14SM

North America
Supplementary Material

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Table of Contents

SM14.1 Table for 14.4 Indigenous Peoples and Climate Change

Table SM14.1 | Summary of the observed impacts and projected risks and adaptation for Indigenous Peoples in North America, with evidence assessed

Impact, risk and/or adaptation	References
Indigenous knowledge and science Indigenous knowledge and science are resources for understanding climate-change impacts and adaptive strategies (*very high confidence*).	Battiste and Henderson (2000); Houser et al. (2001); Maynard (2002); Trosper (2002); Davidson-Hunt and Berkes (2003); Hassol (2004); Simpson (2004); Barrera-Bassols and Toledo (2005); Mustonen (2005); Berkes et al. (2007); Dodson (2007); Cochran et al. (2008); Sakakibara (2008); Toledo et al. (2008); Turner and Clifton (2009); Wildcat (2009); Lemelin et al. (2010); Sakakibara (2010); Weatherhead et al. (2010); Alexander et al. (2011); McNeeley and Shulski (2011); Sánchez-Cortés and Chavero (2011); Colombi (2012); Ford (2012); McCarty et al. (2012); Campos et al. (2013); Cunningham Kain et al. (2013); Gearheard et al. (2013); Nancy and Spalding (2013); Sena and UN Permanent Forum on Indigenous Issues Secretariat (2013); Toledo (2013); Bennett et al. (2014); CTKW (2014); Intergovermental Panel on Climate Change (2014); Maynard (2014); Sena (2014); Gadamus et al. (2015); Kootenai Culture Committee (2015); Quispe and UNPFII (2015); UNGA (2015); Council of Athabascan Tribal Governments (2016); Daniel et al. (2016); Dockry et al. (2016); Ford et al. (2016); Johnson et al. (2016a); Johnson et al. (2016b); Kermoal and Altamirano-Jiménez (2016); Hiza-Redsteer and Wessells (2017); Merculieff et al. (2017a); Merculieff et al. (2017b); Raymond-Yakoubian and Angnaboogok (2017); UNGA (2017); Behe et al. (2018); David-Chavez and Gavin (2018); Ikaarvik (2018); Jantarasami et al. (2018); McGregor (2018); Nelson and Shilling (2018); Sheremata (2018); UNGA (2018); Bachelet (2019); Bering Sea Elders Group (2019); Billiot et al. (2019); Carter et al. (2019); FAQI (2019); Greenwood and Lindsay (2019); Ijaz (2019); Mikraszewicz and Richmond (2019); Ratima et al. (2019); Thompson et al. (2019); Tom et al. (2019); Donatuto et al. (2020); Ford et al. (2020); Gift Lake Métis Settlement (2020); Kenote (2020); Latulippe and Klenk (2020); Lewis et al. (2020); Metcalfe et al. (2020); Popp et al. (2020); Timler and Sandy (2020); Vogel and Bullock (2020); Atlas et al. (2021); BIA (2021b); Camacho-Villa et al. (2021); Cameron et al. (2021); Fast et al. (2021); Fischer et al. (2021); Hauser et al. (2021); Jones et al. (2021); Lake (2021); Yua et al. (2021)
Indigenous livelihoods and economies Current and projected climate-change impacts disproportionately harm Indigenous Peoples' livelihoods and economies (*very high confidence*).	Ford et al. (2006); ICC Canada (2008); Ellis and Brigham (2009); Ford (2009); Meakin and Kurtvits (2009); Swinomish Indian Tribal Community (2009); Hori (2010); Kronik and Verner (2010); Wesche and Chan (2010); Confederated Salish and Kootenai Tribes of the Flathead Reservation (2013); Cozzetto et al. (2013); Dittmer (2013); Ford et al. (2013); Grah and Beaulieu (2013); Lynn et al. (2013); St. Regis Mohawk Tribe (2013); Tam et al. (2013); The Navajo Nation Department of Fish and Wildlife et al. (2013); Barbaras (2014); Brubaker et al. (2014b); Brubaker et al. (2014c); Chapin et