., 2016; Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018a; Lee et al., 2019). These reductions in cold-related mortality are generally considered relatively small.

Observed and projected trends in winter mortality highlight that non-climate factors may have a greater role in driving winter mortality than cold temperature, and that these deaths are expected to occur with or without climate change (Ebi and Mills, 2013; Ebi, 2015; Sarofim et al., 2016a). This challenges the assumption that warmer winters due to climate change would dramatically lower winter season mortality (*medium evidence, medium agreement*).

14.5.6.3 Wildfire-Related Morbidity

Smoke from intensified wildfire activity in North America is associated with respiratory distress (*very high confidence*), and persists long distances from the wildfire and beyond the initial high-exposure time (see Box 14.2; Hutchinson et al., 2018). Exposure to wildfire smoke increases hospital admissions (McLean et al., 2015; Alman et al., 2016; Reid et al., 2016; Yao et al., 2016; Rojas-Downing et al., 2017). Increased wildfire smoke from climate change is projected to result in more respiratory hospital admissions in the western USA by 2046–2051 (A1B) (Liu et al., 2016; Rojas-Downing et al., 2017).

The magnitude of health risks varies by age (Le et al., 2014; Reid et al., 2016; Liu et al., 2017a; Liu et al., 2017b), gender (Delfino et al., 2009; Rojas-Downing et al., 2017), socioeconomic conditions (Henderson et al., 2011; Rappold et al., 2012; Reid et al., 2016) and underlying medical conditions (Liu et al., 2015). The intersectionality of these subgroups plays an important role in health-related vulnerability to wildfire smoke. Among the elderly in the western USA, risks of respiratory admissions from wildfire smoke was significantly higher for African American women in lower-education counties (Liu et al., 2017b). For Indigenous Peoples, medical visits for respiratory distress, heart disease and headaches increased during a wildfire in California (Lee et al., 2009). In northern Canada, Indigenous livelihoods were disrupted during a wildfire, which negatively impacted mental, emotional and physical health (Dodd et al., 2018a; Howard et al., 2021).

14.5.6.4 Vector-Borne Disease

Climate change creates conditions that enable earlier seasonal activity and general northern expansion of ticks (Ogden et al., 2014), increasing human exposure to tick-borne diseases in North America (*very high confidence*). Lyme disease incidence and geographic extent has already increased in Canada and the USA (Eisen et al., 2016), which has been associated with climate change (Ogden et al., 2014), including warmer temperatures (Cheng et al., 2017; Lin et al., 2019). Climate change is projected to increase disease spread into new geographic regions, lengthen the season of disease transmission and increase tick-borne disease risk in North America across emissions scenarios throughout this century (*very high confidence*), with regional variability (Roy-Dufresne et al., 2013; Feria-Arroyo et al., 2014; Monaghan et al., 2015; Robinson et al., 2015; McPherson et al., 2017). Chagas disease is transmitted by triatomines, and most of the Mexican population (88.9%) already reside in areas with at least one infected vector species in both rural and urban populations (Carmona-Castro et al., 2018). Chagas has already extended its range into the southern USA, and the triatomines' niche is projected to expand northward this century (Garza et al., 2014; Carmona-Castro et al., 2018) in both rural and urban areas (Carmona-Castro et al., 2018).

Climate change is projected to impact the distribution, abundance and infection rates of mosquitoes in North America (*high confidence*), which will increase risk of mosquito-borne diseases including West Nile virus, chikungunya and dengue (*medium confidence*). The geographic distribution of West Nile virus is projected to expand in North America this century (A1B) (Harrigan et al., 2014). In the USA and Canada, mosquitoes are projected to emerge earlier in the year and remain active longer into the fall; however, mosquito population dynamics vary by location with northern locations projected to have an increased vector abundance, and currently hot areas may become *too* hot, thus negatively affecting mosquito survival (A2, A1B, B1) (Chen et al., 2013; Morin and Comrie, 2013; Brown et al., 2015a).

Local transmission of chikungunya virus has emerged in Mexico and the USA since AR5, and areas suitable for transmission are projected to expand (RCP4.5 and RCP8.5) (Tjaden et al., 2017). Although chikungunya virus is not currently in Canada, climate change is projected to make southern British Columbia suitable for virus transmission this century, particularly under RCP8.5 (Ng et al., 2017).

The dengue mosquito vector is well established in Mexico and the southeast USA. In northwest Mexico, incidence of dengue cases is associated with minimum monthly temperature (Diaz-Castro et al., 2017), and the geographic range of the vector in the USA is restricted, in part, by low temperatures. Thus, a northward range expansion is projected; however, future dengue risk also depends on built environments and competition with other mosquito species (Colón-González et al., 2013a; Eisen and Moore, 2013). Climate change is projected to increase the geographic range and extend the seasonal activity of the dengue vector in the southern USA by 2045–2065 (A1B); however, transmission is projected to be limited by low winter temperatures in the mainland USA, potentially preventing its permanent establishment (Butterworth et al., 2017). In Mexico, increased dengue cases are projected this century (A1B, A2, B1) (Colón-González et al., 2013b).

14.5.6.5 Water-Borne Disease

Heavy precipitation events are associated with contaminated drinking water and water-borne disease in North America (*high confidence*). Acute gastrointestinal illnesses increase with many hydro-climatological variables, including precipitation, streamflow and snowmelt (Harper et al., 2011; Wade et al., 2014; Galway et al., 2015). Extreme precipitation is associated with *Campylobacter* and *Salmonella* infections in the USA, particularly in counties characterised by farms and private well water (Soneja et al., 2016). In Canada, human *Giardia* infections are associated with increased temperature, precipitation, pathogen presence in livestock manure, and river water level and flow (Brunn et al., 2019). Land-use patterns and aquifer-types are associated with water-borne disease, and ecological zones with higher water-borne rates are projected to expand in range in Canada by 2080 (Brubacher et al., 2020).

In North America, stormwater and water treatment infrastructure play important roles in reducing water-borne disease risk during precipitation events (*high confidence*). In the USA, heavy precipitation events are associated with higher rates of childhood gastrointestinal illness in municipalities with untreated drinking water, but not in municipalities with treated drinking water (Uejio et al., 2014). In Mexico, disparities in access to treated water are a key determinant of morbidity in children under age 5 years (Jiménez-Moleón and Gómez-Albores, 2011; Romero-Lankao et al., 2014a). In remote communities in Alaska and Northern Canada, challenges in water service provision and maintenance can increase risk of water-borne disease during high-impact weather events (Harper et al., 2011; Bressler and Hennessy, 2018; Harper et al., 2020). In older sections of many North American cities, sewage treatment plant capacity is exceeded by overflow of combined sanitary and storm sewer systems during heavy precipitation events, resulting in bypass of untreated and microbiologically contaminated wastewater discharge into drinking water sources (Jagai et al., 2017; Olds et al., 2018; Staley et al., 2018). These sewer overflow events are associated with increased gastrointestinal illness across age groups (Jagai et al., 2017).

14.5.6.6 Food-Borne Disease

Warmer air temperature, changes in precipitation, extreme weather events and ocean warming can increase microbial pathogen loads in food (*very high confidence*). Indeed, temperature and extreme weather are top factors influencing food safety in Canada (Charlebois and Summan, 2015). Outbreaks of *Vibrio parahaemolyticus* have been associated with the consumption of raw oysters harvested from higher-than-usual ocean temperatures in Canada and Alaska (McLaughlin et al., 2005; Taylor et al., 2018). Warmer air temperature increases *Campylobacter*, *Salmonella* and *E. coli* prevalence in Canadian meat products (Smith et al., 2019), higher microbial load in American produce (Ward et al., 2015) and increased *Campylobacter* spp., pathogenic *E. coli* and *Salmonella* spp. infections in humans (Akil et al., 2014; Valcour et al., 2016; Uejio, 2017).

Climate change is projected to increase food safety risks (*medium confidence*); however, the actual burden of food-borne disease will depend on the efficacy of public health interventions (*high confidence*). Increased ciguatera fish poisoning is associated with increased sea surface temperatures (SSTs) and tropical storm frequency, and this risk is projected to increase this century (Gingold et al., 2014). *Campylobacter* infection in humans due to food contamination from flies is projected to increase this century in Canada (Cousins et al., 2019), and increased housefly populations are projected this century in Mexico (Meraz Jimenez et al., 2019). Climate change may also lead to new emerging food-borne disease risks. For instance, *V. cholerae* is a pathogen previously restricted to tropical regions; however, due to warming ocean temperatures, its detection has significantly increased along Canadian coasts (Banerjee et al., 2018).

Climate change is projected to increase human food-borne exposure to chemical contaminants (*medium confidence*). Increases in SST have been associated with greater accumulation of mercury in seafood, marine mammals and fish (Ziska et al., 2016). This particularly increases food safety risks in the Arctic, with methylmercury and polychlorinated biphenyl concentrations in high trophic animals projected to increase under high-emission scenarios by 2100 (Alava et al., 2017; Alava et al., 2018).

Climate-related food-borne disease risks vary temporally, and are influenced, in part, by food availability, accessibility, preparation and preferences (*medium confidence*). For example, seafood risks are more pronounced in coastal regions due to high seafood consumption (Radke et al., 2015). In Alaska and northern Canada, where locally harvested foods are critical to diet, climate change may introduce new pathogens to local food sources through wildlife range changes, warming temperatures affecting safe fermentation and drying preparation methods, and food temperature control in below-ground cold storage in or near permafrost (King and Furgal, 2014; Harper et al., 2015; Rapinski et al., 2018).

14.5.6.7 Nutrition

Agricultural productivity declines due to climate change (Section 14.5.4) are projected to lower caloric availability and increase the prevalence of underweight people and climate-related deaths in North America by 2050 (IMPAACT) (Springmann et al., 2016a; Springmann et al., 2016b; Springmann et al., 2018); however, this lower caloric availability could also reduce obesity, which could result in deaths avoided (Springmann et al., 2016a; Springmann et al., 2016b). The climate-related deaths per capita due to reduced fruit and vegetable consumption is projected to exceed the mortality due to reduced caloric intake in North America by 2050, particularly in Canada and the USA (Springmann et al., 2016a; Springmann et al., 2016b). These climate-change projections underscore the importance of focusing on nutritional security in North America, instead of only considering caloric intake.

Shifting to a more sustainable diet can have adaptation and mitigation co-benefits while simultaneously improving health outcomes for North Americans. Transitioning to more plant-based diets is projected to reduce climate-related deaths in Canada, the USA and Mexico by 2050 (Springmann et al., 2016a; Springmann et al., 2016b), while simultaneously reducing food-related GHG emissions per capita in North America by 2050 (Springmann et al., 2018).

Nutrition impacts will not be experienced uniformly within countries (Shannon et al., 2015; Zeuli et al., 2018). In Alaska and Canada, IK has documented how climate change has already impacted locally harvested foods and challenged nutrition security (CCP6; Lynn et al., 2013; Petrasek MacDonald et al., 2013; Harper et al., 2015; Hupp et al., 2015; Bunce et al., 2016). For First Nations coastal communities in western Canada, decreased access to traditionally harvested seafood is projected to reduce nutritional status by 2050 (RCP2.5, RCP8.5), with higher nutritional impacts for men and older adults (Marushka et al., 2019). Substitution of seafood with non-traditional foods (e.g., chicken, canned tuna) would not replace the projected nutrients lost (Marushka et al., 2019), challenging assumptions that market food substitutions could be effective adaptation strategies for Indigenous Peoples

14.5.6.8 Mental Health and Wellness

Climate change has had, and will continue to have, negative impacts on mental health in North America (*high confidence*) (Figure 14.8). Climate change impacts mental health through multiple direct and indirect pathways stemming from extreme weather events, slower, cumulative events, and vicarious or anticipatory events (Cunsolo Willox et al., 2013; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Yusa et al., 2015; Schwartz et al., 2017; Trombley et al., 2017; Burke et al., 2018b; Cunsolo and Ellis, 2018; Dodd et al., 2018b; Hayes et al., 2018; Middleton et al., 2020b). Climate-change disruptions to infrastructure, underlying determinants of health and changing-place attachment are also stressors on mental health (Vida et al., 2012; Cunsolo Willox et al., 2013; Burke et al., 2018b; Obradovich et al., 2018).

In North America, climate change has been linked to strong emotional reactions; depression and generalised anxiety; ecological grief and loss; increased drug and alcohol usage, family stress and domestic violence; increased suicide and suicide ideation; and loss of cultural knowledge and place-based identities and connections (Cunsolo Willox et al., 2013; Durkalec et al., 2015; Harper et al., 2015; Fernández-Arteaga et al., 2016; Schwartz et al., 2017; Trombley et al., 2017; Burke et al., 2018b; Cunsolo and Ellis, 2018; Clayton, 2020; Dumont et al., 2020).

Suicide is projected to increase in Mexico and the USA by 2050 due to rising temperatures (RCP8.5) (*limited evidence*) (Burke et al., 2018b). Literature on climate change and mental health in North America is increasing; however, few population-level quantitative studies exist, although they are increasing (e.g., Burke et al., 2018b; Kim et al., 2019; Dumont et al., 2020; Middleton et al., 2021).

14.5.7 Tourism and Recreation

Tourism is one of the largest and fastest-growing industries in North America, contributing 2.5 trillion USD to North America's GDP in 2019 (WTTC, 2018; Duro and Turrión-Prats, 2019). The USA is the world's largest tourism economy (with a 1.839 trillion USD contribution to the global GDP in 2019), Mexico is ranked ninth (196 billion USD) and Canada thirteenth (108 billion USD) (WTTC, 2018). The tourism industry is both impacted by climate change and significantly contributes to it through the emission of GHGs from travel and activities (Becken and Hay, 2007). By 2060, under RCP8.5, Canada and the USA are projected to benefit from climate-induced changes in tourism expenditures of up to 92 and 21%, respectively, whereas Mexico could experience a 25% decrease (OECD, 2015; Scott et al., 2019a).

14.5.7.1 Observed Impacts and Projected Risks of Climate Change

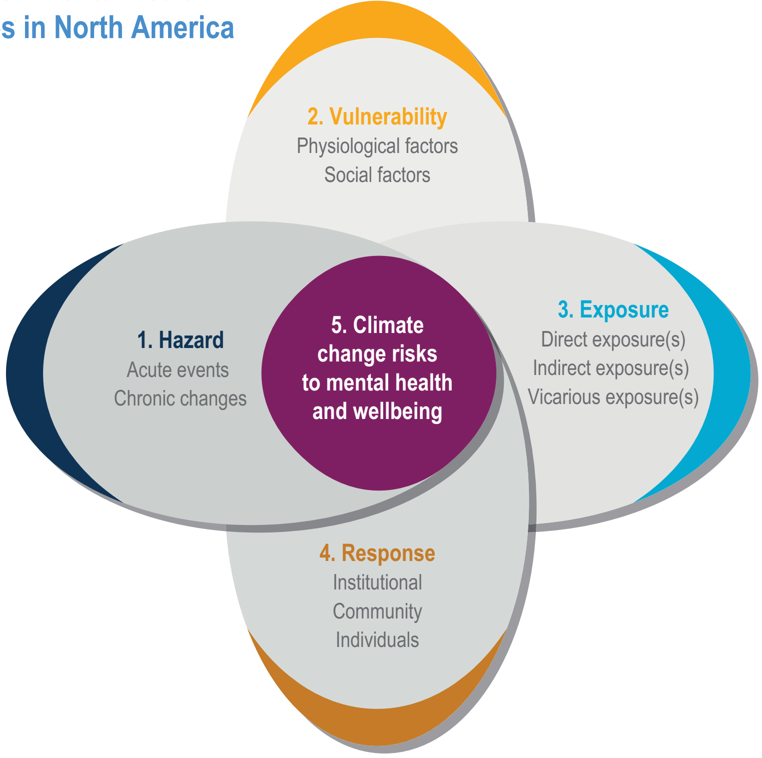
14.5.7.1.1 Alpine and Nordic skiing, snowmobiling and other winter sports

Winter tourism activities with hard limits to adaptation, particularly those that occur at sea level where less precipitation is expected to fall as snow (i.e., Nordic skiing, snowmobiling, snowshoeing), are at the highest risk from climate change and may experience irreversible impacts well before 2°C of warming above pre-industrial levels (*high confidence*) (Figure 14.9). During record warm winters, alpine ski resorts in eastern Canada experienced reductions in ski season lengths of between 11 and 17 d (Rutty et al., 2017) and resorts in the northeast USA (US-NE) experienced decreased skier visits by 11.6% and reductions in operational profits of 33% amounting to 40–52 million USD (Dawson et al., 2009). Even with advanced snowmaking as an adaptation to warmer temperatures, average ski season lengths are projected to decrease 8% (RCP2.6, 2050s) to 73% (RCP8.5, 2080s) in Ontario, Canada (*CA-ON*) (Scott et al., 2019b), 12% (RCP4.5, 2050s) to 22% (RCP8.5, 2080s) in Quebec, Canada (*CA-QC*), and 13% (RCP4.5, 2050s) to 45% (RCP8.5, 2080s) in the northeast USA (*US-NE*) (Wobus et al., 2017; Scott et al., 2020). Season length for snowmobiling and cross-country skiing is projected to decrease more dramatically (*high confidence*), that is, by 80% (RCP4.5) to 100% (RCP8.5) by mid-century (CCP5; Wobus et al., 2017). The number of outdoor skating days may decrease by 34% in Toronto and Montreal, and 19% in Calgary, by 2090 under RCP8.5 (Robertson et al., 2015). The skating season length for the Rideau Canal in Ottawa, Canada, a UNESCO World Heritage Site attracting 1.3 million visitors annually, may decrease by 3.8±2.0 d per decade with later opening dates of 2.6±1.5 d per decade (Jahanandish and Alireza, 2019).