al. (2014); Donatuto et al. (2014); Nania et al. (2014); Parlee et al. (2014); Durkalec et al. (2015); Berner et al. (2016); Brinkman et al. (2016); Stults et al. (2016); Yakama et al. (2016); Lewis and Peters (2017); Medeiros et al. (2017); Melvin et al. (2017); Nyland et al. (2017); Petersen et al. (2017); Scott et al. (2017); Angel et al. (2018); Conant et al. (2018); Dupigny-Giroux et al. (2018); Great Lakes Indian Fish and Wildlife Commission (2018); Hori et al. (2018a); Hori et al. (2018b); Jantarasami et al. (2018); Markon et al. (2018); May et al. (2018); McGregor (2018); Oficina Internacional del Trabajo (2018); Wall (2018b); Agnew::Beck (2019); Heeringa et al. (2019); ITK (2019); Kapp (2019a); Khalafzai et al. (2019); Marushka et al. (2019); Shinbrot et al. (2019); Anderzén et al. (2020); Centre for Indigenous Environmental Resources et al. (2020); Cold et al. (2020); Hasbrouck et al. (2020); Human Rights Watch (2020); ICC Alaska (2020); Ross and Mason (2020b); Ross and Mason (2020a); Segal et al. (2020); Settee (2020); Tangen (2020); Gibson et al. (2021)
Indigenous Peoples' health 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*).	Norgaard (2007); Pfeiffer and Huerta Ortiz (2007); Pfeiffer and Voeks (2008); Sakakibara (2009); Bell et al. (2010); Swinomish Indian Tribe Community (2010); Riley et al. (2011); Vanderslice (2011); Ford (2012); Cozzetto et al. (2013); Doyle et al. (2013); EPA (2013); Jamestown S'Klallam Tribe and Adaptation International (2013); Redsteer et al. (2013a); Redsteer et al. (2013b); Voggesser et al. (2013); Brubaker et al. (2014c); Ford et al. (2014); Hanrahan et al. (2014); Cunsolo Willox et al. (2015); Bad River Band of Lake Superior Tribe of Chippewa Indians and Abt Associates Inc. (2016); Chief et al. (2016); Confederated Salish and Kootenai Tribes of the Flathead Reservation (2016); Gamble et al. (2016); Grand Traverse Band of Ottawa Chippewa Indians (2016); Norton-Smith et al. (2016); Puyallup Tribe of Indians (2016); Rosol et al. (2016); Yakama et al. (2016); Alexander et al. (2017); Scott et al. (2017); Udall and Overpeck (2017); Bell and Brown (2018); Blackfeet (2018); Campo Caap (2018); Chavarria and Gutzler (2018); Conant et al. (2018); Edwin and Mölders (2018); Gonzalez et al. (2018); Jantarasami et al. (2018); Kloesel et al. (2018); Markon et al. (2018); May et al. (2018); Meadow et al. (2018); Mihychuk (2018); Peacock et al. (2018); Ratelle et al. (2018); Reo and Ogden (2018); Rioja-Rodríguez et al. (2018); Stevenson (2018); Tom et al. (2018); Wilson (2018); Bisbal and Jones (2019); Christianson et al. (2019); EPA (2019); FAQI (2019); Horn and Webel (2019); ITK (2019); Lac du Flambeau (2019); Lee et al. (2019); Marks-Marino (2019c); Mashpee Wampanoag (2019); Norgaard and Tripp (2019); Peralta and Scott (2019); Ristroph (2019); Tlingit and Haida (2019); Billiot et al. (2020a); Billiot et al. (2020b); Cunsolo et al. (2020); Gobler (2020); Kirezci et al. (2020); Marks-Marino (2020); Martin et al. (2020a); Middleton et al. (2020a); Middleton et al. (2020b); Mottershead et al. (2020); Palinkas (2020); Stewart et al. (2020); Ute Mountain Ute Tribe (2020); Woo et al. (2020); Adams et al. (2021); Arsenault (2021); Donatuto et al. (2021); National Tribal Air Association (2021); Preece et al. (2021); Schlinger et al. (2021); United States Federal Emergency Management (2021); Walker (2021); Whyte et al. (2021a); Whyte et al. (2021b); Wiecks et al. (2021)

Impact, risk and/or adaptation	References
Climate-related disasters and extreme environmental events Indigenous Peoples are affected dramatically by climate hazards and other climate-related extreme environmental events (*very high confidence*).	Delta Environmental Services and Wilbur Smith Associates (2005); Knutson et al. (2007); Hennessy et al. (2008); ITF (2008); GAO (2009); Karl et al. (2009); Papiez (2009); Swinomish Indian Tribal Community (2009); Redsteer et al. (2010); Riley et al. (2011); Steinman and Vinyeta (2012); Ballard and Thompson (2013); Cohen et al. (2013); Cozzetto et al. (2013); Crimmins et al. (2013); Doyle et al. (2013); Jamestown S'Klallam Tribe and Adaptation International (2013); Madrigano et al. (2013); Redsteer et al. (2013a); Redsteer et al. (2013b); Shinnecock Indian Nation (2013); Southern Ute Indian Tribe and GAP Consulting LLC (2013); Voggesser et al. (2013); Brubaker et al. (2014a); Brubaker et al. (2014b); Johnson and Gray (2014); Maldonado et al. (2014); Nania et al. (2014); Druen et al. (2014); Thompson et al. (2014); DOE (2015); Golden et al. (2015); Maldonado (2015); Marino (2015); Chief et al. (2016); Citizen Potawatomi Nation et al. (2016); Confederated Salish and Kootenai Tribes of the Flathead Reservation (2016); Confederated Tribes of the Umatilla Indian Reservation (2016); Hoh Indian Tribe (2016); Jamestown S'Klallam Tribe (2016); Norton-Smith et al. (2016); Oneida Nation Pre-Disaster Mitigation Plan Steering Committee and Bay-Lake Regional Planning Commission (2016); Peterson et al. (2016); Port Gamble S'Klallam Tribe (2016 2021); Puyallup Tribe of Indians (2016); Yakama et al. (2016); Burkett et al. (2017); Keene (2017); Krueger (2017); McNeeley (2017); Patrick (2017); Quinault Indian Nation (2017); Wall (2017); Bronen et al. (2018); Carter et al. (2018); Conant et al. (2018); Crepelle (2018); Doyle et al. (2018); EPA (2018); GAO (2018); Goode (2018); Haynes et al. (2018); IHS (2018); Jantarasami et al. (2018); Kloesel et al. (2018); Maldonado (2018); Markon et al. (2018); May et al. (2018); McNeeley et al. (2018); Patrick (2018); Pershing et al. (2018); Redsteer et al. (2018); Wall (2018a); Collins et al. (2019); Dannenberg et al. (2019); Emanuel (2019); Jeo Consulting Group (2019); Kapp (2019b); La Jolla Band of Luiseno Indians (2019); Lac du Flambeau (2019); Marks-Marino (2019a); Marks-Marino (2019b); Marks-Marino (2019c); Mashpee Wampanoag (2019); McKinley et al. (2019); Pala Band of Mission Indians (2019); Ristroph (2019); Sharp (2019); Sioui (2019); University of Alaska Fairbanks Institute of Northern Engineering et al. (2019); Ute Mountain Ute Tribe and Wood Environment Infrastructure Solutions Inc (2019); Affiliated Tribes of Northwest Indians (2020); Bamford et al. (2020); Beym and Jones (2020); Billiot et al. (2020a); Billiot et al. (2020b); Centre for Indigenous Environmental Resources et al. (2020); Cheung and Frölicher (2020); Comardelle (2020); Congressional Research Service (2020); Cooley (2020); Crepelle (2020); Cunsolo et al. (2020); Fayazi et al. (2020); Hoell et al. (2020); LaDuke and Cowen (2020); Laufkötter et al. (2020); Low (2020); Lummi Indian Business (2020); Marks-Marino (2020b); McNeeley et al. (2020); NIFC (2020); NWAC (2020); Palinkas (2020); Port Gamble S'Klallam Tribe (2020 2021); Sauchyn et al. (2020); State of Alaska (2020a); State of Alaska (2020b); Thistlethwaite et al. (2020); Bridgeview Consulting LLC (2021); Cozzetto et al. (2021a); Cozzetto et al. (2021b); Donatuto et al. (2021); Gaughen et al. (2021); Indigenous Climate Action et al. (2021); Jurkowski et al. (2021); Maldonado et al. (2021); Marks-Marino (2021); Morales et al. (2021); Muckleshoot Tribal Council (2021); National Tribal Air Association (2021); Schlinger et al. (2021); United States Federal Emergency Management (2021); Walker (2021); Whyte et al. (2021a); Whyte et al. (2021b); Wiecks et al. (2021); Yellow Old Woman-Munro et al. (2021); Zambrano et al. (2021)
Indigenous self-determination and self-governance 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*).	Clinton (2000); Grossman (2008); Wildcat (2008); Doolittle (2010); Wilson and Smith (2010); McInerney-Lankford et al. (2011); Sorenson (2011); Kuslikis (2012); Parker and Grossman (2012); Campos et al. (2013); Kronk Warner and Abate (2013); Callison (2015); Warner (2015a); Warner (2015b); Maldonado et al. (2016); Angel et al. (2018); Dupigny-Giroux et al. (2018); Tribal Climate Adaptation Guidebook Writing Team et al. (2018); Whyte et al. (2018); Hepler and Kronk Warner (2019); National Congress of American Indians (2019); Reyes (2019); Thompson et al. (2019); Tribal Adaptation Menu Team (2019); AFN (2020); Centre for Indigenous Environmental Resources et al. (2020); Donatuto et al. (2020); Ferguson and Weaselboy (2020); Irlbacher-Fox and MacNeill (2020); Metcalfe et al. (2020); Sloan Morgan (2020); Whitney et al. (2020); BIA (2021a); Cozzetto et al. (2021a); Cozzetto et al. (2021b); Huntington et al. (2021); Jones et al. (2021); Maldonado et al. (2021); McClain (2021); Morales et al. (2021); Sawatzky et al. (2021); Singletary et al. (2021); STACCWG (2021); Whyte et al. (2021a); Whyte et al. (2021b); Wiecks et al. (2021); Wildcat et al. (2021)