14.5.7.1.2 Beach, coral reef and protected areas tourism

Sea level rise, increased storm surge, wave action, algae blooms, extreme air temperatures, and changes in wind and precipitation patterns threaten coastal tourism infrastructure, submerge beaches, erode walking paths on coasts, and impact destination attractiveness, tourism demand and recreation economies (*very high confidence*). Warm weather tourism activities, including beach tourism, snorkelling and national park visitation, will have more time to implement adaptation

Climate change impacts on mental health and adaptation responses in North America



1 Hazard

Acute events
(e.g., storms, floods, heat events, wildfires)

Chronic changes
(e.g., drought, changing seasonal and environmental norms)

2 Vulnerability

Socio-economic inequities

Indigenous identity

Pre-existing health conditions
(e.g., chronic physical and mental health conditions)

Occupation (e.g., farmers, Indigenous livelihoods, fishers)

Gender (genders differentially affected)

Age (e.g., youth and seniors particularly at risk)

3 Exposure

Direct exposure(s) (e.g., experiencing acute or chronic hazard events)

Indirect exposure(s)
(e.g., displacement, relocation, disruptions to food systems, cultural activities, place-based knowledge sharing and livelihoods)

Vicarious exposure(s)
(e.g., seeing friends and family suffer, mediated experiences of climate change, anticipating future changes)

4 Key adaptation responses

Scale of adaptation

Institutional
State and state-level actors: Enhanced locally-based and culturally-relevant mental health services, informed policies, early interventions

Community
Community planning and design for current and future climate risks, increased climate-informed wellness programming, climate-focused training for health providers

Individuals
Awareness, validation, preparedness, mental health supports, land-based programming and nature therapy

5 Climate change risks to mental health and wellbeing

Mental illness
(e.g., PTSD, depression, suicide)

Diminished wellbeing
(e.g., stress, sadness, climate-related grief and anxiety, impaired mental functioning)

Diminished social relations
(e.g., domestic violence, loss of culture, reduced social capital)

Figure 14.8 | Pathways through which climate change impacts mental health risk in North America

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strategies to reduce climate risks as significant and widespread impacts are not expected until 3°C–4°C of warming (Figure 14.9; Rutty and Scott, 2015; Atzori et al., 2018; Santos-Lacueva et al., 2018; Duro and Turrión-Prats, 2019). Thirty percent of hotels along the Gulf of Mexico and Caribbean Sea are exposed to flooding and 66% are located on eroding beaches (Lithgow et al., 2019). Coral reef cover in Akumal Bay, Mexico, decreased by 79% between 2011 and 2014 (Gil et al., 2015; Manuel-Navarrete and Pelling, 2015). The recreation value of coral reef tourism in Florida, Puerto Rico, and Hawaii is expected to decrease by 90% by mid-century under RCP8.5 (Section 14.4.2; EPA, 2017). Wildfires and insect outbreaks have contributed to reduced desirability for tourism across forest and mountain regions (Bawa, 2017; Hestetune et al., 2018; White et al., 2020). Visitors to Utah's National Parks declined 0.5–1.5% during wildfire years between 1993 and 2015, resulting in 2.7–4.5 million USD in lost revenue (see Box 14.2; Kim and Jakus, 2019). Trees damaged by insects have caused campground and hiking trail closures in the western USA and Alaska (Arnberger et al., 2018). Seal level rise, flooding, coastal erosion, changing air and sea temperatures, changing humidity and extreme weather events are putting cultural heritage sites at risk (Fatorić and Seekamp, 2017; Hollesen et al., 2018; Tetu et al., 2019).

14.5.7.1.3 Arctic tourism

Cruise and yacht tourism in the North American Arctic have increased rapidly over the past decade as changes in sea ice has expanded open-water areas and season length (Johnston et al., 2016; Pizzolato et al., 2016; Dawson et al., 2018). The risk of a major accident or incident among Arctic-going yachts and some expedition passenger vessels is very high relative to other ships (*high confidence*) due to the combined increases in mobile ice, especially along the Northwest Passage (Barber et al., 2018a; Howell and Brady, 2019; Copland et al., 2021; Lemmen et al., 2021), limited regulation for private yachts (Dawson et al., 2014; Dawson et al., 2017), the propensity for cruise ships to travel into newly ice-free and poorly charted areas, and the increasing number of non-ice-strengthened vessels operating in the region (Dawson et al., 2018; Copland et al., 2019; Copland et al., 2021). Compounding risks include a lack of hydrographic charting and the lack of emergency response infrastructure (e.g., spill response, search and rescue, salvage) (Amap, 2017). Tourism demand for polar bear viewing in Churchill, Manitoba, Canada, may change due to climate-related declines in polar bear health (Gil et al., 2015; Manuel-Navarrete and Pelling, 2015), but may be offset by 'Last Chance Tourism' (LCT), a niche tourism market of individuals who explicitly seek to visit vanishing landscapes and/or disappearing flora and fauna (Lemelin et al., 2010). The ethics of promoting LCT has been questioned considering that more visitation to sensitive sites increases local impacts as well as travel-related emissions (Groulx et al., 2016; Groulx et al., 2019).

14.5.7.2 Emerging Responses and Adaptation

Compared with other economic sectors (Section 14.5.8), the tourism industry has high adaptive capacity (*high confidence*) (Figure 14.9). Investments in climate-resilient infrastructure within Canadian National Parks have increased visitation rates during the shoulder seasons (Fisichelli et al., 2015; Lemieux et al., 2017; Wilkins et al., 2018), regional collaboration among US and Canadian park agencies has enhanced adaptive capacity through integrated planning and management (Lemieux et al., 2015), and technological advancements have reduced the vulnerability of alpine winter sports from warming temperatures (e.g., snowmaking, refrigerated surfaces, chemical additives) (Rutty and Scott, 2015; Scott et al., 2019b; Scott et al., 2020). Snowmaking as an adaptation strategy affects mitigation efforts by increasing the need for energy and fuel (Scott et al., 2019b).

Tourists are also highly adaptable and, depending on their levels of place attachment, location loyalty and socio-demographics, are *very likely* to substitute the timing or location of their travel activity based on climate and climatic-driven environmental changes (Rutty and Scott, 2015; Atzori et al., 2018). Lemieux (2017) found that if the state of the Athabasca Glacier (CA-PR) (Figure 14.1) were to change negatively as a result of climate change, 83% would travel elsewhere, and if large infrastructure were built as an adaptive measure for viewing receding glaciers at Jasper National Park, 40% of tourists would no longer visit.

Hard and soft limits to adaptation exist in the tourism sector (Manuel-Navarrete and Pelling, 2015). For example, machine-made snow, without the use of environmentally harmful chemical additives that are banned in most jurisdictions, can only be made efficiently in temperatures below –2°C, but projections indicate warming temperatures above this threshold (Wobus et al., 2017; Scott et al., 2019a). Multi-jurisdictional adaptation planning for parks and protected areas in the USA has been hindered by a lack of funding and communication, and funding trade-offs that could be remedied through coordination (Lemieux et al., 2015). Social inequalities generated by the tourism development process must also be considered by climate-related interventions to prevent the perpetuation of inequalities that may exist, particularly in less developed regions and rapidly developing regions. For example, new developments in Hawaii, Florida, Quebec and popular resort areas in Mexico have led to social inequalities through increased property taxes leading to the marginalisation of local residents away from these areas in favour of wealthy tourists (Section 14.5.9; Manuel-Navarrete and Pelling, 2015).

14.5.8 Economic Activities and Sectors in North America

Economic sectors highly reliant on climate, such as agriculture, tourism, fisheries and forestry, have higher levels of exposure and sensitivity (*high confidence*) and greater overall risk to climate change compared with other economic sectors such as mining, construction and manufacturing (*medium confidence*). However, the cascading nature of climate impacts related to trade (see Box 14.5), labour productivity (Section 14.5.8.1.5) and infrastructure (Section 14.5.8.1.2) means that there is no economic sector in North America that will be unaffected by climate change (*very high confidence*) (Figure 14.10). For Canada, this assessment is further supported by the Canadian Climate Assessment (Lemmen et al., 2021). The combined economies of Canada, Mexico and the USA represented ~28% of the global GDP in 2019, with the USA accounting for almost 90% of the total activity for North America (World Bank, 2020a). The risks posed at different global warming levels (GWLs) for any given economic activity or sector are presented in Figure 14.10. By combining expert judgement with a systematic review of the literature for each sector, the information in Figure 14.10

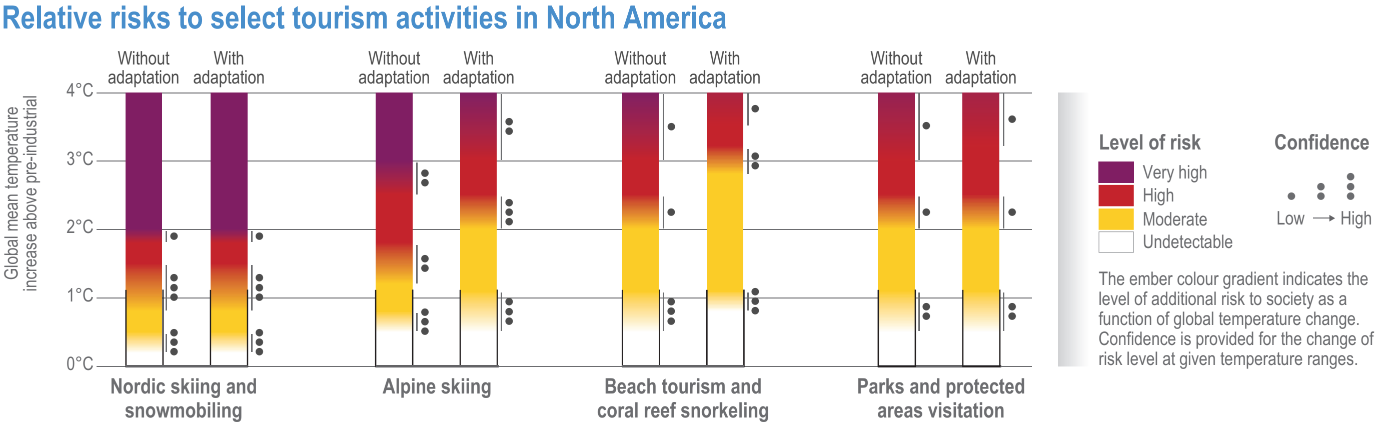


Figure 14.9 | Burning ember of the relative risks to select tourism activities in North America with and without adaptation as a function of global mean surface temperature increase since pre-industrial times. Risks to tourism activities include: **(a)** season length reductions from warming temperatures for Nordic skiing and snowmobiling, **(b)** season length reductions from warming temperatures and precipitation changes for alpine skiing, **(c)** visitor-experience changes as a result of warming surface and ocean temperatures for beach tourism and degrading coral reef systems for snorkelling and **(d)** visitor-experience changes related to warming temperatures and changing landscape aesthetic for Parks and Protected Areas. Risks assessed cover all of North America (c,d), or are specific to certain regions (a,b) . The supporting literature and methods are provided in Supplementary Material (SM14.4).

represents a broader synthesis, especially for sectors with a smaller literature base and at higher GWLs. The assessment of the risks of climate change on tourism (Section 14.5.7) and the interactions between sectors through trade (see Box 14.5) are discussed separately.

14.5.8.1 Observed Impacts and Projected Risks of Climate Change

14.5.8.1.1 Agriculture, fisheries and forestry

The wide range of observed and projected impacts of climate hazards on food and fibre in North America are documented in Section 14.5.4 (also see Chapter 5). Agriculture (US-NW: corn and soybeans), fisheries (cod and pollock) and forestry (Boreal Forest timber yield) are expected to experience substantial and widespread risks by 2°C of global warming above pre-industrial levels (*medium* to *high confidence*) (Figure 14.10). Economic models generally show economic losses in the agricultural sector across North America, especially at higher GWL (Section 14.5.4; EPA, 2017; Boyd and Markandya, 2021), although the effects in local economies, especially rural areas of the USA that are highly dependent on agriculture, will be substantial even at lower GWLs (Gowda et al., 2018). Full evaluations of climate risks for forestry and fisheries are presented in Sections 14.5.1 and 14.5.4 (also see Section 14.6), respectively.

14.5.8.1.2 Transportation

Transportation infrastructure, including roads, bridges, rail, air, sea and pipelines, are highly vulnerable to rising temperatures, SLR, weather extremes, changing ice conditions, permafrost degradation and flooding (*high confidence*), resulting in damage, disruption to operations, unsafe conditions and supply chain impacts (see Box 14.5; Board and Council, 2008; Natural Resources Conservation Service; Andrey and Palko, 2017; Jacobs et al., 2018; Lemmen et al., 2021). In the Mexican states of Veracruz, Tabasco, San Luis Potosí, Chiapas and Oaxaca, 105,000 infrastructure sites, mostly major connecting roads, were found to be at risk of flooding from tropical storms (De la Peña et al. 2018). Low water levels in the Great Lakes has severely impacted US grain transport (Attavanich et al., 2013). High-intensity rain events destroyed 1000 km of roads and washed out hundreds of bridges and culverts in 2013 resulting in an estimated 6 billion CAD (considering the 2013 CAD value) in damages and recovery costs in Alberta, Canada (Palko and Lemmen, 2017). In 2019, the rail line from Winnipeg to Churchill Manitoba, which is the only ground transportation to the community and to Canada's only deep-water Arctic port, was reopened after being closed for over 2 years due to the cumulative effects of flooding, permafrost degradation and political challenges (Lin et al., 2020). In the USA, the number of heat-related train delays has increased (Bruzek et al., 2013; Chinowsky et al., 2019) and, by the end of the century, may cause economic losses of 25–45 billion USD (RCP4.5) or 35–60 billion USD (RCP8.5) (Chinowsky et al., 2019). Sea ice reduction in the North American Arctic has led to a rapid increase in ship traffic (Huntington et al., 2015; Phillips, 2016; Pizzolato et al., 2016; Huntington et al., 2021b; Li et al., 2021) with cascading risks related to invasive species introduction, accident rates, black carbon emissions, underwater noise pollution for marine mammals and risks to subsistence harvesting activities in Indigenous communities (Ware et al., 2014; Council of Canadian Academies, 2016; Huntington, 2021; Verna et al., 2016; Chan et al., 2019).

14.5.8.1.3 Energy, oil and gas, and mining

Climate change is increasing the demand for electric power for cooling and threatens existing power supply (*high confidence*) (Section 14.5.5). Increased energy demand often occurs during peak energy usage and especially during heatwaves (Cruz and Krausmann, 2013; Leong and Donner, 2015). Cooling represented 74% of peak electricity demand in Philadelphia on a particularly hot day in July 2011 (Waite et al., 2017; IEA, 2018b). In Canada, warming temperatures are expected to reduce demand for heating by 18–33% and increase demand for cooling by 14–126% by 2070 compared with 1959–1989 and 1998–2014 baseline periods, respectively (Berardi and Jafarpur, 2020). The effects on hydropower are uneven across the region with the potential for increases in capacity in

Canada but declines of over 20% in Mexico (RCP4.5 and RCP8.5) (Turner et al., 2017). Electricity demand in the USA is projected to increase by 5.3% per degree Celsius rise in temperature (Hsiang et al., 2017). Energy infrastructure, such as drilling platforms, refineries and pipelines, and evacuation routes, are also increasingly vulnerable to higher sea levels, hurricanes, storm surges, mobile multi-year sea ice, erosion, inland flooding, wildfires and other climate-related changes (Zamuda et al., 2018).

Operational efficiency and human safety at mining and energy production sites is expected to be adversely affected by increases in extreme events (Section 14.2), including storms, heavy rains, riverine flooding and wildfires (*high confidence*). General remoteness of many mining sites (especially in the North American Arctic) exacerbates risks related to emergency responses to extreme events such as wildfire (*medium confidence*). The 2016 Fort McMurray wildfire in Alberta, Canada, forced the evacuation of 88,000 people and the shutdown of mine operations. Damages were minimal because companies had undertaken proactive FireSmart interventions specifically developed for the industry (see Box 14.1; Council of Canadian Academies, 2019). Onshore oil field production in Tabasco, Mexico, which accounts for 16% of the country's daily output, was interrupted by extensive flooding (Cruz and Krausmann, 2013). Two-thirds of mine operators globally, including major operators in North America, have experienced production challenges related to water shortages and flooding (Carbon Disclosure Project, 2013). Water availability stress due to climate change is lower in Canada than in the USA and Mexico, and mines in Canada may be less exposed to this risk (World Resourcs Institute, 2012) with some exceptions, that is, water-intensive oil sands mining in the Athabasca River basin in Canada (Section 14.5.3; Leong and Donner, 2016).Warming temperatures also have the potential to alter the nature, characteristics and quality of mineral resources such as kaolin or limestone (Phillips, 2016).

14.5.8.1.4 Construction

In the USA, construction workers comprise 6% of the total workforce but accounted for 36% of all occupational heat-related deaths from 1992 to 2016 (Dong et al., 2019). It is expected that total labour hours among outdoor construction workers will decrease by 0.53% (±0.01%) per degree Celsius based on existing warming trends (Hsiang et al., 2017; also see EPA, 2017). Risks are expected to be exacerbated as SLR and storm surge expands the risk zone for coastal flooding exposing more property to inundation and enhancing construction demand (see Box 14.4; Section 14.5.5.1.3; EPA, 2017). Meeting existing and projected demand for water in affected regions could also require building new desalination plants. For example, Texas has constructed over 44 desalination plants across the state because of a lack of freshwater to meet potable water demand and due to climate-driven droughts (Kloesel et al., 2018b). Other infrastructure damaged by floods and SLR will need to be reassessed and perhaps relocated away from the coast. Relocation requires availability of land that frequently does not exist within urban areas (Lithogow, 2019). Some US tribes and Indigenous groups in Canada lack the financial resources to build climate-resilient infrastructure, such as housing and sewage treatment facilities, to assure clean drinking water (Martínez et al., 2014; Salgado and Luisa Martinez, 2017; Lithgow et al., 2019).

Permafrost thaw in northern North America will result in increased construction and reconstruction needs (*medium confidence*) related to direct damage to buildings, roads, airport runways and other critical infrastructure including decreased bearing capacities of building and pipeline foundations, damage to road surfaces, and deterioration of reservoirs and impoundments used for wastewater and mine tailings containment (Pendakur, 2017; Meredith et al., 2019). Ice roads have become less safe due to warming, pavement damage has increased related to seasonal thaw–freeze cycles and there have been interruptions in airport operations, water and sewage service, and school operations in the Canadian territories of Yukon and Nunavut (Canadian Western and Eastern Arctic, i.e., CA-WA and CA-EA in Figure 14.1) (Council of Canadian Academies, 2019). By the end of the century, the economic impact of projected reconstruction of Alaska's public infrastructure due to climate change (mainly from permafrost thaw) is estimated to range from 4.2 billion USD (RCP4.5) to 5.5 billion USD (RCP8.5) (Melvin et al., 2017; Markon et al., 2018).