SM14.2 Tables for Section 14.5.4 Food and Fibre

Table SM14.2 | Summary of observed impacts of, and adaptation to, climate change in agriculture in Mexico

Region	Impacted crop	Observed change	Comments	Adaptation	References
National	Soil (environmental enabler)	Droughts, reduced soil fertility	Temperature in soil will increase, suitability loss from 22 to 18% Soil erosion and degradation		Galloza et al. (2017)
National/south	All	ENSO has never been as variable as during the past few decades.			Li et al. (2013);
National	Wheat	(–5.5%) since 1980		increase planted area	Hernandez-Ochoa et al. (2018)
National	Maize (production)	Low precipitation during 1997–1998 led to a 25% decrease in the total production of maize		Use of genomic estimates for rapid breeding of drought-tolerant varieties; a shift in cultivation practices, particularly the planting time	Murray-Tortarolo et al. (2018)

Region	Impacted crop	Observed change	Comments	Adaptation	References
South (Oaxaca)	Maize	Changing rainfall patterns; soil had lost its ability to retain soil moisture	TK Traditional system that retains water (cajete)	Agroecological resilience, agrobiodiversity, minimise risk from climate and pests	Rogé and Astier (2015)
Central (Guanajuato)	Maize	Maximum temperature rise of 0.092°C yr^{-1} (1961–2009)	Urban and peri-urban agriculture	Change of crop, use of native seeds, incorporation of organic matter and reforestation with native species	Vélez-Torres et al. (2016)
Central (State of Mexico, Puebla, Veracruz)	Maize, wheat, barley		Integrates climate change, soil degradation and water balance scenarios	Two adaptation actions were evaluated: changing planting date and increase of organic mulches.	Monterroso-Rivas et al. (2018b)
Central (Guanajuato, Jalisco, State of Mexico, Michoacán and Querétaro)	Maize	T_{max} (0.8°C), T_{min} (0.74°C) Precipitation (131 mm) June and September Hailstorm increase in frequency	Seasonal climate changes coincide with the most vulnerable stage or flowering period of maize	Use of local, water-deficit-tolerant varieties, polycultives, opportune weeding or agroforestry	Altieri and Nicholls (2009); Mastachi-Loza et al. (2016)
Central (Veracruz)	Coffee	During 1980–2011 decrease in tonnes per ha harvested from 3.0 to 2.3 t/ha (–23%)			Loreto et al. (2017)
North and South America	Maize, soybean, wheat	72, 30 and 57%, respectively	During ENSO (same directional response of each crop for North America and South America)		Anderson et al. (2017)
Chiapas, Oaxaca, Veracruz	Coffee	Tendency of the average annual temperature of the principal coffee production states in Mexico: Chiapas, Oaxaca and Veracruz are the states evaluated from1985 to 2019. Since 2006, a marked increase in the temperature (over the average 24–25°C) has been observed, and it remains above average.	Climate driven instability in the flowering and fruit generation cycles and a rise in temperature and irregular rainfall has favoured the proliferation of *Hemileia vastatrix* (coffee rust) in coffee-growing areas >1400 m above sea level	Fundamental role of native biodiversity in *Hemileia vastatrix* management, agroforestry systems and organic production schemes; soil and plant nutrition for crop reinforcement	Torres Castillo et al. (2020)
Central (Veracruz)	Coffee	During 1980–2011 decrease in tons per ha harvested from 3.0 to 2.3 t/ha (–23%)			Loreto et al. (2017)
	Coffee	Droughts, heavy rains	Flowering reduction	Soil management	Manson (2018)

Note:
ENSO: El Niño–Southern Oscillation

Table SM14.3 | Projected impacts of climate change on agriculture in Mexico

Region	Crop	Projected impact (change in suitability, percentage of surface)	Models (GCMs) and Scenarios	Comment	References
Semiarid region of Central Mexico	Water	Decline of up to 9.16% in the available water for groundwater recharge and runoff	7 models; 2 scenarios 2050s and 2080s	B1 and A1B	Herrera-Pantoja and Hiscock (2015)
National	Soil	Soil moisture deficit, shift to the next drier regime	3 models; 2 scenarios (RCP4.5 and RCP8.5)	1.5°C warming scenario	Gomez Diaz et al. (2019)
National	Maize suitability	–57 to –2.4%	2 models (HADGEM2-ES and MPI-ESM-LR); 1 scenario (RCP8.5) by 2075–2099	Land suitability	López-Blanco et al. (2018)
National	Maize in agricultural land suitability	–18 to 5% (RCP4.5) –16 to 11% (RCP8.5)	3 models (GFDL, HAGDEM, and REA); 2 scenarios (RCP4.5 and RCP8.5)	Agricultural land suitability	Gómez Díaz et al. (2020)