14.5.8.1.5 Manufacturing

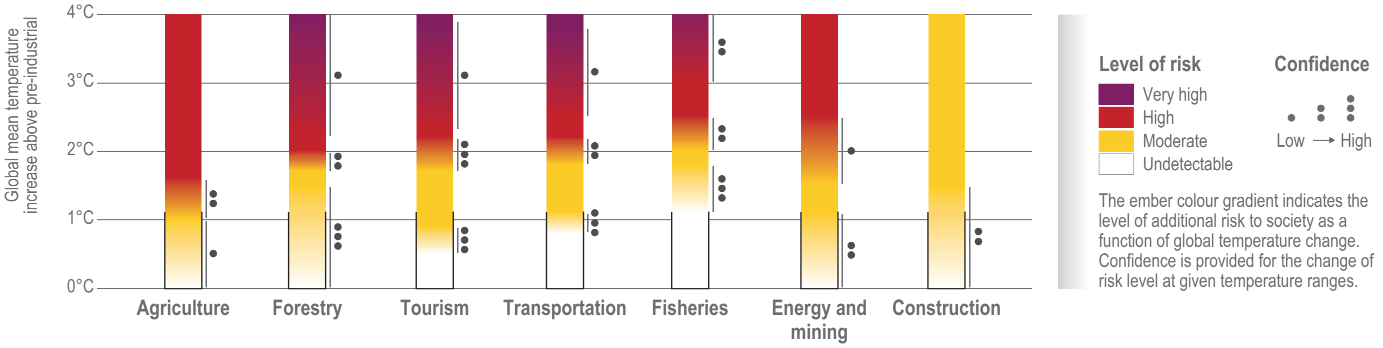
Twelve million Americans (Bureau of Labor Statistics, 2015), 1.5 million Canadians (Statistics Canada, 2020) and 9 million Mexicans (Statistics Mexico, 2021) are employed in manufacturing. The southeast USA and Texas have the highest manufacturing output, with 34% of total US output (700 billion USD yr^{-1}). The impact of climate change on manufacturing varies greatly by region. Vulnerability of the sector to climate change stems from exposure of workers to increasing temperatures and humidity, exposure of facilities to SLR and flooding, and changes in water supply and quality required in many manufacturing processes (Lall et al., 2018).

14.5.8.1.6 Labour Productivity

Climate change is negatively affecting working conditions and labour productivity in North America (*medium confidence*) (Section 14.5.6.1; see Box 14.5). Working conditions in temperatures above a heat index of 85°F (29.4°C) are correlated with potentially hazardous health conditions (Tustin et al., 2018), and for every degree Celsius increase in temperature, labour productivity is estimated to be reduced by 0.11% for low-risk workers and 0.53% for high-risk workers (i.e., construction, mining, agriculture and manufacturing) (Hsiang et al., 2017). By mid-century (RCP8.5), temperature increase, changing water availability and SLR are projected to result in a 0.6% drop in labour productivity in auto, timber, textile and chemical manufacturing in the southeast and Texas regions (Kinniburgh et al., 2015; Hsiang et al., 2017). Labour productivity in the US automobile industry decreases by 8% for every six or more days of consecutive unusually hot weather (above 90°F/32.2°C) (Cachon et al., 2012). Thirty percent of California workers are employed in high-risk industries, such as agriculture, with exposure to high temperature leading to loss in productivity (Rogers et al., 2015). Under RCP8.5 increases in extreme temperatures, labour productivity in the USA is projected to decrease, costing 190 billion USD in lost wages by 2090 (EPA, 2017; Kjellstrom et al., 2019; also see Gubernot et al., 2014; Kiefer et al., 2016; Carter et al., 2018).

14.5.8.2 Current and Potential Adaptation

Adaptation options are highly diverse and sector specific (EPA, 2017). Regardless of economic sector, companies that implement effective and rapid response options that address climate change stressors



Relative risks to economic sectors in North America

Figure 14.10 | Burning ember of the relative risks to economic sectors in North America as a function of projected global mean surface temperature increase since pre-industrial times. Impacts on economic sectors include: **(a)** changing crop yield leading to economic loss for agriculture, **(b)** changes in the quality and quantity of timber yields, **(c)** reductions in season length and economic viability for tourism activities, **(d)** increased maintenance and reconstruction costs to transportation infrastructure, **(e)** changes in fisheries catch, **(f)** reduced productivity in mining and energy operations, (g) reduced labour productivity in outdoor construction and (h) increased maintenance and reconstruction costs to transportation systems. Risks to economic sectors and activities were sometimes assessed across all of North America (c, d), within specific regions (a, b) and for specific crops or species (a: corn and soybean, e: cod and pollock). The supporting literature and methods are provided in Supplementary Material (SM14.4).

will have a competitive advantage (Gasbarro et al., 2016, Lemmen, 2021). Most companies focus on short-term risk management and, consequently, short-term adaptation is often favoured over long-term approaches particularly in the private sector, which will be ineffective for climate-change risk reduction over the long term (Gasbarro et al., 2016).

Investment and coordination of climate services (forecasting) can support many economic sectors across North America. In 2017, 15% of Standard and Poor's (S&P, US industry credit rating agency) 500 companies publicly disclosed an effect on earnings from weather events, reflecting a growing trend (Williams et al., 2018). Existing US federal-sponsored planning tools provide guidance to states and to plan for SLR and flooding with large threats to commercial sectors (US Department of Transportation, 2015). The NOAA Coastal Services Center SLR and coastal inundation viewer[7], the Army Corps of Engineers Sea Level Change Curve simulator, and Climate Central's interactive portal (Ocean at the Door) all provide access to visualisations of future SLR that are available to US coastal cities and towns for commercial planning purposes. Similar resources are being developed and are available for Canada including Canada's Climate Atlas[8].

Adaptation options for transportation and related infrastructure include engineering and technological solutions, as well as innovative policy, planning, management and maintenance approaches (Natural Resources Conservation Service, 2008; Jacobs et al., 2018). For northern transportation, new technologies and infrastructure adaptations can be employed to facilitate heat extraction (e.g., air convection embankments, heat drains, thermosyphons, high albedo surfacing, gentle embankment slopes) (McGregor et al., 2010b; United Nations, 2020) Adaptation options for roads include changing pavement mixes to be more tolerant to heat or frost heaving, expanding drainage capacity, reducing flood risks, enhancing travel advisories and alerts, elevating or relocating new infrastructure where feasible and changing infrastructure design requirements to include climate-change considerations or to introduce new flood event thresholds (Natural Resources Conservation Service, 2008; EPA, 2017; Pendakur, 2017). Railroads are testing temperature sensors on rail tracks to provide early warning of buckling. Sensors that signal when tracks are approaching dangerous temperatures may help to avoid accidents (Hodge et al., 2014; Chinowsky et al., 2019).

Adapting building codes more uniformly to changing climate conditions, such as SLR, storms, winds and wildfires, reduces risk (Olsen, 2015; Maxwell et al., 2018b). North America has not, on the whole, adapted its building code regulations to consider the dynamic challenges of climate change, although some specific efforts *have* been made, including the addition of requirements for wildfire within California's building codes and Canada's climate-resilient building and core public infrastructure initiative, which involves updating building codes and standards to improve climate resiliency (see Box 14.4; Lacasse et al., 2020). To enhance safety, some outdoor workers have been fitted with heat sensors to analyse or assess how warming may affect productivity and well-being (Runkle et al., 2019). Other options include raising public roads and seawalls, initiating buy-outs of property owners in flood risk areas and improving storm water drainage. Adopting approaches like the International Future Living Institute's Living Building Challenge (LBC) may inform future regulatory processes (Eisenberg, 2016). The LBC[9] has seven thematic areas that inform building design, although only a subset of those are relevant for climate change including water, energy and materials considerations.

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[7] See https://coast.noaa.gov/digitalcoast/tools/slr.html

[8] See https://climateatlas.ca

[9] See https://living-future.org/basics

Box 14.5 | Climate-Change Impacts on Trade Affecting North America

Trade, defined as the sum of exports and imports, accounts for 30% of North American GDP. Trade flows within North America are valued at $1.3 trillion USD annually (2019 dollars). Variations within the region are notable: Mexico relies on trade for 80% of its GDP and Canada for 66% (World Bank, 2020a). Canada and the USA traded over 55.2 billion USD worth of products related to the agriculture industry between 2015 and 2018 (Government of Canada, 2019). Canada, the USA and Mexico have the longest-running trade pacts globally and these agreements have played a major role in supporting economic and social development in the region (see (Frankel and Rose, 2005; Eaton et al., 2016; World Bank, 2020b); however, recent changes to the North American Free Trade agreement do not clearly address climate change (Lucatello, 2019).

Climate risks may create shocks to the trade system by damaging infrastructure and disrupting supply chains in North America (*medium confidence*). Sea level rise, flooding, permafrost thaw, landslides and increased frequency and magnitude of extreme weather events are projected to impact transportation infrastructure which will pose challenges to the movement of goods, especially in coastal areas (Lantuit et al., 2012; Doré et al., 2016; Hjort et al., 2018; Koks et al., 2019; Lemmen et al., 2021). Maritime ports are at the greatest risk from climate hazards (Messner et al., 2013; Slack and Comtois, 2016), followed by roads, rail and airports (Anarde et al., 2017). Due to the transnational nature of trade, extreme weather disruptions in one region are likely to lead to cascading effects in other regions (*high confidence*) (Lemmen et al., 2021). For example, climate change will have negative impacts for global food and energy trade where reductions in crop production and fish stocks in some regions could cause food and fish price spikes elsewhere (Figure 14.10; Sections 14.5.4 and 5.11.8; Beaugrand et al., 2015; Lam et al., 2016; IPCC, 2019a).

Climate-change impacts may alter current trade practices and patterns with implications for regional economic development in North America, especially in the Arctic (*medium confidence*). Climate change is causing modal shifts in cargo shipping. For example, lower water levels in lakes and rivers (e.g., Mackenzie River, Mississippi River) impact freight transport and may cause a shift from marine transport to more GHG-intensive rail, road or air transport (Koetse and Rietveld, 2009; Du et al., 2017; Pendakur, 2017). Sea ice change is creating new Arctic marine trade corridors (Melia et al., 2016; Pizzolato et al., 2016; Ng et al., 2018; Bennett et al., 2020; Mudryk et al., 2021), including shorter and potentially more economical routes such as the Northwest Passages (see Box CCP6.1). Warming temperatures have also reduced the season length for ice roads, which are heavily relied upon to service remote communities and remote industries including forestry and mining (Section 14.5.8.1.2; Pendakur, 2017).

Effective and equitable trade policies can act as important adaptation strategies (*medium confidence*). Higher temperatures have had no direct effect on developed countries' exports, but have significantly reduced growth in exports among developing countries, which in turn can increase the price of goods that developed countries then import (Costinot et al., 2016; Constant and Davin, 2019). Schenker (2013) estimated that the climate impacts on trade from developing to developed countries could be responsible for 16.4% of the total expected cost of climate change in the USA in 2100 and, thus, North America would benefit from increased investment in effective and equitable trade policies and adaptation in developing regions. Under an RCP8.5 scenario (~2.6–4.8°C warming) and within current trade integration, climate change could lead to up to 55 million undernourished people by 2050. These projections decrease by 64% (20 million people) with the introduction of reduced trade tariffs and the lessening of institutional and infrastructure barriers (Janssens et al., 2020). Although most studies focus on global food security (i.e., agriculture), it is likely that the same challenges exist for other commodities and manufactured goods.

14.5.9 Livelihoods

Exposure and vulnerability to climate hazards have varied across North America by region and population (*high confidence*). These differences have been often underpinned by social and economic inequalities and have been observed between households, social groups, rural and urban communities, and Indigenous Peoples (*high confidence*). These vulnerabilities have also been observed to contribute to maladaptation (*medium confidence*) (Section 14.5.9.1). Social and economic trends and development will determine near-term impacts on livelihoods from projected climate hazards; livelihoods will also adapt to the risks and opportunities (*high confidence*) (Section 14.5.9.2). Actions to enhance the livelihoods of the most vulnerable social groups in North America will lessen the impacts of climate hazards on them (*high confidence*) (Section 14.5.9.3).

14.5.9.1 Observed Impacts

Livelihoods are 'the resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access' (Section 8.1.1; IPCC, 2018). While often understood as subsistence or traditional ways of life (Oswal, 1991), livelihoods are often conceptualised more broadly as encompassing the economic, cultural, and social capitals or assets, capabilities, and activities that individuals, households and social groups use as the means to make a living (DFID, 1999; Obrist et al., 2010).

Past and current patterns of development in North America have propagated and perpetuated vulnerabilities that have created differential impacts on livelihoods from climate hazards (*high confidence*). Predatory and extractive economies have underpinned

Box 14.6 | The Costs and Economic Consequences of Climate Change in North America

Observed Impacts

Extreme weather events, including hurricanes, droughts and flooding, and wildfires, have been partly attributed to anthropogenic climate change (*high confidence*) (Table SM 16.21; e.g., Rupp et al., 2015; Emanuel, 2017). Direct, indirect and non-market economic damages from extreme events have increased in some parts of North America (*high confidence*). The number of extreme events with inflation-adjusted damages totalling more than 1 billion USD has risen in the USA over the past decades (NOAA, 2020; Smith, 2020), and similar increases have been observed in Canada (Boyd and Markandya, 2021). Factors other than climate change, including increases in exposure and the value of the assets at risk, also explain increasing damage amounts (Freeman and Ashley, 2017; Vano et al., 2018). Climate change explains a portion of long-term increases in economic damages of hurricanes (*limited evidence, low agreement*). Studies of US hurricanes since 1900 have found increasing economic losses that are consistent with an influence from climate change (Estrada et al., 2015; Grinsted et al., 2019), although another study found no increase (Weinkle et al., 2018).

Formal attribution of economic damages from individual extreme events to anthropogenic climate change has been limited, but climate change could account for a substantial fraction of the damages (*limited evidence, medium agreement*). Two recent studies have shown approaches for how damages may be attributed for individual events in the USA. Assuming a direct proportionality between attributable risk of the event to the attributable economic damages, one study suggested that 30–75% of the direct damages from Hurricane Harvey was caused by climate change, with a best estimate of 67 billion USD out of an estimated 90 billion USD total of attributable damages (Frame et al., 2020). Another study modelled the component of the flooding from Hurricane Sandy due to rising SLR and mapped that to coastal damages. That study estimated that 8.1 billion USD (13% of the total) was attributable to the climate influence on SLR (Strauss et al., 2021).

The effect of climate change has been identified in aggregate measures of economic performance, such as GDP, in North America and globally (*medium confidence*), although the magnitude of these changes is difficult to constrain (*medium confidence*). Climate change has been observed to affect national GDP level and economic growth (*low confidence*). The extent to which climate has affected GDP may be challenging to identify statistically (Cross-Working Group Box ECONOMIC in Chapter 16). Observed GDP effects are generally slightly negative in the USA, higher and negative for Mexico, and the directionality of the effects in Canada varies by study and modelling approach (Burke et al., 2015; Colacito et al., 2018; Kahn et al., 2019).

Projected Risks

Projections of market and non-market economic damages demonstrate the substantial economic risks of climate impacts associated with high-temperature pathways (RCP8.5) (*high confidence*). Since AR5, a wide range of estimates of the costs of climate change have been developed for the USA (EPA, 2015a; Houser et al., 2015; EPA, 2017; Hsiang et al., 2017; Martinich and Crimmins, 2019), with ongoing processes to update national estimates for Canada and Mexico (Semarnat, 2009; NRTEE, 2011; Estrada et al., 2013; Sawyer et al., 2020). While the magnitudes of the estimates depend on approach and assumptions in the methods and expectations of future socioeconomic conditions, these studies show substantial projected economic damages across North America by the end of the century, especially for warming greater than 4°C (*high evidence, high agreement*). Whether these damages translate into GDP effects is not clear for Canada. Some modelling approaches show modest GDP increases in 2050 and 2100, while others suggest modest decreases although it is anticipated that the economic effects for Canada will be large and negative (Boyd and Markandya, 2021). Large costs and risks, such as those associated with extreme events such as wildfires (Hope et al., 2016) and the increased need for infrastructure replacement (Neumann et al., 2015; Maxwell et al., 2018a), will have compounding effects in the markets by disrupting economic activities (see Box 14.5).

Market and non-market risks and costs will not be experienced equally across countries, sectors and regions in North America (*high confidence*). For the USA, energy expenditures and improvements in agricultural yields are projected to result in net gains in the north and Pacific Northwest whereas in the south, higher heat-related mortality, increases in energy expenditures, SLR and storm surge are projected to result in economic losses by the end of century (Hsiang et al., 2017). No region in the USA is expected to avoid some level of adverse effects (*medium evidence, high agreement*) (EPA, 2017; Martinich and Crimmins, 2019). Economic models generally show losses in the agricultural sector across North America, especially at higher GWL (Boyd and Markandya, 2021; EPA 2017). Some models show large gains in parts of Canada, although these models do not capture the full range of climate hazards including change in precipitation or extreme events (Boyd and Markandya, 2021).

Economics of Adaptation Opportunities

Economic analysis can help reveal where the avoided economic damages are greater than the costs of adaptation, improving decision making for adaptation planning and efforts in North America (*high confidence*). Detailed assessment of total needs and costs of climate adaptation are limited (Sussman et al., 2014), but estimates suggest that the costs are large (*low evidence, high agreement*). Cost–benefit

Box 14.6 (continued)

and other economic analyses that incorporate damage estimates are expanding for adaptation decision making (Li et al., 2014), especially for technical options in areas with high exposure such as coastal areas in Mexico (Haer et al., 2018) and Alaskan infrastructure (Melvin et al., 2017). Cost–benefit analysis has also been applied to coordinating planning across jurisdictions in North America for SLR and flood control (Adeel et al., 2020). Adaptation costs in the USA are lower on RCP4.5 compared with RCP8.5 emission pathways (Martinich and Crimmins, 2019). Adaptation, however, cannot be based solely on the cost–benefit analysis due to the high level of uncertainty related to climate risks (Cross-Chapter Box DEEP in Chapter 17).

Improving projections of future economic risk and damages facilitates the development of tools that can be used for economic analysis of climate policies (*high confidence*). Monetised estimates of the damages from climate change have been developed and refined since AR5, motivated in part by efforts to estimate the Social Cost of Carbon (SCC) (National Academies of Sciences, 2017). Support for these efforts and the use of SCC in regulatory analysis of mitigation and adaptation efforts have been pledged across the national and subnational governments of Canada, the USA and Mexico. Harmonising SCC and consistent use can further enhance coordination of mitigation and adaptation decision making (Auffhammer, 2018; Aldy et al., 2021). Using these damages estimates can also inform other policy and tools that improve the consideration of climate impacts in markets and decision making (Report of the Climate-Related Market Risk Subcommittee, 2020).

economic activity in North America historically and currently. While generating substantial wealth, these patterns have also driven social and economic inequality (*medium evidence, high agreement*) (Jasanof, 2010; Shove, 2010; Klinsky et al., 2016; Robinson and Shine, 2018). Patterns of development that reinforce these structures remain a large contributor to current social–environmental risks and have affected all kinds of contemporary livelihoods (Chapter 18; Cannon and Müller-Mahn, 2010; Koch et al., 2019).

Climate impacts have damaged livelihoods across North America, especially those of marginalised people (*high confidence*) and deepened inequalities for these groups (*medium confidence*). Across North America, climate change has affected livelihoods with larger effects on individuals, households and communities that are already more vulnerable due to a range of pre-existing social and environmental stressors (Olsson et al., 2014; Hickel, 2017; Koch et al., 2019) such as Indigenous Peoples, urban ethnic minorities and immigrants (Guyot et al., 2006; Gronlund, 2014; Klinenberg, 2015). These impacts have also contributed to a deepening of inequalities for marginalised groups (*medium evidence, high agreement*) (Audefroy and Cabrera Sánchez, 2017; García et al., 2018). As climate hazards further degrade their livelihoods, these groups have faced additional challenges to avoiding or escaping poverty (Ruiz Meza, 2014). Furthermore, these groups have needed to use their more limited resources to manage present challenges, restricting their future capacities to adapt (Tolentino-Arévalo et al., 2019). Climate impacts have also affected the livelihoods of the middle classes (Domínguez et al., 2020) who have become more vulnerable due to changes in their social and economic security (Garza-Lopez et al., 2018). Gender has also been recognised as a determinant of differential vulnerability with implications for women's livelihoods (Cross-Chapter Box GENDER in Chapter 18).

Migration and mobility have been an important part of livelihoods in North America (*high confidence*). Movement across North America has been reinforced by social, cultural and economic ties (see Box 14.5). For example, middle class retirees from Canada and the USA engage from temporary, seasonal to permanent migration to the warmer climates of the southern USA and Mexico, often benefiting from the lower cost of living (Domínguez et al., 2018). Temporary or semi-permanent labour migration, generally followed by remittances, has been an important part of livelihoods for rural areas in Mexico (*high confidence*) and has been employed as a response to climate hazards (*low evidence*). Drought in rural areas which are highly dependent on subsistence agriculture have observed migration to urban areas in Mexico (Nawrotzki et al., 2017). Evidence of international migration in response to climate hazards is sparse with difficulties in identifying a climate signal due to the multi-causal nature of migration decision making (Cross-Chapter Box MIGRATE in Chapter 7). There is limited evidence of extreme weather events or climate hazards on migration from Mexico to the USA (Nawrotzki et al., 2015b; Nawrotzki et al., 2015c; Nawrotzki et al., 2016; Murray-Tortarolo and Salgado, 2021).

Pre-existing social vulnerabilities have also led to forced displacement from extreme weather events (*low confidence*). In the USA, compounding effects of SLR and storm surge interacted with pre-existing social vulnerabilities of local communities to generate large-scale displacement after the effects of Hurricane Katrina on New Orleans in 2005 (Jessoe et al., 2018). The processes of relocation and recovery in New Orleans was further shaped by vulnerability where out-migration was more likely to be minorities and economically disadvantaged, while the recovery was predominantly in neighbourhoods that were wealthier prior to the disaster (Fussell et al., 2014; Fussell, 2015). Newer evidence from Hurricane Maria in Puerto Rico in 2017 has shown an initial spike in displacement with slower recovery with more vulnerable communities returning at higher rates (DeWaard et al., 2020); however, overall out-migration trends have been consistent with long-term economic migration (Santos-Lozada et al., 2020). Interactions of slower onset climate hazards with displacement, such as observed in Shishmaref, Alaska, have revealed the challenges in attribution of migration to climate as it intersects with socioeconomic conditions and lived experiences (Marino and Lazrus, 2015).

Maladaptation has also been occurring in livelihoods, especially as it relates to agricultural practices that are less resilient to climate hazards and competition for land use (*limited evidence, high agreement*). Focusing on examples in Mexico (see Section 14.5.4.3 for US and Canada examples), for some Mexican Indigenous Peoples, the replacement of ancestral farming practices with technological adaptations like transgenic crops has reduced their resilience by making them more dependent on external inputs and more expensive supplies while increasing putting their health at risk with herbicide and insecticide use (Mercer et al., 2012). Existing power structures have also interacted with climate hazards to generate maladaptive outcomes (Quintana, 2013). Mennonite communities in the northern state of Chihuahua, Mexico, have pursued commercial agricultural markets that lead them to shift to transgenic crops and to overexploit local groundwater resources in a region experiencing multi-year droughts. These actions have led to conflict with other local farming groups with less economic capital to access groundwater (Quintana, 2013). Climate mitigation measures may also have adverse effects on local livelihoods with implications for adaptive capacity. The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) mitigation programme has been highlighted as a trade-off between an international/national carbon mitigation strategy and the ability of some Mexican rural communities to improve their food security (Section 5.6.3.3; Barbier, 2014).

14.5.9.2 Projected Risks

Livelihoods will evolve as a result of both challenges presented directly or indirectly from climate impacts as well as socioeconomic changes and technological developments (*high confidence*). Livelihoods, however, can be undermined by many of the projected climate risks with the impacts depending on adaptive capacity and adaptation limits (*high confidence*) (Section 8.4.5.1). Real areas in Mexico and the southern USA with agriculture-based livelihoods and projected reduction in precipitation will be adversely affected (Section 14.5.4; Esperon-Rodriguez et al., 2016). Outdoor workers in rural and urban areas will be exposed to higher health risks from higher temperatures and heatwaves (Section 14.5.8). Reduced livelihoods will also be associated with adverse mental health effects (Section 14.5.6.8).

Future climate hazards will deepen patterns of social inequality as vulnerable groups may also experience intersecting impacts that adversely affect their livelihoods (*medium confidence*). Health, in particular, will be a key intersection as marginalised and disadvantaged groups often have poorer health status and hold occupations that may involve higher exposure to climate hazards. African Americans are expected to experience the largest impacts on their health status due to differential exposure and vulnerability to climate hazards (Section 14.5.6; Marsha et al., 2016).

Displacement, migration and resettlement will increase along higher-emission pathways (*medium confidence*). Combining projections of SLR and population scenarios for the USA, Haer et al. (2013) and Hauer et al. (2016) have estimated the magnitude of the population at risk in coastal communities, numbering in the millions. In the near term, where climate hazards influence out-migration, it will mostly augment existing patterns as migration is strongly influenced by existing social networks (Section 7.3.2). Planned relocation and resettlements will reduce the exposure to climate hazards for the involved populations but could adversely affect their livelihoods in the absence of supportive programmes (Section 7.3.2; Jantarasami et al., 2018a), since livelihood outcomes strongly depend on socioeconomic conditions.

14.5.9.3 Adaptation

Climate hazards undermine adaptation by damaging livelihoods (*high confidence*). Many actions that enhance and promote resilient livelihoods can have substantial benefit for adaptation to climate hazards (*medium confidence*). Livelihoods in the context of climate change are characterised by adjustments that then feed back into the assets that comprise a livelihood. Social capital—in the form of household and community cohesion—facilitates the development of adaptation strategies to the impacts of climate change in rural and urban communities at the household level and for small groups (Barbier, 2014; Nawrotzki et al., 2015b; Nawrotzki et al., 2015c). Cultural capital, especially in the form of Indigenous knowledge and local knowledge, can guide adaptation practices in North America (Akpinar Ferrand and Cecunjanin, 2014), preserving Indigenous cultures and enhancing future adaptation and resilience (see Box 14.1; Pearce et al., 2012; Audefroy and Cabrera Sánchez, 2017). In Mexico, rainwater harvesting (practised by some Mayan communities) and the use of local–traditional varieties of maize have assisted in the adaptation to climate impacts and promoted food security (Akpinar Ferrand and Cecunjanin, 2014; Hellin et al., 2014). Funding and support for these social adaptation strategies have been uneven (Barbier, 2014; Romeo-Lankao et al., 2014). The legacy of colonialism and historical patterns of development will continue to shape the adaptation responses and resiliency of Indigenous Peoples (Todd, 2015; Davis and Todd, 2017; Whyte, 2017; Cameron et al., 2019).

Migration is a common adaptation strategy to maintain and diversify people's livelihoods and will continue to play an important role when households manage climate and social risks (*high confidence*) (Section 7.4.3). In the near term, actions that enhance *in situ* adaptive capacities as well as foster safe and orderly migration can result in synergies for both adaptation and development (Cross-Chapter Box MIGRATE in Chapter 7). Populations that experience less mobility or cannot engage in voluntary migration as an adaptation may need additional support to adapt to climate hazards, for example, northern communities that are at risk of climatic events (Hamilton et al., 2016). Policies associated with the transition from high-GHG intensive extractive industries, sometimes referred to as 'just transitions', may also support *in situ* livelihoods if they also aim to address and redress existing inequalities to reduce vulnerabilities (McCauley, 2018); however, these policies could result in maladaptation if they create new inequalities or generate other environmental damages.

14.5.10 Violence, Crime and Security

Elevated rates of various types of crime have been associated with higher temperatures in the USA and Mexico (*medium confidence* based on *limited evidence* and *high agreement*) (Section 14.5.10.1). If social relationships prevailing now and in the recent past continue, projections show future crime rates in the USA and Mexico increasing with increasing temperatures (*low confidence*) (Section 14.5.10.2).

Degradation of human security and conflicts exacerbated by climate change–even outside of North America–will increase the demand for humanitarian assistance, foreign aid and resettlement (*medium confidence*) (Section 14.5.10.2).

14.5.10.1 Observed Impacts

14.5.10.1.1 Violence and crime in the past and present

Crime, including violent crime, has been associated with higher temperatures in the USA (*medium confidence*). Studies of crime statistics in the USA have revealed a relationship between temperature and a range of violent crimes including aggravated assaults, rapes and homicides; effects for property crimes are weaker (*limited evidence, medium agreement*) (Ranson, 2014; Houser et al., 2015; Heilmann and Kahn, 2019; Mares and Moffett, 2019). These effects have been observed in US urban centres (Hsiang et al., 2013; Mares, 2013; Ranson, 2014; Schinasi and Hamra, 2017; Heilmann and Kahn, 2019) and more generally across the USA (Mares and Moffett, 2019). Differential effects have also been observed within urban areas. Observed higher rates of domestic and intimate partner violence during periods of high heat in less affluent neighbours in Los Angeles have been associated with disparities in access to air conditioning and greenery (Heilmann et al., 2021). By contrast, Lynch et al. (2020a) found no significant correlation between annual homicide rate and annual temperature for New York City (Lynch et al., 2020b). For Mexico, Burke et al. (2018a) found temperature linkages with intergroup killings by drug-trafficking organisations, homicides and suicides. No linkages between temperature and crime have been reported for Canada. Differences in spatial and temporal aggregation of the crime statistics as well as in the measure of climate change or variability explain some of the differences between studies. Several causal pathways can explain these relationships (Miles-Novelo and Anderson, 2019; Lynch et al., 2020b). The dominant theory is that weather changes result in changes in behavioural patterns that lead to more opportunities for crimes. For example, studies that disaggregate by month often report significant positive associations between temperature anomalies and violent crime (especially aggravated assaults, rapes and homicides), particularly in the cold season (Harp and Karnauskas, 2018; Mares and Moffett, 2019). Smaller increases in crime during positive warm-season temperature anomalies may be due to people seeking shelter in cooler indoor spaces, decreasing crimes of opportunity (Section 7.2.7; Gamble and Hess, 2012).

The archaeological record has been used to infer linkages between climatic variability and social process, including violence (inferred with *medium confidence*). Past North American societies have been exposed to greater climatic variability than is documented in the instrumental record. Because future climatic conditions are likely to exceed those known for the recent past (Cross-Chapter Box PALEO in Chapter 1), the North American archaeological record can illuminate possible relationships between climate variability and violence that cannot be observed in the present record. In the upland southwest US between 600 and 1280 CE, one study found that violence significantly increased as climatically controlled maize production decreased and interannual variability increased (*low evidence, high agreement*) (Kohler et al., 2014); massive emigration from the northern Southwest in the last half of the 1200s CE is connected with, though not completely explained by, climatic variability (Scheffer et al., 2021). In the central and southern Maya lowlands, following centuries of increasing populations and attempts to produce more maize (Roman et al., 2018), episodes of drought and/or increased summer temperatures in the 9th and 10th centuries (Dunning et al., 2012; Kennett et al., 2012) accompanied increased conflicts and social disintegration including collapse of long-lived dynasties, cessation of monumental inscriptions (Carleton et al., 2017) and emigration (*medium evidence, medium agreement*). Such findings reinforce research on contemporary societies that climate-induced farming shortfalls in regions dependent on agriculture may induce or exacerbate conflict, especially in interaction with unfavourable demographic, political and socioeconomic factors (*medium evidence, medium agreement*) (Section 7.2.7; e.g., Koubi, 2019).

14.5.10.1.2 Security

Climate change poses risks to peace (Section 16.5.2.3.8) that could affect North America (*medium confidence*). Military and security communities are adapting their planning, operations and infrastructure to current impacts of climate change in North America and globally (*medium agreement, medium evidence*). Arctic nations are renewing their military capacity and expanding their constabulary presence around their existing boundaries (Choi, 2020). There is increasing awareness that climate change causes weather patterns and extreme events that directly harm military installations and readiness through infrastructure damage, loss of utilities, and loss of operational capability (Duffy-Anderson et al., 2019). Transboundary disputes and competition over resources, such as fish (Østhagen, 2020), are a concern in the changing Arctic and increases in military and constabulary operations are being observed (Jönsson et al., 2012; Smith et al., 2018; Eyzaguirre et al., 2021).

14.5.10.2 Projected Risks

14.5.10.2.1 Violence and crime

Projections of future crime derived from the empirical relationships between temperature and crime in the USA show the potential for increased criminality under RCP8.5 compared with RCP4.5 (*low confidence*). For RCP8.5, holding all socioeconomic conditions at 2015 levels, violent crime could increase 0.6–2.1% by mid-century and 1.9–4.5% by late century (Houser et al., 2015). The rise in property crime is projected to be smaller as property crime flattens at higher temperatures (Hsiang et al., 2013). Using relationships between crime and monthly temperatures established for five US regions by Harp and Karnauskas (2018), Harp and Karnauskas (2020) project 18,800 additional violent crimes annually beyond 2014 levels by the end of the 21st century under 1.5°C warming, rising to 48,200 under 4°C warming. Aggregating data by states weighted by population density, Mares and Moffett (2019) project an average annual increase of 0.94% across seven categories of violent and property crime for each anomalous degree Celsius of warming (an average annual increase of about 100,000 crimes). Changing socioeconomic conditions in the future may either reduce or exacerbate the projected contemporaneous relationship between temperature anomalies and crime (Agnew, 2011; Lynch et al., 2020b), whereas adaptation could weaken these relationships.

14.5.10.2.2 *Defence and security*

Climate change will affect ecosystems (Section 16.5.2.3), living standards (Section 16.5.2.3.4), health (Section 16.5.2.3.5) and food security (Section 16.5.2.3.6) globally, and these changes may exacerbate violence and political instability (*medium confidence*) with implications for national security in North America (*medium confidence*). Climate variability, hazards and trends, to date, have played a role in exacerbating conflict, but the influence of climate appears to be minor and more uncertain than the roles of low socioeconomic development, low state capability and high intergroup inequality (Mach et al., 2019). More profound impacts from climate change on weather and seasons, as well as changing socioeconomic conditions, could lead to patterns of violence that cannot be predicted by projecting relationships between current climate and violence into the future (Section 14.6.3; Mach et al., 2019). If global levels of violence increase, there will be increased demand for international efforts, including disaster aid and humanitarian efforts (Eyzaguirre et al., 2021). Climate change and geopolitical goals interact in the Arctic (Smith et al., 2018). New transportation corridors and the potential access to natural resources could lead to competition for access to and control over the region (Section CCP6.2.6; see Box CCP6.1; FAQ CCP6.2; Estrada, 2021). Governance structures exist to manage geopolitical manoeuvring and to protect the human security of Arctic populations (Sections 14.5.10.3, 7.2.7.1).

14.5.10.3 Adaptation Options

14.5.10.3.1 *Violence and crime*

Co-benefits from adaptation options include improving the liveability of, and quality of life in, cities, reducing socioeconomic vulnerability and exposure to locally higher temperatures (*medium confidence*). Urban settings in the USA have disproportionately higher exposure to urban heat island effects in low-income and minority neighbourhoods in US cities (Section 14.5.5.1). Co-benefits from adaptation responses in the urban landscape can reduce socioeconomic vulnerabilities and exposure to higher temperatures (Section 14.5.5.3). Evaluation of adaptation efforts to reduce crime rates that have been associated with temperature are limited. In Los Angeles, a link has been inferred between violence and older buildings that may lack air conditioning (Heilmann et al., 2021). By contrast, access to air conditioning did not appear to lessen crime rates in Mexico (Baysan et al., 2019).

14.5.10.3.2 *Defence and security*

Existing environmental and international agreements that consider climate risks can contribute to cooperation (*medium confidence*). Strengthening and empowering existing environmental and diplomatic avenues (e.g., the Arctic Council and international agreements such as the United Nations Convention on the Law of the Sea, and various subnational actors and agreements) (Section CCP6.3.2) to incorporate risks from climate impacts could enhance cooperative avenues for defusing conflict (Huebert et al., 2012). Improving the consideration of climate risks in efforts to expand economies and trade (see Box 14.5), and improvements in peacekeeping (Section 7.4.4; Barnett, 2018) could also reduce future conflict risks.

14.6 Key Risks

Ten key risks from climate change were identified for North American based on definitions and assessment approaches outlined in Chapter 16, which were extended to include the development of a risk database and analysis that included expert evaluation of interactions between climate hazards and sectors (Figure 14.11; SM14.3).

14.6.1 Key Risks of Climate Change for North America

In North America, divergent perceptions regarding the attribution and implications of climate change pose a key risk to adaptation mainstreaming (KR1). This lack of adequate adaptation in turn amplifies threats to human life and safety from intensifying extreme events, fires and storms (KR2). Climate change hazards pose risks to economic and social well-being (KR3), marine social–ecological systems (KR4), unique terrestrial ecosystems and their services (KR5), freshwater services (KR6), physical and mental health (KR7), food and nutritional security (KR8), and commerce and trade (KR9). Cumulatively, these risks interact to imperil the quality of life for North American communities, cities and towns (KR10).