Region	Crop	Projected impact (change in suitability, percentage of surface)	Models (GCMs) and Scenarios	Comment	References
National	Sorghum in agricultural land suitability	–16 to 12% (RCP4.5) –11 to 7% (RCP8.5)	3 models (GFDL, HAGDEM and REA); 2 scenarios (RCP4.5 and RCP8.5)	Agricultural land suitability	Gómez Díaz et al. (2020)
National	Wheat in agricultural land suitability	–34 to –23% (RCP4.5) –38 to –15% (RCP8.5)	3 models (GFDL, HAGDEM and REA); 2 scenarios (RCP4.5 and RCP8.5)	Agricultural land suitability	Gómez Díaz et al. (2020)
Central (Tlaxcala)	Barley	–16 to 2%	2 models; 3 scenarios (RCP4.5, RCP6.0, and RCP8.5)		Calderón-García et al. (2015)
Veracruz	Coffee				
Change (% in yields)					
National	Maize (production)	0.05 to –30%	14 models from the CMIP5 ensemble; 4 scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5)		Murray-Tortarolo et al. (2018)
North (Durango)	Maize	–55 to –70%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Central West (Jalisco, State of Mexico)	Maize	10 to –55%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099	Method includes climate change, soil degradation and water balance scenarios.	Montiel-González et al. (2017); Reyer et al. (2017); Monterroso-Rivas et al. (2018a); Arce Romero et al. (2020)
South (Oaxaca)	Maize	5 to –10%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
North (Zacatecas)	Beans	8 to –51%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Central (State of Mexico)	Beans	–80 to –100%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
North (Sonora)	Wheat	–28 to 2%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Central (Guanajuato, Puebla)	Wheat	–25 to –82%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099	Puebla includes climate change, soil degradation and water balance scenarios.	Monterroso-Rivas et al. (2018a); Arce Romero et al. (2020)
National	Wheat	–6. 9 to –7.9%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2050	CO_2 effect	Hernández-Ochoa (2018)
South (Chiapas, Campeche)	Soybean	–8 to 57%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Northeast (Tams)	Sorghum	–81 to 31%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Central (Guanajuato)	Sorghum	–60 to –14%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Central (State of Mexico, Hidalgo, Veracruz, Tlaxcala)	Barley	–92 to 56%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099	Tlaxcala includes economic impacts . Veracruz includes climate change, soil degradation and water balance scenarios.	Monterroso-Rivas et al. (2018a); Arce Romero et al. (2020)

Region	Crop	Projected impact (change in suitability, percentage of surface)	Models (GCMs) and Scenarios	Comment	References
Central (State of Mexico, Veracruz)	Potato	–61 to 2%	5 models; 2 scenarios (RCP4.5 and RCP8.5) 2015–2039, 2045–2069 and 2075–2099		Arce Romero et al. (2020)
Veracruz	Coffee		3 GCMs,		
Southeast (Tabasco)	Coffee	The mean potential yields would decrease by 41% by the year 2050 due to the effect of the increase in daytime temperatures on the maximum photosynthetic ratio.	An ensemble of 23 models; 3 scenarios (SRES A2, B1 and A1B)	Increase *Coffea canephora* P (robusta variety)	Navarro-Estupinan et al. (2018)
Veracruz	Coffee	–34%	3 models; 2 scenarios (RCP4.5 and RCP8.5)	Soil fertility and coffee production	Brigido and Herrera (2015)
		–7 to –10%	3 scenarios (A2, A1B, B1)	Includes soil and water balance	Rivera-Silva et al. (2013)

Table SM14.4 | Impacts to crops from climate-impact drivers from recent[a] greenhouse, field and modelling studies in North America

Climate-impact driver	Impact to crops	Location	References
Decreased irrigation water (simulated –25% reduction) for irrigated crops (projected)	Change in yield from 25% water supply reduction: alfalfa (–4%), apples (–4%), barley (–9%), broccoli (–0.5%), cauliflower (–0.3%), citrus (–1%), corn (–1.5%), cotton (–23.6%), grapes (–0.5%), lettuce (–1%), melons (–0.7%), onions (–0.2%), potatoes (–0.5%), sugar beets (–2.4%), wheat (–9.2%)	Southern mountain region, USA	Frisvold and Konyar (2012)
–50% water availability (greenhouse experiment)	Bell pepper (*Capsicum annuum* L.) (–65%)	Canada	Aladenola and Madramootoo (2014)
–50% water availability (deficit irrigation field experiment)	Onion (–22%)	Southern plains, USA	Leskovar et al. (2012)
Extreme heat: increase in daily maximum temperatures and heat waves (projected)	Maize (–18 to –27%) Cotton (–26 to –38%)	Southwest USA	Elias et al. (2018)
Increased ozone (+25%) Increased CO_2 (+250 ppm)	Snap bean: –24.4% (O_3) +6.5% (CO_2)	USA	Burkey et al. (2012)
Increased CO_2 (+250 ppm) Increased temp (+4°C) (greenhouse experiment)	Habanero pepper: changes in flowering and fruiting of habanero pepper in response to higher temperature and CO_2 CO_2: +32.4% Temperature: –36.4%	Mexico	Garruña-Hernández (2012)
Weather extremes impacting crops (observed)	Crop losses and insurance payments to compensate farmers for drought, heat, hail, frost and other extreme events	Midwest USA	Kistner et al. (2018); Reyes and Elias (2019)
Longer growing seasons and warmer winters (projected)	Increased weed and pest pressure	Northern USA	Wolfe et al. (2018)

Note:
(a) The literature is from 2012 to 2020.

Table SM14.5 | Projected changes in North American livestock

Climate-impact driver	Impact to livestock	Location	References
Extreme heat: increase in daily maximum temperatures and heatwaves	Livestock heat stress (according to the Temperature–Humidity index (THI)); slow livestock growth, reduced profitability, reduced fertility, increased parasites and pathogens	Southeastern USA, southern Great Plains, Northeast USA, Puerto Rico	St-Pierre et al. (2003); Key and Sneeringer (2014); Hristov et al. (2018); Ortiz-Colón et al. (2018)
Drought: increase in drought area, intensity and severity	Diminished water sources; diminished forage production	Varies across North America, varies seasonally and annually	Havstad et al. (2018)
Increased CO_2 concentrations	Reduced forage quality and benefit to invasive plant species	North Central USA	Derner et al. (2018)
Increased frequency and magnitude of weather extremes	Requires greater adaptive capacity to maintain viable production systems	Northern Great Plains	Derner et al. (2018)
Temperature and precipitation changes	Reduced net primary production and biomass for livestock feeding	Mexico	Monterroso Rivas et al. (2011)

Table SM14.6 | Observed and projected climate-change impacts on aquaculture

Region	Time period of impact/ reference period	Stressor	Taxa	Environment	Impact	Evidence/source	Type of study[a]	References
North America; USA and Canada	Past	OA	Molluscs (calcifying)	Marine	Growth, calcification, mortality, reduced attachment	Negative responses reported in the majority of experiments and in the industry; also agreement across climate change modelling in vulnerability and production assessments; *robust*	Review; current risk assessment; RCP8.5 (2100); future risk assessment	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019); Stewart-Sinclair et al. (2020)
Global	Experimental	OA	Finfish	Both	Metabolism	*Limited*	Review	Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019); Clements et al. (2020)
Global	Past	OA	Seaweed	Marine	Mixed: calcifiers *likely* impacted, non-calcifiers benefit	*Limited* (largely experimental); more solution/ mitigation than impact oriented in the literature of farmed production	Review and experimental	Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019); Reid et al. (2019)
North America; USA and Canada; global	Past, current, future (i.e., 2100)	Temperature increase	Finfish	Both	Growth and mortality	Lots of literature on the effects of temperature, but the exact response, positive or negative, is mixed; new ENSO/La Niña extreme temperature marine declines, cooler temperature production declines; freshwater no effect. Large-scale climatic effects on traditional Hawaiian fishpond aquaculture; new farmed cobia experiments of marine heatwaves and HAB, heatwaves driving impact of growth and feeding; *robust*	Review; time-series estimation; model projections; vulnerability assessments	McCoy et al. (2017); Froehlich et al. (2018); Ahmed et al. (2019); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019); Bertrand et al. (2020); Le et al. (2020)
North America; USA and Canada; global	Past, current, future (i.e., 2100)	Temperature increase	Mollusc	Both	Growth and mortality	Lots of literature on the effects of temperature, but the exact response, positive or negative, is mixed; *robust*	Review	Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019); Reid et al. (2019); Weiskerger et al. (2019)
North America; USA and Canada; global	Past, current, future (i.e., 2100)	Temperature increase	Seaweed	Marine	Growth and mortality	Some literature on the effects of temperature, but the exact response, positive or negative, is mixed; *robust*	Review	Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019); Reid et al. (2019)
Global/ regional	Past	Storms/ extremes	All	Freshwater	Growth and mortality	Extremes from current and past events (e.g., extreme ENSO events), *limited evidence* of impact on freshwater declines, aquaculture and vulnerability comparatively low	Vulnerability assessment; review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019)
Global/ regional	Past	Storms/ extremes	All	Freshwater	Growth and mortality	Extremes from current and past events (e.g., extreme ENSO events), *limited evidence* of impact on freshwater declines, aquaculture and vulnerability comparatively low	Vulnerability assessment; review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019)

Region	Time period of impact/ reference period	Stressor	Taxa	Environment	Impact	Evidence/source	Type of study[a]	References
Global/ regional	Past	Storms/ extremes	All	Freshwater	Growth and mortality	Extremes from current and past events (e.g., extreme ENSO events), *limited evidence* of impact on freshwater declines, aquaculture and vulnerability comparatively low	Vulnerability assessment; review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Froehlich et al. (2019)
Global/ regional	Past	SLR/floods	All	Marine	Growth and mortality	Increased events and vulnerability, especially low-lying pond systems and hatcheries	Vulnerability assessment; review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)
Global/ regional	Past	SLR/floods	Seaweed	Marine	Growth and mortality	*Limited evidence*	Review	Froehlich et al. (2018)
Global/ regional	Past	Storms/ extremes	Finfish	Marine	Growth and mortality	Extremes from current and past events (e.g., extreme ENSO events) have negatively impacted marine aquaculture.	Review	Bertrand et al. (2020); Sippel et al. (2020)
Global/ regional	Past							
Global/ regional	Past	Storms/ extremes	Mollusc	Marine	Growth and mortality	Extremes from current and past events (e.g., extreme ENSO events) have negatively impacted marine aquaculture.	Review	Froehlich et al. (2018); Sippel et al. (2020)
Global/ regional	Past	Storms/ extremes	Seaweed	Marine	Growth and mortality	*Limited evidence*	Review	Froehlich et al. (2018); Sippel et al. (2020)
Global	Future	Hypoxia	Mollusc		Growth and mortality	*Limited evidence*	Review	Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)
Global	Future	Hypoxia	Seaweed	Marine	Growth and mortality	*Limited evidence*	Review	Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)
Global	Future	HAB	Finfish		Growth and mortality	*Limited evidence*	Review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)
Global	Future	HAB	Mollusc		Growth and mortality	*Limited evidence*	Review	Handisyde et al. (2017); Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)
Global	Future	HAB	Seaweed	Marine	Growth and mortality	*Limited evidence*	Review	Froehlich et al. (2018); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019)