14.6.2 Key Risks Across Sectors in North America

KR1: In the public and policy domains, divergent perceptions of anthropogenic climate change which pose a risk of inaction on adaptation efforts to reduce exposure and socioeconomic vulnerability

Complex factors, including individual beliefs, ideology, world view, partisan identity as well as societal context, influence how the public, as well as professional groups, communities and policymakers, perceive and understand climate change (*high confidence*) (Sections 14.3.3, 14.3.4). While there is expert scientific consensus on anthropogenic climate change, rhetoric, misinformation and politicisation of science have contributed to misperceptions (*high confidence*), polarisation on the severity of impacts and risks to society, indecision and delayed action (*high confidence*) (Section 14.3.1). In North America, this impedes adaptation efforts (Section 14.3.4) and inflates climate risks (*high confidence*).

KR2: Risk to life, safety and property from intensifying extreme events

Human life and safety across North America, and especially along the coasts of Mexico, the Hawaiian Islands, Gulf of Mexico, Atlantic Canada and southeast USA, will be placed at risk from SLR and severe storms and hurricanes, even at 1.5°C GWL (*very high confidence*) (Sections 14.5.2, 14.5.5; see Box 14.4). Warming, heatwaves and increases in wildfire activity in many regions of North America pose risks to air quality, health, lives and property (see Box 14.2). More extreme precipitation and flooding pose a risk to human morbidity, mortality and safety in fluvial flood zones and areas downstream of levees, dams and flood culverts. The increasing intensity of storm events poses a risk of landslides, erosion and flooding in shoreline and urban communities, especially high-bank areas along exposed coasts, in Arctic and temperate areas where winter sea ice has diminished and in low-lying coastal areas where SLR and

Rapid assessment of relative risk by sector and climate hazard for North America

based on an assessment of asset-specific vulnerability and exposure across climate hazards

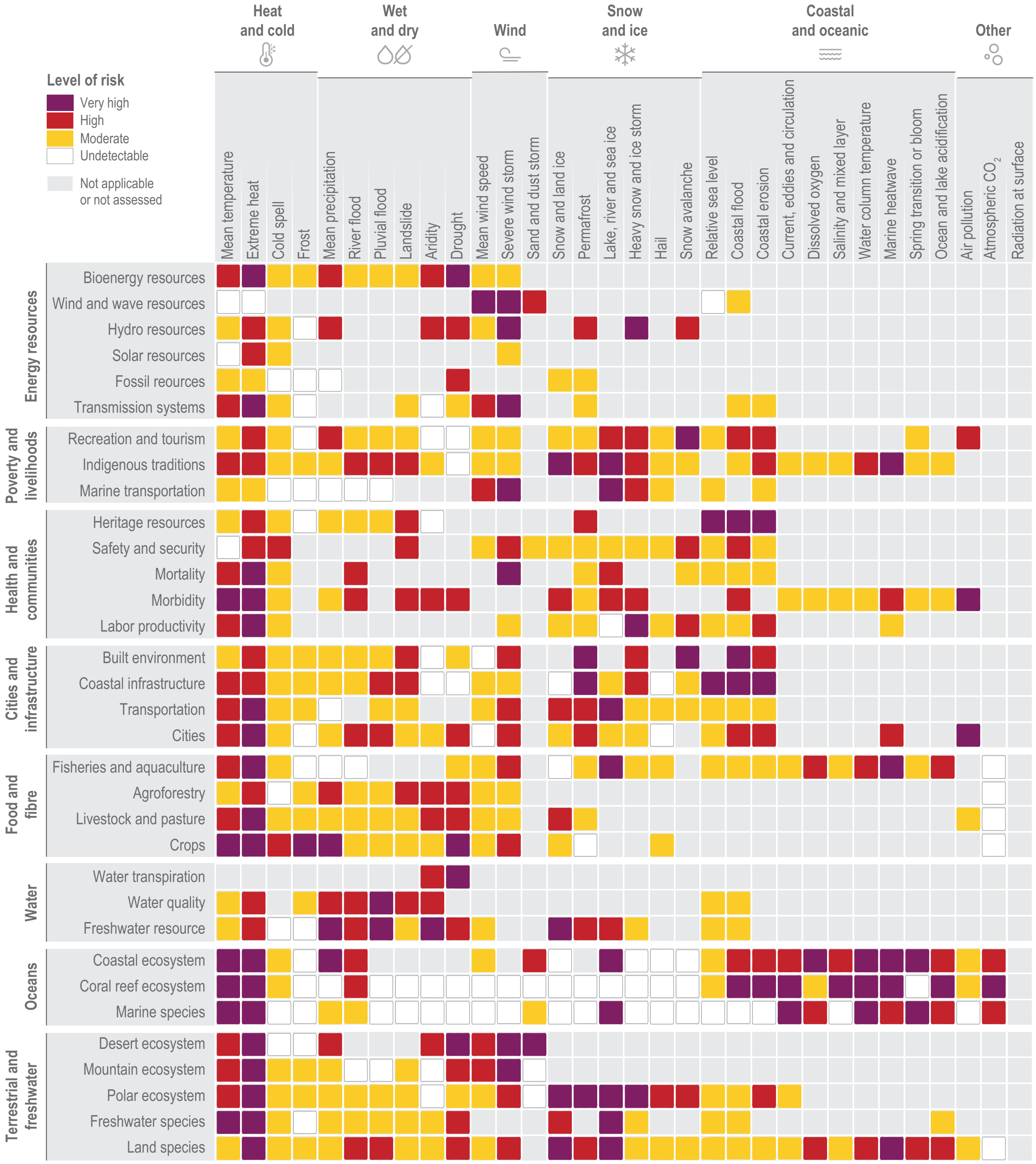

Figure 14.11 | Rapid assessment of relative risk by sector (*y*-axis) and climate hazard (*x*-axis) for North America based on an assessment of asset-specific vulnerability and exposure across climate hazards (see SM14.3 for methodological details). For each unique combination, the hazard-by-sector risk was ranked as very high (very high risk and *high confidence*), high (significant impacts and risk, *high to medium confidence*), medium (impacts are detectable and attributable to climate change, *medium confidence*), low or not detected (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted. Risks identified through the rapid assessment were further evaluated in the chapter assessments (see corresponding sector text for full assessment of risk and impacts).

storm surge often overwhelm existing natural coastal features and engineered structures (Section 14.5.5; see Box 14.4).

KR3: Cumulative damages from climate hazards which pose a substantial risk to economic well-being and shared prosperity

Climate-change impacts are projected to cause large market and non-market damages (*high confidence*). By end of century under higher GWL scenarios (>4°C), these damages are expected to reach several tens of billions of USD annually in Canada and hundreds of billions annually in the USA. Losses in labour productivity and wages, and damages to coastal properties, will be especially large; however, all sectors in the USA and most sectors in Canada are projected to see substantial relative damages on high-emission pathways by mid- to end of century compared with lower-emission pathways. Economic sectors with hard limits to adaptation (i.e., winter tourism) or that are highly affected by climate variability (i.e., agriculture and fisheries) will be at more risk at lower temperatures than other economic sectors (Sections 14.5.7, 14.5.8). Strategic implementation of adaptation strategies coupled with lower-emissions scenarios result in multi-billion-dollar reductions in economic damages (Section 14.5.8; see Box 14.6).

KR4: Risk of degradation of marine and coastal ecosystems, including loss of biodiversity, function and related services with cascading effects for communities and livelihoods

Ocean warming will increase the frequency and intensity of MHWs (see Box 14.3), accelerate unprecedented rates of sea ice loss, and alter ocean circulation, chemistry and nutrient cycling in ways that profoundly impact marine productivity, biodiversity and food webs (*very high confidence*) (Section 14.5.2). Collectively these impacts pose a risk to nearshore ecological and human systems (*high confidence*), increasing the probability of phenological mismatches, large-scale redistribution of species, and species population declines (Section 14.5.4) with cascading impacts that strain cultural and economic systems reliant on marine productivity across North America (*high confidence*). Nearshore areas of Chesapeake Bay (USA) and Akimiski Island, mid-western James Bay and the coasts in the Pacific ranging from the Gulf of Alaska through Baja Peninsula, have a high proportion of species near their upper thermal limit, and are areas that are particularly susceptible to climate-change risk.

KR5: Risk to major terrestrial ecosystems leading to disruptions of species, ecosystems and their services

Major risks to terrestrial ecosystems across North America, such as semiarid landscapes, rangelands, boreal and temperate forests, and Arctic tundra, include significant ecosystem transformations and shifts in species abundances and ranges, and major vegetation types (e.g., transitions from forests to grasslands), with cascading implications for regional biodiversity (*very high confidence*). Warming increases the risk of permafrost thaw with propagating impacts on species and communities in the Canadian and US Arctic (*high confidence*) (CCP6). 6Forest disturbances, including wildfire, drought, insects and pathogens, are expected to increase with warming, acting synergistically to raise the prevalence of tree mortality and ecosystem transformation (*medium confidence*) (Section 14.5.1). These changes will reduce services provided by terrestrial ecosystems, including timber yields and carbon sequestration (*medium confidence*).

KR6: Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture and other human uses

Droughts and earlier snowmelt runoff will increase water scarcity during the summer peak water demand period especially in regions with extensive irrigated agriculture, leading to economic losses and increased pressures on groundwater as a substitute for diminished surface water supplies (*medium* to *high confidence*) (Section 14.5.3). Streams in North America are expected to continue to warm, with important ramifications for aquatic ecosystems (*high confidence*), reducing habitat for salmon and trout species that are economically and culturally important (Section 14.5.1). Warming and drying coupled with other stressors (e.g., pollutants, nutrients and invasive species) pose a risk to ecosystem structure and function in lakes, streams and reservoirs across many parts of North America (*high confidence*) (Sections 14.5.1, 14.5.3). Warming increases in heavy rainfall and nutrient loading pose risks for water quality and HABs (*medium* to *high confidence*) (Section 14.5.3).

KR7: Risk to human health and well-being, including mental health

Heat-related human mortality is projected to increase in North America as a result of climate change and ageing populations, poverty, chronic diseases and inadequate public health systems (*very high confidence*) (Section 14.5.6.1). Gradual changes to temperature and precipitation are impacting urban ecosystems and creating ecosystem regime changes resulting in the poleward expansion among insects that bring risks related to vector-borne diseases such as West Nile virus and Lyme disease (*high confidence*) (Section 14.5.6). Climate change is expected to lead to wide-ranging mental health challenges related to an increase in the psychological burdens of climate change (*high confidence*), particularly for individuals with existing mental health conditions, who live in severely impacted areas or who are reliant on climate for livelihoods and cultural well-being (e.g., Indigenous Peoples and farmers) (Section 14.5.6.8).

KR8: Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries and aquaculture productivity and access

Cascading and interacting impacts of climate change threatens food systems as well as food and nutritional security for many North Americans, especially those already experiencing food and nutritional scarcity, women and children with high nutritional needs and Indigenous Peoples reliant on subsistence resources (*high confidence*) (Section 14.5.6). In agricultural regions experiencing aridification and where water scarcity precludes substantial expansion of irrigation, warming and extreme heat pose a risk to food and forage crop and livestock production (*high confidence*) (Section 14.5.4). Ocean warming and MHWs will continue to disrupt commercial capture fisheries through species redistribution and changes to yield (*high confidence*), and warming waters and OA will increasingly impact aquaculture production (*high confidence*) (Section 14.5.4). Interactions between competing aspects of human security (e.g., food, energy and water) will be exacerbated by climate change (*high confidence*) (Sections 14.5.3, 14.5.4, 14.5.8).

KR9: Risks to major infrastructure supporting commerce and trade with implications for sustainable economic development, regional connections and livelihoods

Climate change and extreme events are expected to increase risks to the North American economy via infrastructure damage and deterioration (*high confidence*), disruption to operations, unsafe conditions for workers (*medium confidence*) and interruptions to international and inter-regional supply chains (*medium confidence*) (Section 14.5.8; see Box 14.5). These climatic impacts will have cascading implications for local livelihoods, sustainable economic development pathways and regional connectivity, and will reinforce pre-existing social inequities (*medium confidence*). Infrastructure damage will also disrupt economic activities, including manufacturing, tourism, fisheries, natural resource extraction and energy production (*high confidence*) (Section 14.5.8).

KR10: Risk to the quality of life in North American communities, cities and towns

In major North American cities and settlements, vulnerability to climate change has increased and is projected to continue to rise (*medium confidence*) (Section 14.5.5). Concentrated populations with unequal adaptive capacities, exposure of valuable assets, ageing infrastructure, and differing degrees of institutional capacity and effectiveness will underpin climate hazards (Section 14.5.5). Coastal, riverine and urban flooding displacing communities and coastal ecosystems (Section 14.5.5.2) will become a dominant risk to urban centres (*high confidence*) and will cause disruptions to transportation and trade infrastructure (Section 14.5.8). Large wildfires endangering lives, livelihoods, property and key infrastructure, and economic activities will contribute to compromised air quality and municipal water contamination (Section 14.5.6; see Box 14.2).

14.6.3 Cumulative Risk, Tipping Points, Thresholds and Limits

Across North America, climate change poses a risk to social–ecological systems increasingly destabilised by compounding climate impacts and non-climate pressures (*high confidence*) (Sections 14.5.1–14.5.3) that erode the connectivity and redundancy underpinning system resilience (Sections 14.5.1–14.5.5; Xiao et al., 2017a; Koven et al., 2020; Malhi et al., 2020; Turner et al., 2020). Accelerating climate change and increasingly severe hazards and shocks may induce abrupt changes or push systems, people and species to critical points–tipping points–where a small additional change causes a disproportionately large response, triggering feedbacks that lock systems into novel regimes (Scheffer et al., 2001; Scheffer, 2010; Anderies et al., 2013; Lenton, 2013; Iglesias and Whitlock, 2020; Lenton, 2020a). Climate-change tipping points can compound and amplify climate impacts and risk, induce disparate climate burdens and benefits across human and ecological systems, and irreversibly restructure ecosystems and livelihoods (e.g., species extinctions, fisheries collapse, community-managed relocation) (Lynham et al., 2017). Examples of systems with potential tipping points in North America include (a) permafrost and sea ice loss triggering transformation of ecological and human systems (including substantial shipping opportunities) in the Arctic that are permanent and irreversible except on geological timescales, and which are potentially underway (*high agreement, low evidence*) (Section 14.6.2; see Box 14.3, CCP6), (b) mid-latitude forest ecosystems at low to middle elevations in western North America where wildfire and cumulative climate and non-climate pressures may restructure forests and succession in ways that promote transition to new vegetation types (Section 14.5.1) and (c) agricultural communities in northern Mexico and the southwest USA where aridification and drought may interact with water resource policies, economic opportunities and pressures, and farm practices to induce either adaptation (via changes in irrigation practices) or farm abandonment, land-use transformation and livelihood changes (due to heat stress, soil deterioration or reduced economic viability) (Sections 14.5.3, 14.5.4, CCP6, Yumashev et al., 2019; Turner et al., 2020; Heinze et al., 2021).

Identification of critical thresholds, elements and connections within a system may also help identify potential positive tipping points, that is, focal components or processes in a system where a relatively small investment or intervention can induce a large benefit and enable self-reinforcing transformative adaptation (Section 14.7; Chapter 17; Tàbara et al., 2018; Lenton, 2020b; Otto et al., 2020). Under low-mitigation scenarios, compounding risks and higher-carbon-emission scenarios increase the potential that amplifying feedback loops and fatal synergies across sectors could lead to existential threats to the social–ecological systems of North America (*medium confidence*). Societal collapse has been linked to shifts in climate regimes, especially when societies have lost resilience due to slowly mounting social–ecological challenges, while other studies reveal that social continuity and flexibility enable historical climate resilience and prosperity under changing environments (FAQ 14.2; Lenton et al., 2019; Otto et al., 2020; Degroot et al., 2021; Richards et al., 2021).

Accounting for tipping points, interactions and reinforcing dynamics among ecological, social and climate processes is necessary for comprehensive analyses of climate-change risk, cost and urgency, as well as effective adaptation design and implementation (Section 14.7; Cai et al., 2015; Steffen and et al., 2018; Lenton et al., 2019; Narita et al., 2020; Dietz et al., 2021). Multiple lines of evidence across sectors assessed in this chapter suggest that after mid-century and without carbon mitigation, climate-driven changes to ecological and social boundary conditions may rapidly push many systems into disequilibrium (*medium confidence*), emphasising the importance of prioritising adaptation actions with co-benefits for mitigation (Section 14.5.4; see Box 14.3). Reducing climate hazards through mitigation and removing catalysts of system instability through adaptation measures that increase system resilience (e.g., ecosystem restoration) will help reduce the risk that systems move across a tipping point from a desirable to an alternate or undesirable state (Sections 14.5.4, 14.7; see Box 14.3; Narita et al., 2020; Turner et al., 2020; Heinze et al., 2021).

Frequently Asked Questions

FAQ 14.2 | What can we learn from the North American past about adapting to climate change?

The archaeology and history of Indigenous Peoples and Euroamerican farmers show that climate variability can have severe impacts on livelihoods, food security and personal safety. Traditional societies developed numerous methods to cope with variability but have always expanded to the limits of what those adaptations permit. Current knowledge and technology can buffer societies from many negative effects of climate change already experienced but will be severely challenged by the novel conditions we are now creating.

People came into North America more than 15,000 years ago and have experienced both massive and minor shifts in climate ever since. At the end of the last very cold phase of the most recent Ice Age, about 11,500 years ago, temperatures rose extremely rapidly—as much as 10°C (18°F) in a decade in some regions. This undoubtedly contributed to the extinction of large mammals like mammoths and mastodons that people hunted alongside many other resources (see Cross-Chapter Box PALEO in Chapter 1). There were so few people on the land, though, and other resources were so abundant, that the long-standing human means of coping with climate variability—switching foods and moving on—were sufficient.

Following the end of the Ice Age, populations across North America grew for the next few thousand years, at a rate that increased once people began to domesticate corn (maize), beans and squash (the 'three sisters') as well as other crops. However, more people meant less mobility, and farmers traditionally are also more invested in their fields and remaining in place than foragers are to hunting grounds. Other means of coping with vulnerability to food shortage caused by climate variability included some continued hunting and gathering of wild resources, planting fields in multiple locations and with different crops, storage in good years, and exchange with neighbours and neighbouring groups.

According to archaeological evidence, however, these adaptation strategies were not always sufficient during times of climate-induced stress. Human remains showing the effects of malnutrition are fairly common, and conflict caused in part by climate-induced shortfalls in farming has left traces that include fortified sites, sites placed in defensible locations and trauma to human bone. Larger and more hierarchical groups emerged, first in Mesoamerica and then in the southwest and southeast USA as well as the Midwest USA. These groups offered the possibility of buffering poor production in one area with surplus from another, but they also tended to increase inequality within their borders and often attempted to expand at the expense of their neighbours, introducing new sources of potential conflict. Dense hierarchical societies also arose in other areas such as the northwest coast where agriculture was not practised but resources, such as salmon and roots, were abundant and either relatively constant or storable.

These societies were not immune to climate hazards despite their greater population and more formal organisation. Archaeological evidence strongly suggests that drought, or growing conditions that were too hot or cold, contributed to the decline of groups ranging from Classic-period Maya states in Mesoamerica, to the somewhat less hierarchical societies of Chaco in the southwest USA and Cahokia in the Midwest USA (Figure FAQ14.2.1). The usual pattern seems to be that climatic variability compounded social and environmental problems that were already challenging these societies.

If societies in North America prior to the Euroamerican colonisation were vulnerable to climate variability, surely were not the more recent and technologically advanced societies of North America at lower risk? The 20th century Dust Bowl created in the US and Canadian prairies suggests otherwise. Severe drought conditions throughout the 1930s—which, to make matters worse, peaked during the Great Depression—did not cause either the USA or Canada to collapse. But both countries suffered massive economic losses, regional loss of topsoil and regional human strife (including loss of crops, income and farms) leading to migration. Yet anthropogenic global climate change was of little or no consequence in the 1930s. While farming practices made climate stress worse, the climate variability itself was either completely, or mostly, within the envelope of historical climate variability that earlier human societies had experienced.

Indigenous Peoples and Euroamerican farmers and ranchers have a long history of mostly successful adaptation to changing weather patterns. The wisdom held by Indigenous Peoples deep knowledge of how plants, animals and atmospheric conditions provide early warning signals of approaching weather shifts, and stories about how past communities have tried to cope with climate-related resource shortfalls. Long-standing community-level management of resources also helps prevent shortfalls, and institutions such as kin groups, church groups, clubs and local governments (which exist in communities of both Euroamericans and Indigenous Peoples, in different forms) can be powerful aids in ameliorating shortfalls and resolving conflict.

Box FAQ 14.2 (continued)

Examples of areas where past climate variability has contributed to crises

Image credit Nate Crabtree

Large scale droughts in the 12th and 13th centuries CE, and cooling temperatures in the 13th century, contributed to farmers leaving the northern Pueblo area in the 13th century.

Photo credit Arthur Rothstein.

Dust-bowl conditions caused by drought and land management were especially severe in this area.

Many cities in the Central Maya Lowlands declined or disappeared in the 9th and 10th centuries CE under pressure from drought, increased summer heat, deforestation, and warfare.

Image credit: Image credit: iStock/id 543832440

Like the N. Pueblo area, the mound complex of Cahokia at the center of this zone was affected by droughts in the 12th and 13th centuries CE, and possibly by flooding.

Image credit: Ira Block/National Geographic Creative

Figure FAQ14.2.1 | Examples of areas where past climate variability has contributed to crises. Climatic variability is most likely to lead to crisis when it is accompanied by social, demographic and political conditions or environmental mismanagement that compound climatic impacts on societies.

Box FAQ 14.2 (continued)

Still, Indigenous knowledge and traditional knowledge among Euroamerican farming communities provide guidelines for how to cope with *traditional* problems. Contemporary governmental restrictions (such as legal water-rights allocations, international borders and tribal-lands boundaries) have limited the adaptive capacity that Indigenous societies have developed over the centuries. Now human-caused climate forcing, if not mitigated by reducing heat-trapping GHGs, is expected to produce climates in North America that have no local analogues in human history even as it destroys heritage sites that are sources of knowledge about palaeoclimates and the diverse ways of coping with them that past peoples have discovered. Just as past peoples often *avoided* local climate change by moving on, in a world where mobility options are severely limited, a lesson from archaeology and history is that we should use our hard-won knowledge of the causes of climate change to avoid creating futures with no past analogues to provide useful guidance.

Frequently Asked Questions

FAQ 14.3 | What impacts do changes in the North American Arctic have within and outside the region?

The North American Arctic is warming at nearly three times the global average, creating a cascading web of local, regional and global impacts within and beyond polar regions. Changes in the Arctic not only effect global ocean circulation and climate regulation, but also facilitate new Arctic transportation routes and support transboundary resources with geopolitical, environmental and cultural implications as conditions change.

Rapid warming and extreme temperatures in the Arctic is leading to unprecedented seasonal sea ice loss, permafrost thaw and increasing ocean temperatures. Cascading from these biophysical changes are cultural, socioeconomic and political consequences that are widespread and largely unprecedented in human history. Changes in sea ice create safety hazards for Indigenous Peoples and northerners who rely on frozen seas and rivers for transportation between remote communities and to subsistence hunting areas. Thawing permafrost, especially that of ice-rich permafrost, creates challenges and costs for a region with low population density and a small tax base to support major infrastructure investments. Warmer ocean temperatures induce large-scale distributional shifts and reduced productivity and access to the largest North American fisheries. Ice-associated marine mammals, such as polar bears, seals and walruses, have declined precipitously with decreasing sea ice in the Bering Sea, and widespread ecosystem changes from fish through birds and marine mammal species have altered the system with uncertain outcomes for these productive ice-driven ecosystems. Newly ice-free shipping routes are increasing regional and geopolitical tensions and may facilitate novel threats like the spread of invasive species and safety hazards to local hunters and fishers. The local and regional impacts of climate change in the North American Arctic are profound and span social, cultural, health, economic and political imperatives.

Although the region is remote, changes in the Arctic impact the rest of the world. The Arctic serves as a regulator of global climate and other ecological processes through large-scale patterns related to air and ocean circulation. These vitally important processes are nearing points beyond which rapid and irreversible (on the scale of multiple human generations) changes are possible. The magnitude of cascading changes over the next two centuries includes regional warming and temperature extremes, permafrost declines and sea ice loss beyond that experienced in human existence. This includes macro-scale risks related to SLR from the melting of glaciers and thermal expansion of oceans. Changes in the Arctic are more pronounced than elsewhere and portend climate-change impacts in other areas of the globe.

Adaptation in the Arctic is underway and lessons learned on what works and what is effective and feasible to implement can provide global insights. Successful adaptation in the North American Arctic region has been attributed, in part, to the explicit and meaningful inclusion of IK and Indigenous self-determination, and diverse perspectives in decision-making processes, strong local leadership, co-management approaches, technological investment in integrated climate modelling and projections, and multilateral cooperation.

14.7 Adaptation in North America

14.7.1 Overview of Observed Adaptation in North America

Climate adaptation efforts have increased across all North American regions and sectors (*high confidence*). Support for, and implementation of, adaptation policies, plans and measures have not been equal across the public and private sectors, regions or varying levels of governance (*high confidence*) (Table 14.7). To date, reactive (coping-based) and incremental adaptations have helped North Americans avoid greater damages from observed climate impacts (*medium confidence*). There is increasing agreement that worsening impacts and expanding risk conditions may exceed current adaptation capacities by mid-century under high-emissions scenarios (RCP8.5) (*medium confidence*).

14.7.1.1 Individuals and Households

Across North America, individuals and households have taken action to reduce climate-influenced risks (*high confidence*). These autonomous adaptations comprise the majority of the observed responses in the peer-reviewed literature (Berrang-Ford and et al., 2021). The increased use of cooling systems (which could be maladaptive unless there are innovations) (Section 14.5.5.3; Barreca et al., 2016), creating defensible space around homes in wildfire-prone areas (see Box 14.2), and the modification or redesign of housing structures along coasts (Koerth et al., 2017), are important household responses to existing risks. Although these actions have played a role in reducing risks, the capacity to undertake such actions is not uniform across individuals in North America and has exacerbated existing social inequities, especially in coastal areas (Keenan et al., 2018; de Koning and Filatova, 2020). Additionally, these adaptation activities often are taken without consideration of the impact on mitigation efforts (Kates et al., 2012; Fedele et al., 2019; Shi and Moser, 2021).

14.7.1.2 Local and Subnational Governments

The majority of local jurisdictions in North America have undertaken some level of adaptation. These efforts largely have focused on planning and less on implementation (*high confidence*). Some subnational governments, namely states and provinces, have engaged in advanced adaptation planning efforts (*high confidence*). Indigenous Peoples in North America have undertaken substantial activities (Section 14.4; see Box 14.1).

Many cities across North America have undertaken adaptation planning (Section 14.5; Hughes, 2015; Reich et al., 2016; Moser et al., 2017; Auditors General, 2018; McMillan et al., 2019) with some financing adaptation implementation, for example, in the case of SLR (see Box 14.4). Adaptation actions commonly implemented in cities include climate-informed building codes, enacting energy conservation measures, modifying zoning and increasing green infrastructure (Section 14.5.5.3; see Box 14.7; Binder et al., 2015; Maxwell et al., 2018a; Moss et al., 2019; Brown et al., 2021). The majority of cities have formed practitioner networks to share information (ICLEI Canada, 2016; Vogel et al., 2016; C40 Cities, 2018) and supporting learning and collaboration through regional collaborations that include utility managers and the private sector (Fünfgeld, 2015; Moser et al., 2017).

In Canada, the Map of Adaptation Actions[10] presents over 200 adaptation case studies addressing a variety of climate-related impacts (Warren and Lulham, 2021). The City of Saskatoon, in developing its Climate Action Plan (which includes a Corporate Climate Adaptation Strategy), engaged with local businesses, non-governmental organisations (NGOs), residents and experts to identify potential risks (and benefits) requiring action (City of Saskatoon, 2019). Similarly, the City of Surrey specifically used community outreach programmes to develop its Coastal Flood Adaptation Strategy (CFAS) through a value-based planning approach (City of Surrey, 2019). Municipal asset management, local services and community well-being were key considerations for the City of Selkirk, Manitoba, when developing an adaptation strategy as well as ensuring a budgeting process that supports implementation (City of Selkirk, 2019). As of 2019, 8 of 13 Canadian provinces and territories have high-level climate adaptation strategies. The scope of these efforts vary by jurisdiction as a review conducted by federal and provincial auditors in Canada identified several deficiencies related to a lack of detailed implementation plans, obligated funding and specific timelines (Auditors General, 2018).

Progress in Mexico on adaptation implementation at the local level has been extensive (INECC and Semarnat, 2018). Activities include executing programmes for relocating infrastructure in high-risk zones in priority tourist sites, incorporating adaptation criteria in public investment projects that involve construction and infrastructure management, water management, application of climate adaptation norms for the construction of tourist buildings in coastal zones, and improving the security of key water, communication and transportation infrastructure (Sections 14.5.5, 14.5.7, 14.5.8). Additionally, local capacity and protocol to respond to extreme weather events as a function of climate change have been integrated more regularly into community-based hazard mitigation plans. States and municipalities in Mexico must have climate policies that are consistent with the guidelines of national strategies (Section 14.7.1.5) and state-level programmes on climate change, in addition to other state and municipal laws. As a result, these entities have developed and implemented early warning systems designed to protect the population from climate-related risks, such as strong storms and hurricanes (INECC and Semarnat, 2018).

Implementation of adaptation initiatives and specific actions in US cities has increased in the approximately 5 years between the 3rd US National Climate Assessment (NCA3) (Melillo et al., 2014) and the 4th Assessment (NCA4), and adaptation responses have been observed widely (Lempert et al., 2018). ICLEI-USA provides numerous resources for adaptation planning and implementation for cities, Indigenous Peoples and Regional Governments[11]. The Georgetown Center for Climate maintains a comprehensive resource for tracking adaptation progress for States[12]. As of 2021, 18 US states have completed climate adaptation plans, and six states have plans underway as of

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[10] See https://changingclimate.ca/case-studies

[11] See https://icleiusa.org

[12] See www.georgetownclimate.org/adaptation/plans.html

the time of this report (Georgetown Climate Center, 2021). California, in particular, has adopted sustained climate assessment to allow for more rapid iterations on adaptation planning (Bedsworth et al., 2018; Miao, 2019). Across all US states, however, adaptation activities do not have readily accessible budgets, such that levels of funding cannot be assessed directly (Gilmore and St. Clair, 2018).

14.7.1.3 National and Multi-National Governance

The federal government of each North American country has developed policies and actions that promote climate adaptation (Figure 14.12). Recognising the cultural, economic and social networks that span North America, the federal governments have also committed to engagement on adaptation and resilience across borders and through cooperation on domestic adaptation efforts (The White House, 2016). Each country also outlines their respective adaptation efforts through submissions under the UN Framework Convention on Climate Change, including their nationally determined contributions (NDCs) under the Paris Agreement. The federal governments also support adaptation efforts in other countries through international climate negotiations as well as related agreements, such as the Sendai Framework for Disaster Risk Reduction and efforts to support the achievement of the Sustainable Development Goals (SDGs).

Mexico's 2020 update to its first NDC communicated extensive adaptation efforts (Government of Mexico, 2020). The measures outlined in this document highlight the importance of co-benefits for adaptation efforts as they relate to the SDGs and to support mitigation commitments. Ecosystem-based solutions and NbS (see Box 14.7) are the basis for much of the synergies between adaptation and mitigation efforts. These plans are supported by domestic legislation through the General Law on Climate Change, which includes the Climate Change Adaptation Process (CCAP). The CCAP provides a holistic systems approach for identifying instruments and institutional arrangements for adaptation implementation (Semarnat and INECC, 2015; INECC and Semarnat, 2018). This approach includes guidance for planning (e.g., the Climate Change Mid-Century Strategy, the Special Climate Change Program 2014–2018) and formalises its adaptation commitments to the Paris Agreement.

In Canada, the Federal Adaptation Policy Framework (Government of Canada, 2011) guides domestic action to develop adaptation knowledge, build adaptive capacity, and mainstream adaptation into federal policy, in support of the Pan-Canadian Framework on Clean Growth and Climate Change (Government of Canada, 2016), which included specific adaptation measures and investments to build resilience. In August 2021, the government initiated a National Adaptation Strategy with development anticipated through 2022. Additionally, the government facilitates efforts and funds research, capacity building and information sharing across sectors and among government departments (Government of Canada, 2021a). The Canadian Centre for Climate Services provides access to climate data, tools and information[13]. In Canada's revised NDC, near-term commitments to protecting land and oceans, and efforts related to sustainable and resilient energy systems, are highlighted as examples of co-benefits between climate-change adaptation and mitigation (Government of Canada, 2021b).

The USA has experienced substantial revisions to its climate policy and its international engagement since AR5 with implications still unclear (Bomberg, 2021). Since AR5 and until early 2020, many congressionally mandated federal efforts (Beavers et al., 2016; Parris et al., 2016; Rockman et al., 2016; Caffrey and Hoffman, 2018) faced programmatic challenges, but most continued to provide research and capacity development to support adaptation implementation across the USA. Importantly, the US government sustained the national climate assessments (Lempert et al., 2018). Recently, the administration has re-engaged with the Paris Agreement and the USA has submitted an NDC (Government of the United States of America, 2021); however, adaptation was not directly addressed. Subsequent Executive orders mandate adaptation planning at the federal level (e.g., USEO 13754; USEO 14008). As of the time of this report, the US climate policy landscape is rapidly evolving, including major legislative initiatives (e.g., Green New Deal) (Boyle et al., 2021).

14.7.1.4 Private Sector, Including Companies, NGOs, Professional Organisations, Academic Institutions and Communities of Practice

The private sector comprises a diverse set of actors who influence, interact with and support adaptation efforts, generally through shared governance with the public sector. The weight of evidence points to the benefits of these collaborations and the importance of voluntary code-making and self-regulation (Section 17.4.2.1.6). In North America, NGOs and professional organisations have been important agents of change in the adaptation field (Bennett and Grannis, 2017; Stults and Meerow, 2017). Efforts have included supporting community-based resilience, network building, Internet-based guidance and resources, case studies, workshops and other services to support adaptation action (e.g., vulnerability assessments, scenario-based planning).

Market and financial mechanisms have provided important buffering capacity against climate shocks in North America. Insurance products are being developed to meet emerging climate risks, especially related to availability and pricing of flood insurance in Canada (Thistlethwaite, 2017; Davies, 2020) and the USA (Kousky et al., 2021). Some existing US flood insurance products provided through joint public and private arrangements has led to rebuilding in flood-prone locations (Zellmer and Klein, 2016). The price of these products may limit their uptake in low-income neighbourhoods (Cannon et al., 2020).

Professional organisations have participated in the development and adoption of measures to integrate climate resilience into the built environment. This includes new designs, guidelines, codes, standards and specifications, in addition to infrastructure inventories that incorporate evaluation of vulnerabilities and identification of priority at-risk areas (Amec Foster Wheeler and Credit Valley Conservation, 2017; ASCE, 2018a). These efforts are supported by provincial/state and federal initiatives (e.g., Canada's Climate Lens (Infrastructure Canada, 2018), and California's Climate-Safe Infrastructure Working Group

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[13] See www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services.html

https://doi.org/10.1017/9781009325844.016

(Climate-Safe Infrastructure Working Group, 2018)). Infrastructure Canada has undertaken Canada-wide initiatives to improve infrastructure resilience to climate change[14]. The Standards Council of Canada (SCC) established the Northern Infrastructure Standardization Initiative[15] engaging stakeholders, including Indigenous Peoples, to develop standards specific for addressing climate-change impacts on northern infrastructure design, planning and management, and community development (Standards Council of Canada, 2020).

Professional organisations in the USA (e.g., National Medical Association, American Institute of Architects, Association of Metropolitan Water Agencies, Water Utility Climate Alliance, American Society of Adaptation Professionals) have engaged with their members particularly through training about urban adaptation (Stults and Meerow, 2017). The private sector and citizens (Klein et al., 2018) have been involved in the management of increasing flood risk, such as the adoption of property-level flood protection (Thistlethwaite and Henstra, 2018; Valois et al., 2019), implementing FireSmart Canada and Firewise USA guidance (see Box 14.2). In Canada, Engineers Canada developed the PIEVC Protocol to provide guidance for professionals in engineering and geoscience[16].

Research-based institutions have accelerated the development of Internet-based tools for visualising and exploring climate information, in addition to furthering the scholarship on adaptation. In the USA, joint university, foundation and government programmes have contributed to advancing the field with products such as oceanographic and fishery climate forecasting tools (Section 14.5.2), in addition to methods for evaluating water resource plans under uncertainty about future mean and extreme conditions (ASCE, 2018a; Ray et al., 2020). Some regional research centres focus on stakeholder engagement in addition to research; these include the National and Regional Climate Adaptation Science Center Network of the US Geological Survey[17], the US Department of Agriculture's Climate Hub Network[18] and the Climate Program Office of NOAA[19] which includes the Regional Integrated Science Assessment Network[20] to support delivery of climate services. So-called networks of networks, consisting of NGOs as well as state and city government programmes, have provided an alternative to federal support. For example, the Science for Adaptation Network was formed subsequent to dismantling the federal advisory group to the US National Climate Assessment (Moss et al., 2019).