Notes:

OA: ocean acidification; SLR: sea level rise; HAB: harmful algal blooms; ENSO: El Niño–Southern Oscillation

(a) Experimental, risk/vulnerability assessment, adaptation evaluation; review, time-series estimation; model projections

Table SM14.7 | Adaptation in aquaculture

Sub-region	Time period of impact/ reference period	Type	Adaptation	Taxa	Agree-ment	Evidence	Language to use	Source
USA, Canada, global	Past (recent decade)	Aquaculture	Clear adaptive and integrated policy	All	*High*	Review of social and policy literature; surveys and interviews of stakeholders and experts; farm-level and community technical coping most common; focused on US ocean acidification (OA); knowledge sharing needed	Medium	Sanchez-Jerez et al. (2016); Froehlich et al. (2018); Brugère et al. (2019); Food Agriculture Organization of the United Nations (2019); Ford et al. (2020); Galparsoro et al. (2020)
Global	Experimental future conditions	Aquaculture	Genetic	Bivalve	*Medium*	*Limited* for OA; some evidence of long-term adaptive potential exists (e.g., epi-genetics, cryopreservation, selective breeding); some evidence of short-term coping (e.g., hybridisation and polyploidisation); evidence that technologies exist but uptake slow; linked consideration for disease and growth	Low	Sae-Lim et al. (2017); Food Agriculture Organization of the United Nations (2019); Reid et al. (2019); Clements et al. (2020)
Global	Past (recent decade) and future	Aquaculture	Genetic	Finfish	*Medium*	Temperature and associated extremes most studied; hybridisation and polyploidisation short-term coping; longer-term selective breeding and technologies exist but uptake slow; linked consideration for disease and growth	Medium	Food Agriculture Organization of the United Nations (2019)
North America, global	Current	Aquaculture	Mitigation	Farmed seaweed	*Emerging*	Local buffering of OA and hypoxia; high biophysical potential, cost and scale prohibitive	Low	Duarte et al. (2017); Froehlich et al. (2019)
North America, global	Current (2050)	Aquaculture	Set production goals	All	*High*	Aquaculture will fill climate-driven 'production gaps' in the future.	Medium	Food Agriculture Organization of the United Nations (2019); Gentry et al. (2019); Costello et al. (2020)
Global	2100	Aquaculture	Expansion	Finfish	*Medium*	Conditions to support finfish production in artic regions will expand.	Medium	Troell et al. (2017); Klinger et al. (2018); Froehlich et al. (2019)
Global	Future	Aquaculture		All		(a) Provide incentives (e.g., flexible leasing and permitting, increase access to 'crop' insurance) for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be 'climate-proofed' and relocated if necessary; (b) strengthen environmental impact assessments for coastal aquaculture activities to include the additional risks posed by climate change; (c) develop partnerships with regional technical agencies to provide support for development and monitoring of sustainable aquaculture		AR5 Table 30-2 Oceans chapter (Hoegh-Guldberg et al. 2014)