14.7.2 The Solution Space

14.7.2.1 Incremental Adaptation, Barriers and Limits

Adaptation actions to moderate the effects of climate impacts are well documented in North America and have buffered much of the past and currently observed climate impacts (e.g., Lempert et al., 2018; Lemmen et al., 2021). While it is challenging to catalogue adaptation activities, as many are not published or are not necessarily undertaken with climate adaptation as the primary rationale (Section 1.3.2.2), most of the activities identified by sector in this chapter have been primarily incremental adaptation measures (*medium evidence, high agreement*). Many actions are extensions of existing practices for managing climate variability and there is broad agreement that worsening future conditions will exceed the capacity of many of these efforts (Kates et al., 2012; Termeer et al., 2017; Fazey et al., 2018; Fedele et al., 2019; Shi and Moser, 2021).

Progress in adaptation planning and implementation between regions in North America is uneven (Table 14.6; see Box 14.7; Bierbaum et al., 2013; Moser et al., 2017; Auditors General, 2018; INECC and Semarnat, 2018; Shi and Moser, 2021). At the local level (cities) in the USA, commitment of elected officials, financial resources and awareness of climate-change hazards and risks have been identified as driving the variation in climate adaptation (Shi et al., 2015). Adaptation programmes have come under budgetary and political pressures that limit continuity of efforts (Moss et al., 2019). Implementation of adaptation has also faced challenges due to institutional arrangements, constraints and gaps that prevent different levels of government, social organisations and academia to act in an integrated and timely way to consider biodiversity, agriculture and water systems (e.g., see Box 14.7; Bourne et al., 2016; Nalau et al., 2018)

Adaptive capacity in the face of climate risks and impacts has not been equal across North American communities (Sarkodie and Strezov, 2019). Lack of representation, health inequities and economic constraints adversely affect the capacity to respond to change and further exacerbate marginalisation. For example, within many water basins in Canada and the USA, planning processes are often hampered by conflicting interests, asymmetrical information and differential power (ICLEI Canada, 2016; Nordgren et al., 2016; Woodruff and Stults, 2016).

The absence of evidence about the current effectiveness of proposed adaptation actions to guide future actions and investments presents a serious risk to North America, especially at higher GWLs (medium confidence). Evaluating the limits to adaptation and the effectiveness of adaptation actions is hindered by a lack of monitoring and evaluation (Auditors General, 2018; Dilling et al., 2019; Berrang-Ford et al., 2021). Incremental, passive adaptations are often characterised by *soft* limits due to differing access to resources and by perceptions and tolerance of risk (Moser, 2010; Dow et al., 2013). At current warming levels, social–ecological systems have been reaching limits to adaptation in regions with high exposure and high sensitivity (*medium confidence*). However, the implications for adaptation are unclear as soft adaptation limits are mutable and change with evolving knowledge,

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[14] See www.infrastructure.gc.ca/plan/crbcpi-irccipb-eng.html

[15] See www.scc.ca/en/nisi

[16] See www.pievc.ca

[17] See www.usgs.gov/ecosystems/climate-adaptation-science-centers

[18] See www.climatehubs.usda.gov

[19] See https://cpo.noaa.gov

[20] See https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/RISA/About-RISA

Table 14.6 | Adaptation trends and progress across sectors. Adaptation progress consists of assessment (A), planning (P), implementation of strategies (I) and evaluation of efficacy (E).

			Adaptation progress				Limits	
Sector	Strategies	Cases	A	P	I	E	Soft	Hard
Terrestrial ecosystems (Section 14.5.1.1)	Broad use of tools such as scenario planning, structured decision making and adaptation planning frameworks	Planning for climate refugia in the Sierra Nevada of California, USA (Morelli et al., 2016)	H	H	L to M	L	Management agency internal policies which may prevent the flexibility required for implementation of adaptation strategies	Some species may face local extirpation or even extinction if adaptive capacity is overwhelmed
Oceans (Section 14.5.2)	Proactive and rapid management approaches to minimise impacts of increasingly frequent entanglements of protected species, caused by climate-driven changes in prey and fishery activities	Dynamic closure areas to reduce loggerhead turtle bycatch in Hawaiian shallow-set longline fisheries (Howell et al., 2015; Lewison et al., 2015), blue whale ship-strike risk in near-real time (Hazen et al., 2017; Abrahms et al., 2019a) and bycatch of multiple top predator species in a West Coast drift gillnet fishery (Hazen et al., 2018)	H	H	M	M	Lack of coordination and planning at multiple scales as species redistribute across fishery areas, marine protected zones and international and jurisdictional boundaries	Marine species mortality events
Freshwater resources (Section 14.5.3)	Forecasting and warning of harmful algal blooms (HABs) that affect water quality	Reduced human exposure to the increased risk of toxins from HABs in the Great Lakes	M	L to M	L to M	L to M	Financial resources required to enhance water treatment facilities to deal with HABs, technological innovation to improve treatment and removal of HABs, closure of recreational water use	Severe human health effects, mortality of aquatic species
Water availability (Section 14.5.3)	Water allocation policies reassessed to enhance equity, sustainability and flexibility in times of shortage through sharing agreements, improved groundwater regulation and voluntary water transfers	US Colorado River interstate shortage sharing agreement	H	H	M	L to M	Complex legal and administrative challenges, heightening lengthy disputes and costly interstate legal battles	Depletion of finite groundwater resources and reduced flow in hydrologically connected rivers
Food and fibre (Section 14.5.4)	Improved climate resilience through increasing income and harvest/crop portfolio diversification	Fishing communities in the US-SW and US-NE through nature-based aquaculture solutions (Messier et al., 2019; Rogers et al., 2019; Young et al., 2019; Fisher et al., 2021)	H	H	M to H	M	Lack of high-resolution and locally tailored climate-change information	Collapse of fisheries and loss of crops due to excessive warming and extreme events
Cities and infrastructure (Section 14.5.5)	Consideration of the value of green infrastructure and natural assets to meet a range of adaptation needs related to flooding, extreme urban heat, SLR and drought	Municipal Natural Assets Initiative to assist Canadian municipalities to integrate natural assets in financial planning and asset management programmes and consider projected climate changes (Municipal Natural Assets Initiative, 2018)	H	H	M	L to M	Organisations' willingness to take on solutions that are emergent and less tested; capacity for municipalities to undertake the development and assessment of this new infrastructure	Rate and magnitude of climate changes exceeding capacity of natural/green infrastructure to cope
Health and communities (Sections 14.5.5, 14.5.6)	Access to green spaces, cooler infrastructure and cooling stations	The heatwave plan for Montreal which includes visits to vulnerable populations, cooling shelters, monitoring of heat-related illness and extended hours for public pools (Lesnikowski et al., 2017)	H	H	L to M	L to M	Lack of effective warning and response systems, ability to reach at-risk populations, building designs, enhanced pollution controls, urban planning strategies, and affordable, resilient health infrastructure	Extreme increase in heat-related mortality and morbidity
Tourism and recreation (Section 14.5.7)	Diversification of winter-focused recreation and tourism opportunities	Investments in climate-resilient infrastructure within Canadian National Parks which have increased visitation rates during the shoulder seasons (Fisichelli et al., 2015; Lemieux et al., 2017; Wilkins et al., 2018)	H	H	M	L	Social inequalities generated by the tourism development process not considered, such as increased property taxes leading to the marginalisation of local residents in favour of wealthy tourists	Lack of precipitation that falls as snow particularly in lower-elevation areas

			Adaptation progress				Limits	
Sector	Strategies	Cases	A	P	I	E	Soft	Hard
Commerce and transportation (Section 14.5.8)	Improved engineering and technological solutions, in addition to innovative policy, planning, management and maintenance approaches, to enhance climate resilience for transportation and related commerce	For roads, changing pavement mixes to be more tolerant to heat or frost heaving, expanding drainage capacity, reducing flood risks, enhancing travel advisories and alerts, elevating or relocating new infrastructure where feasible and changing infrastructure design requirements (Natural Resources Conservation Service, 2008; EPA, 2017; Pendakur, 2017)	H	H	M	L	Lack of financial resources to build climate-resilient infrastructure, particularly in marginalised communities	Extreme events which may cause significant and irreversible impacts on the transportation sector with major implications for supply chains and global trade

Note:
L: low, M: moderate, H: high

values, interests and perspectives involved in decision making (Adger et al., 2009; Moser et al., 2017). *Hard* limits have been identified for some natural systems, such as species extinctions (Sections 14.5.2.1, 14.5.1.3; Table 14.2).

Adaptation actions in one place or sector can have adverse side effects elsewhere (*medium confidence*). For example, increased use of groundwater for irrigation in response to aridification can reduce baseflows into rivers with adverse impacts on stream ecology and water availability for communities far downstream (Section 14.5.3). Additionally, across multiple sectors in North America, adaptation actions have tended to be sector specific rather than integrating across systems (Gao and Bryan, 2017; Fulton et al., 2019), despite the increasing awareness of cascading impacts and interdependencies (Zimmerman and Faris, 2010; C40 Cities and AECOM, 2017) and risks from possible ecological and social thresholds that have been identified under higher GWL (Section 14.6.3). For example, the water, energy and food nexus in North America has highlighted that food, water and energy security depend on transportation infrastructure (Section 14.5.8.1.2; Romero-Lankao et al., 2018).

14.7.2.2 Adaptation Through Participatory and Robust Decision Making, Indicators and Sustained Assessments

In response to some of the challenges presented in Section 14.7.2.1, substantial progress has been made in the North American context on the development of climate services, indicators, sustained assessments, and participatory and stakeholder-driven robust decision making (*medium confidence*) (Fazey et al., 2018; Fedele et al., 2019; Moss et al., 2019; Boon et al., 2021; Werners et al., 2021).

Decision making related to adaptation policies, plans and projects has become more formalised, emphasising participatory governance and co-production of knowledge. Canada has improved capacity with its Canadian Expert Panel on Climate Change Adaptation and Resilience Results and the recent National Adaptation Plan (Section 14.7.1.5), with the development of a series of indicators to measure progress on adaptation (EPCCAR, 2018; Government of Canada, 2021a). In the USA, indicators have been developed to communicate climate risks and guide adaptation efforts from federal (Kenney et al., 2020) to more regional initiatives (Kenney and Gerst, 2021). These climate indicators have been used to support user-driven assessments and to articulate adaptation goals (Moss et al., 2019; Kenney et al., 2020); however, these frameworks have not sufficiently incorporated monitoring and evaluation into adaptation plans (Lempert et al., 2018; Kenney et al., 2020). Tools and services to facilitate risk assessment and action planning have been made available through federal government climate service efforts, and guidance for their use has been developed (Vano et al., 2018); however, these products have been characterised as insufficiently developed to allow all adaptation practitioners to use these services (Meerow and Mitchell, 2017).

Throughout North America, co-development (or co-production) of adaptation efforts among stakeholders who share common climate vulnerabilities or risk levels (e.g., individuals, groups, communities, businesses or institutions) has been a core attribute of adaptation planning (Mees et al., 2016) and ranges across many sectors (e.g., Sections 14.5.2.2, 14.5.3.3, 14.5.4.3). Participatory efforts and robust decision making have also been observed; some integrated watershed planning processes have high degrees of sustained stakeholder involvement (Section 14.5.3.3; FAQ 14.4; Harris-Lovett et al., 2015; Cantú, 2016).

14.7.2.3 Transformational Adaptation and Climate Resilience

Climate change and its projected impacts pose a substantial risk to North America as a region as well as to sectors, communities and individuals (Section 14.6.2). Incorporating different values and knowledge systems, consideration of equity and justice as core objectives and addressing underlying vulnerabilities are principles that can guide transformational adaptation and resilience (*medium confidence*).

Approaches that advance adaptation within the existing contexts (finances, institutions and processes) have been increasingly promoted by governments to mainstream climate risk into all considerations (Rosenzweig and Solecki, 2014; Van der Brugge and Roosjen, 2015; Boon et al., 2021; Shi and Moser, 2021). Policies and programmes that build upon existing approaches that have inherent climate resilience including Indigenous knowledge-based land and resource management (Section 14.5.4), co-management of agriculture and freshwater resources (Section 14.5.3), NbS (see Box 14.7), links between health and equity, and ecosystem-based management (Sections 14.5.2–14.5.4) have advanced sustainable and equitable climate resilience. Implementing the recommendations in the ASCE committee's report on adaptation to a changing climate (2018a)

Table 14.7 | Simplified example for transitioning from incremental to transformative adaptation approaches to support future climate-resilient sustainable development

		Adaptation approaches			Mitigation	Feasibility dimensions	
Hazard	Response	Incremental	Transformational	Evidence/ agreement	Co-benefits	Barriers	Enablers
Extreme storms causing severe flooding and erosion	Integrated ecosystem and watershed management	Restoration of stream corridors to incorporate environmental flows; continuing to build hardened surfaces and stream diversions in urban areas to accommodate infrequent, yet extreme, storm events	Restoration of streambanks and beds to stabilise and slow flows; use of drought-tolerant plantings and shade trees to reduce evaporation rates; incorporation of pervious surfaces in urban settings in combination with designating wide buffer area within floodplains to accommodate increased frequency of extreme events; integration of equity and justice considerations	*Medium*	Conservation of soil and increased opportunity for carbon sequestration	Sectors working in silos, inadequate financing, inability to identify shared goals (EC, INST, SOC, GEO)	Development of a coordinated suite of adaptation efforts, co-produced among stakeholders and across sectors (INST, SOC, ENV, TEC)

Notes:

This table is modified from the IPCC SR1.5 adaptation feasibility assessment for Land and Ecosystem Transitions (IPCC, 2018). Feasibility dimensions (can be barriers and/or enablers) are as follows: Economic (EC), Technological (TEC), Institutional (INST), Sociocultural (SOC), Environmental/Ecological (ENV) or Geophysical (GEO) (Chapter 16).

and Canada's Infrastructure and Buildings Working Group report has been identified as an opportunity to improve social equity by ensuring the resilience of infrastructure and the services it provides, through adoption of standards and good asset management practices (Amec Foster Wheeler Environment and Infrastructure, 2017; ASCE, 2018a).

Long-term policy signals to incentivise ongoing, scalable adaptation action that is coordinated with mitigation efforts will increase actions and prevent potential maladaptive investment (Moser, 2018; Shi and Moser 2021). Using SDG goals and the NDCs as a framework for inclusive and coordinated partnership and vertical integration across subnational, national and regional planning can promote climate resilient development (CRD) (Section 18.1.3). Coordination of policies and responses have been identified as supporting longer-term, transformational adaptation and minimising risk (Termeer et al., 2017; Fazey et al., 2018). New approaches for enabling and incentivising transformative adaptation in North America are rapidly emerging (Colloff et al. 2017; Fedel et al. 2019; Werners et al. 2021). Evaluation of the feasibility of evolving adaptation strategies is only in the early stages, but recent work has provided the foundation for assessing these considerations (Table 14.7; Chapter 16).

Differing values, perspectives, interests and needs of relevant actors (Dittrich et al., 2016) through participatory processes, such as co-production of knowledge (Meadow et al., 2015; Wall et al., 2017), have been incorporated through the Resilience Dialogues[21] and the development of guidance on climate scenarios (Chaumont, 2014). Framing of adaptation goals strongly determines beneficiaries of resultant policies and underscores the importance of a plurality of perspectives in adaptation governance (Cochran et al., 2013; Plummer, 2013; Allison and Bassett, 2015; Raymond-Yakoubian and Daniel, 2018). Sustained engagement through iterative knowledge development, learning and negotiation has been identified as core for addressing climate risks (Kates et al., 2012; Seijger et al., 2014). Interdisciplinary and inclusive adaptation programmes that embrace and plan for conflict and resolution, and address inequalities, have been part of broadening the opportunities for engagement (Cantú, 2016; Termeer et al., 2017; Parlee and Wiber, 2018; Sterner et al., 2019; Haasnoot et al., 2020).

Equity and justice in climate adaptation have been identified as providing a foundation for resilience in natural, social and built systems (Cochran et al., 2013; Reckien et al., 2017; Schell et al., 2020). This approach recognises that social vulnerability undermines efforts to increase adaptive capacity and that adaptation may also entrench existing social inequities, such as marginalisation of communities of colour, gender discrimination, legacy effects of colonisation and gentrification of coastal communities (Schell et al., 2020; Thomas, 2020). Thus, identifying systemic racism and the effects of colonialism within and across institutions has also been identified as part of achieving more just and equitable adaptation (Shi and Moser 2021). Acknowledgement and incorporation of IK in adaptation planning and implementation also recognises Indigenous sovereignty issues and the importance of the equitable role of Indigenous self-determination in governance and planning (see Box 14.1; Section 14.4; Raymond-Yakoubian and Daniel, 2018).

Strategies have been emerging to facilitate progress by including specific guidance on tools for financing and funding climate-change adaptation infrastructure (Berry and Danielson, 2015; Chen et al., 2016; Zerbe,

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[21] See www.resiliencedialogues.org

Conceptual diagram of the key elements for expanding the adaptation solution space and implementing climate-resilient development

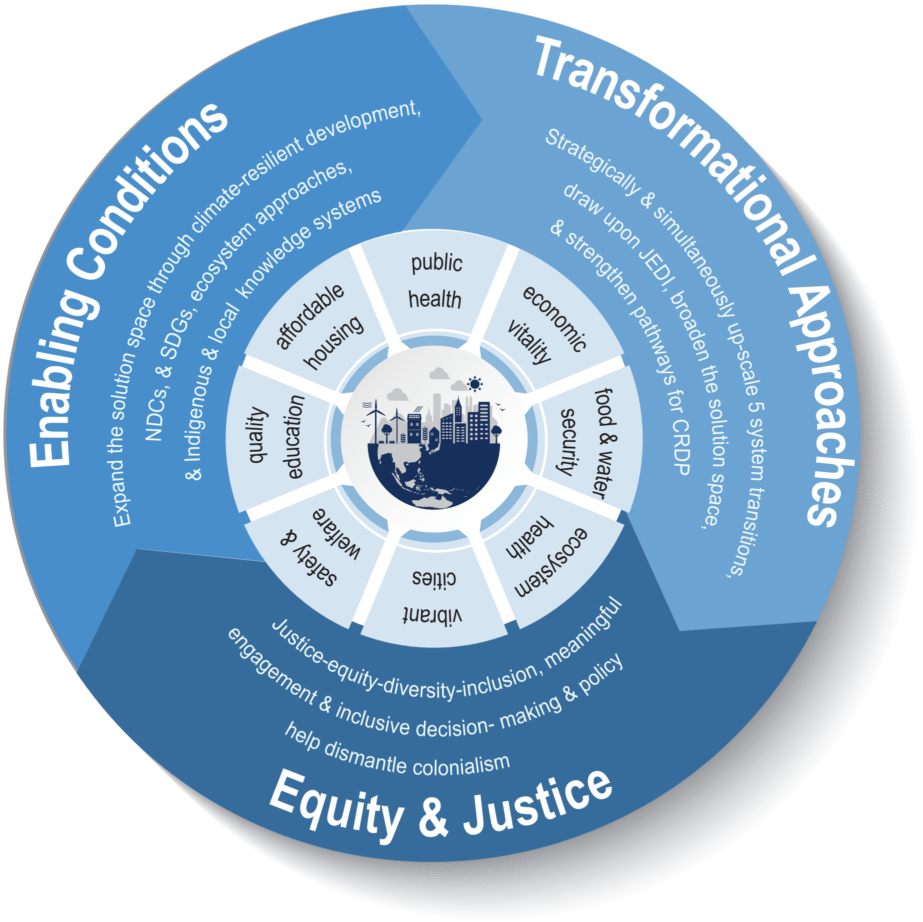


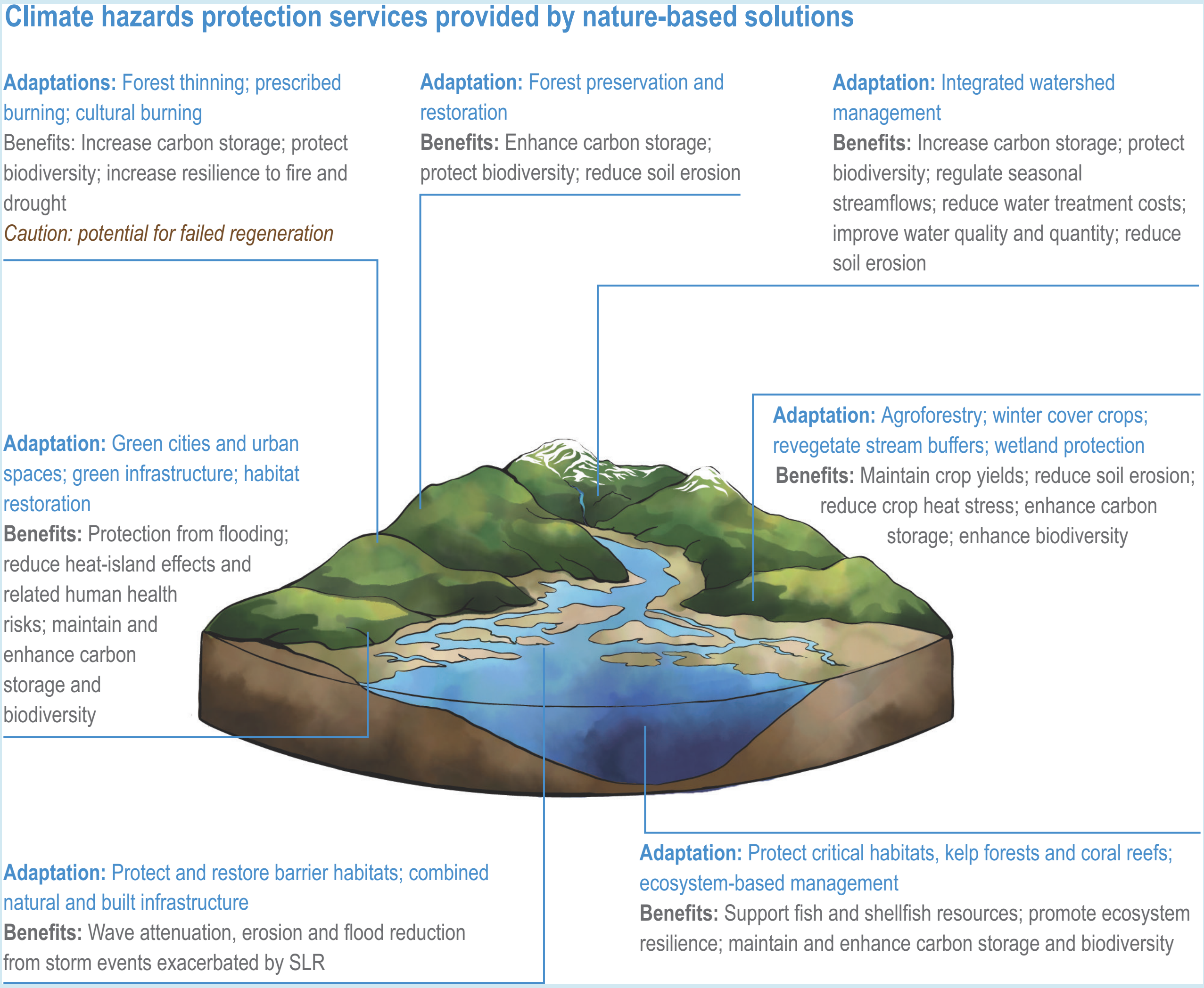
Figure 14.12 | Conceptual diagram of the key elements for expanding the adaptation solution space and implementing climate resilient development (Chapter 18). Adapted from Shi and Moser (2021).

2019). This includes facilitating transitions between incremental and transformational efforts to facilitate CRD (Figure 14.12; Chapter 18).

The extent to which resilient infrastructure contributes to social justice and equity has also been taken into consideration (Climate-Safe Infrastructure Working Group, 2018; Doorn, 2019). Proactive actions focused on small towns and rural areas—including the interdependencies between cities and surrounding areas—increases the potential that small and medium cities can build adaptive capacity at a pace that is commensurate with present and future risks (Moss et al., 2019; Vodden and Cunsolo, 2021). This coordination also creates greater opportunity for translation of knowledge into practice and assessing knowledge in the context that it is to be applied to improve decision making across scales (Enquist et al., 2017; Moss et al., 2019).

Box 14.7 | Nature-based Solutions to Support Adaptation to Climate Change

Nature-based Solutions (NbS) are 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (IUCN, 2016). Such NbS in the context of climate change, or nature-based adaptation see (Box 1.3), can jointly address multiple social–ecological issues related to climate-change hazards, impacts, adaptation and mitigation (Figure Box 14.7.1; Cross-Chapter Box NATURAL in Chapter 2). Successful nature-based adaptation draws from existing adaptation approaches (Borsje et al., 2011; Temmerman et al., 2013; Law et al., 2018; Reguero et al., 2018; Buotte et al., 2019) and is applied across ecological and human systems (*high confidence*) (Table Box 14.7.1; Figure Box 14.7.1).



Climate hazards protection services provided by nature-based solutions

Adaptations: Forest thinning; prescribed burning; cultural burning
Benefits: Increase carbon storage; protect biodiversity; increase resilience to fire and drought
Caution: potential for failed regeneration

Adaptation: Forest preservation and restoration
Benefits: Enhance carbon storage; protect biodiversity; reduce soil erosion

Adaptation: Integrated watershed management
Benefits: Increase carbon storage; protect biodiversity; regulate seasonal streamflows; reduce water treatment costs; improve water quality and quantity; reduce soil erosion

Adaptation: Green cities and urban spaces; green infrastructure; habitat restoration
Benefits: Protection from flooding; reduce heat-island effects and related human health risks; maintain and enhance carbon storage and biodiversity

Adaptation: Agroforestry; winter cover crops; revegetate stream buffers; wetland protection
Benefits: Maintain crop yields; reduce soil erosion; reduce crop heat stress; enhance carbon storage; enhance biodiversity

Adaptation: Protect and restore barrier habitats; combined natural and built infrastructure
Benefits: Wave attenuation, erosion and flood reduction from storm events exacerbated by SLR

Adaptation: Protect critical habitats, kelp forests and coral reefs; ecosystem-based management
Benefits: Support fish and shellfish resources; promote ecosystem resilience; maintain and enhance carbon storage and biodiversity

Figure Box 14.7.1 | Climate hazard protection services provided by Nature-based Solutions

Through a capacity to evolve to keep pace with climate change, these approaches can impart self-sustaining and cost-efficient long-term protection in addition to serving as biodiverse, carbon sinks (Scyphers et al., 2011; Cheong et al., 2013; Temmerman et al., 2013; Rodriguez et al., 2014; Herr and Landis, 2016; Sasmito et al., 2016; Reguero et al., 2018). Nature-based adaptation is generally less expensive and strengthens over time, as compared with built infrastructure which *erodes* with time (*medium confidence*) (Narayan et al., 2016; Smith et al., 2017; Sutton-Grier et al., 2018). Analysis of the impacts of Hurricane Sandy determined that communities located behind wetlands experienced 20% less damage (Narayan et al., 2016). Coral reefs are providing 544 million USD yr^{-1} (Beck et al., 2018a) and mangroves 22 billion USD yr^{-1} in property protection for coastal communities in the USA and Mexico (Beck et al., 2018b). By 2030, flooding from changes in storms, SLR (based on RCP8.5) and increases in built infrastructure in the US Gulf Coast may result in net economic losses of

Box 14.7 (continued)

up to 176 billion USD, of which 50 billion USD could be avoided through implementation of nature-based measures including wetland and oyster reef restoration and other green infrastructure (see Box 14.4; Section 14.5.2; EPA, 2015b; Reguero et al., 2018).

Innovative approaches in Canada (Borsje et al., 2011; Spalding et al., 2014; Soto-Navarro et al., 2020) and the USA (Law et al., 2018; Buotte et al., 2019; Soto-Navarro et al., 2020) have led to social and environmental co-benefits and could address both future climate risk and long-standing social injustices (Hobbie and Grimm, 2020; Schell et al., 2020; Cousins, 2021). Effective nature-based adaptation requires a well-coordinated suite of adaptation efforts (e.g., assessment, planning, funding, implementation and evaluation) that is co-produced among stakeholders and across sectors (*high confidence*) (Millar and Stephenson, 2015; Kabisch et al., 2016; Dilling et al., 2019; Morecroft et al., 2019; Lavorel et al., 2020). Evaluating the efficacy of nature-based adaptation may become more tractable with more uniform guidelines for implementation (Scarano, 2017; Malhi et al., 2020; Seddon et al., 2020), and coordination in scaling-up local-level nature-based adaptation measures is likely to facilitate long-term success (Gao and Bryan, 2017).

Table Box 14.7.1 | Nature-based adaptation in North America

Sector	NbS actions	Benefits	References
Coasts	Conservation and restoration of barrier habitats, salt marshes, mangroves, coral and oyster reefs, sand dunes and river deltas; combined natural and built infrastructure (e.g., oyster reef in front of breakwall)	Wave attenuation; erosion and flood reduction from storm events exacerbated by SLR; novel, created habitats, connectivity; recreation, quality of life	Borsje et al. (2011); Scyphers et al. (2011); Cheong et al. (2013); Pinsky et al. (2013a); Temmerman et al. (2013); Ferrario et al. (2014); Möller et al. (2014); Rodriguez et al. (2014); Spalding et al. (2014); Yates et al. (2014); EPA (2015b); Grenier et al. (2015); Brandon et al. (2016); Herr and Landis (2016); Narayan et al. (2016); Sasmito et al. (2016); Ward et al. (2016); Aerts et al. (2018); Beck et al. (2018a); Morris et al. (2018b); Moudrak et al. (2018); Reguero et al. (2018); Sutton-Grier et al. (2018)
	Watershed approaches such as protecting and restoring forests and wetlands in coastal watersheds, adopting stream buffers in agricultural areas (see agriculture below)	Creation of a less flashy/variable hydrology; reduction in sediment, nutrient, hazardous chemical input to coastal waters and reduction in eutrophication and other water quality impairments, notably in deep waters where fish seek refuge from rising sea surface temperatures	Deutsch et al. (2015b); Boesch (2019); CENR (2010)
Aquaculture	Controlled culture of fish, bivalves, corals and other marine species	Enhancement and restoration of, and reduction in pressure on, wild species and ecosystems; restoration of threatened species such as coral reef species; storage of carbon	Froehlich et al. (2017); Reid et al. (2019); Theuerkauf et al. (2019)
Agriculture	Re-vegetation of stream buffer zones; planting of winter cover crops; wetland protection and restoration; agroforestry	Self-sustaining and cost-efficient long-term protection from soil erosion; maintenance and enhancement of crop yields; enhancement of carbon sinks; enhancement of biodiversity; reduction in nutrient input to coasts	CENR (2010); Boesch (2019); Seddon et al. (2020)
Urban areas	Replacement of impervious surfaces with permeable pavement, green space, parks, wetlands and green infrastructure (e.g., stormwater ponds, bioswales, rain gardens, green roofs); community gardens and urban forests; restoration of natural habitats	Reduction in urban heat island effects and air pollution; self-sustaining and cost-efficient long-term protection from flooding, erosion and SLR; enhancement of carbon sequestration biodiversity, habitat and connectivity; improvement in quality of life and human health benefits	Hobbie and Grimm (2020); Brown et al. (2021)

Box 14.7 (continued)

Sector	NbS actions	Benefits	References
Terrestrial	Forest conservation based on productivity and vulnerability to drought and fire; longer harvest rotations	Increase in carbon storage and biodiversity	Law et al. (2018); Buotte et al. (2020); Soto-Navarro et al. (2020); Mori et al. (2021)
	Forest thinning; prescribed burning; cultural burning	Reduction in wildfire risk and severity; increase in forest resilience to fire; reduction in forest drought stress; increase in carbon storage	See Box 14.2 and citations therein.
	Protection and restoration of natural forests	Regulation of stream flow; reduction in soil erosion; protection and enhancement of biodiversity	Lawler et al. (2020); Seddon et al. (2020)
	Beaver (*Castor canadensis*) reintroduction	Regulation of seasonal stream flow	McKelvey and Buotte (2018); Vose et al. (2018)
Freshwater	Forests to Faucets and other watershed restoration projects for stream and drinking water protection	Improvement in water quality; reduction in drinking water treatment costs; increase in, and regulation of, streamflow	Gartner et al. (2017); Claggett and Morgan (2018); Price and Heberling (2018)

Frequently Asked Questions

FAQ 14.4 | What are some effective strategies for adapting to climate change that have been implemented across North America, and are there limits to our ability to adapt successfully to future change?

Climate adaptation is happening across North America. These efforts are differential across sectors, scale and scope. Without more integrative and equitable approaches across broad scales, known as transformational adaptation, the continent may face limits to the future effectiveness of adaptation actions.

Across North America, progress in introducing climate adaptation is steady, but incremental. Adaptation is typically limited to planning, while implementation is often hindered by ‘soft’ limits, such as access to financial resources, disparate access to information and decision-making tools, the existence of antiquated policies and management frameworks, lack of incentives and highly variable political perceptions of the urgency of climate change.

Cities and other state and local entities are taking the lead in adaptation efforts, particularly in terms of mainstreaming the use of many approaches to adaptation. These approaches include a suite of efforts ranging from assessment of impacts and vulnerability (relative to individuals, communities, jurisdictions, economic sectors, natural resources, etc.), planning processes, implementation of identified strategies and evaluation of the effectiveness of these strategies. Other institutions (e.g., NGOs, professional societies, private engineering and architecture businesses) also are making significant progress in the adaptation arena, particularly at local to regional levels.

The water management and utilities sectors have made significant progress towards implementation of adaptation strategies using broad-based participatory planning approaches. Consideration of climate change is now folded into some ongoing watershed-wide planning efforts. An example is provided by the One-Water-One-Watershed (OWOW) approach followed by the Santa Ana Watershed Project Authority (SAWPA) in southern California. SAWPA is a joint powers authority comprising five regional water districts that provide drinking water to more than 6 million people as well as industrial and irrigation water across the 2400-square-mile watershed. The OWOW perspective focuses on integrated planning for multi-benefit projects and explicit consideration of the impacts of any planning option across the entire watershed. Planning is supported by stakeholder-driven advisory bodies organised along themes that consider a full suite of technical, political, environmental and social considerations. SAWPA provides member agencies with decision-support tools and assistance to implement water conservation policies and pricing regimes, and one member agency is an industry leader on potable water recycling.

The marine and coastal fisheries sector also has shown considerable progress in climate adaptation planning, particularly in terms of assessing impacts and vulnerability of fisheries. Along the Pacific Northwest coast of the USA and Alaska, seasonal and sub-seasonal forecasts of ocean conditions exacerbated by warming (e.g., O_2, pH,

Box FAQ 14.4 (continued)

temperature, sea ice extent) already have informed fisheries and aquaculture management. Similarly, forecasts and warnings have reduced human exposure to the increased risk of toxins from HABs in the Gulf of Mexico, the Great Lakes, California, Florida, Texas and the Gulf of Maine.

Professional organisations and insurance play an important part in mainstreaming climate adaptation. Government and private-sector initiatives can help address adaptation efforts through building-design guidelines and engineering standards, as well as insurance tools that reflect the damages from climate impacts. Through the identification of climate risks and proactive adaptation planning, the private sector can contribute to reducing risks throughout North America by securing operations, supply chains and markets.

Indigenous Peoples and rural community efforts across the continent show great potential for enhancing and accelerating adaptation efforts particularly when integrated with Western-based natural resource management approaches, such as cultural burning and other traditional practices that reduce the buildup of fuels, in addition to prescribed fire and mechanical thinning. In the agricultural sector, examples include planting and cultivation of culturally significant plants, as a traditional practice of soil conservation, in addition to food crops or in lieu of synthetic or mechanical soil treatments.

Future changes in climate (e.g., more intense heatwaves, catastrophic wildfire and post-fire erosion, SLR and forced relocations) could exceed the current capacity of human and natural systems to successfully adapt (or ‘hard limits’). The inclusion and equitable contribution of Indigenous Peoples and rural communities in decision-making and governance processes—including recognition of the interdependencies between cities and surrounding areas—increases the likelihood of building adaptive capacity at a pace that is commensurate with present and future climate-change risks.

Large-scale, equitable transformational adaptation likely will be required to respond to the growing rate and magnitude of changes before crossing tipping points where hard limits exist, beyond which adaptation may no longer be possible. Increasingly, there are calls for accelerating and scaling up adaptation efforts, in addition to aligning policies and regulatory legislation at multiple levels of government. Improved processes for adaptation decision making, governance and coordination, across sectors and jurisdictions, could enhance North America’s capacity to adapt to rapid climatic change. These actions include a focused societal shift, across governments, institutions and transnational boundaries, from primarily technological approaches to NbS that help foster changes in perception of risk and, ultimately, human behaviour.

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