Table SM14.8 | Observed and projected climate-change impacts on fisheries

Climate driver	Type	Summary	Observed change	Ev-idence	Agree-ment	Summary	Projected changes
Climate shocks; variability	Flatfish	Climate change and extreme events have impacted fisheries.	Climate shocks reduce catch, revenue and county-level wages and employment among commercial harvesters in US-NE; climate variability 1996–2017 is responsible for a 16% (95% CI: 10–22%) decline in county-level fishing employment in New England; impacts are mediated by local biology and institutions (Oremus, 2019).	*Robust*	*High*		
Extreme heat	Multiple species	Climate change and extreme events have impacted fisheries.	In the EBS, GOA and N-CC, declines in fish biomass and shifts in distribution were four times higher and greater during MHWs than those of general warming over the same period; pelagic fish showed largest decrease in biomass (7%), as did sockeye salmon and California anchovy (Cheung and Frölicher, 2020).	*Robust*	*High*	Marine heatwaves amplify climate-change impacts on fisheries.	Doubling of impact levels is projected by 2050 among the most important fisheries species over previous assessments that focus only on long-term climate change (Cheung and Frölicher, 2020).
HAB; climate shocks	Shellfish	Climate change and extreme events have impacted fisheries.	Fishery closures during the 2014–2016 MHW and HAB event closed multiple fisheries along the west coast (US-NW, US-SW), differentially impacted small and large vessels with greatest impacts on small-vessel revenue and participation in the fishery; impacts were highest for ports in the N-CC region and least for fishing communities; diverse harvest portfolios and livelihoods supported adaptation (Jardine et al., 2020; Fisher et al., 2021).	*Robust*	*High*		
Mean temperature increase	Fish and shellfish	Climate change has caused declines in fisheries yield and productivity.	Changes in mean maximum sustainable yield of fisheries in multiple regions are associated with warming temperatures over the past century (2001–2010 to 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 and US-SE, while increases of 8–15% were observed in the US-NE and CA-CQ (Free et al., 2019).	*High*	*High*	Climate change will reduce fishery catches and North American subsistence resources; impacts will be higher under high-emission scenarios.	Estimated 17% decrease in (CA-WA) Arctic cod populations due to habitat loss by 2100 under RCP8.5 (high-emission scenario), and greater declines in catch under RCP8.5 relative to SSP2.6, but potential increases in abundance for other Arctic and subarctic species (Steiner (2019). In CA-BC, projected declines in abundance of key Indigenous subsistence resources (e.g., salmon, halibut, herring, rockfish and shellfish) are greater for RCP8.5 than RCP2.6 (–20.8 to –15.0%, respectively) (Weatherdon et al., 2016).
Mean temperature increase	Shellfish	Climate change has caused declines in fisheries yield and productivity.	Juvenile red king crab survival decreased significantly with exposure to higher temperatures; after 150 d, only 3% of crabs survived treatments of ambient temperature plus 4°C and 7.8 pH (Swiney et al., 2017). American Lobster abundances declined (78%) in southern 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 GOM, and 1997 and 2014 for southern New England) (Le Bris et al., 2018).			Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Modest increases (up to 10%) are projected in landings of CA-QC and CA-AT surf clams and shrimp under RCP2.6 by 2100, while projected declines in snow crab up to 16% (RCP2.6, RCP8.5); minor changes projected for lobster and scallop, while mussels projected to increase 21% (Wilson et al., 2020).

Climate driver	Type	Summary	Observed change	Evidence	Agreement	Summary	Projected changes
Mean temperature increase	Shellfish					Climate change will shift fisheries poleward and to depth.	Projected redistributions poleward and changes to access including decreases in access to shellfisheries in CA-QC (Wilson et al., 2020). Poleward distributional shifts (10.3–18.0 km per decade) are greater under RCP8.5 than RCP2.6 for multiple important Indigenous subsistence species in CA-BC and reduce availability of subsistence species by 28% under RCP8.5 by 2100), with impacts declining poleward (Weatherdon et al., 2016).
Multiple	Fish and shellfish					Climate change will impact fisheries livelihoods and increase fishery losses.	By end of century, under RCP2.6, higher are North American fish biomass (9.1%), fishery catch potential (9.7%) and fishery revenue (9.1%), while household costs are lower (by 3.4%) under low-emission scenarios (relative to RCP8.5); gains under lower emissions are greatest for US fisheries (Sumaila et al., 2019).
Multiple	Flatfish					Climate change will alter transboundary stocks.	Climate change (RCP8.5) is projected to shift the relative percentage of catch and profits for US–Canada transboundary stocks of Atlantic cod (higher in Canada than USA) and yellowfin flounder (Much higher in Canada than USA), but has little effect on Pacific halibut; effects are reduced or minimal under RCP2.6 (Palacios-Abrantes et al., 2020; Sumaila et al., 2020).
Multiple	Fish and shellfish					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Climate change drives declines in productivity and catch potential for 24 of 25 evaluated fishery species in Mexico with largest declines for abalone and pacific sardine (–35 and –44%, respectively). Impacts are greatest for artisanal species (Cisneros-Mata et al., 2019). Climate-driven changes to food webs and marine conditions are associated with declines in fish community biomass across all North American coasts except US-SW and the Canadian Arctic. Declines are greatest from CA-BC to the EBS (Carozza et al., 2019).
Multiple	Flatfish					Climate change will shift fisheries poleward and to depth.	Of flatfish in the North Atlantic and North Pacific, 67% are projected to shift poleward 39.1 km per decade under RCP8.5 (Cheung, 2018).
Multiple	Flatfish					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Declines in North American catch potential of flatfish species are projected under RCP8.5 for the EBS, GOA, GOMX, US-SE and US-NE (Cheung, 2018).

Climate driver	Type	Summary	Observed change	Ev-idence	Agree-ment	Summary	Projected changes
Multiple	Multiple species					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Projected biomass of historically large fisheries in the US-NA and CA-QC regions increased until ~2030 after which declines were observed; under RCP8.5, declines of 5–40% were projected by 2090 for most NAFO divisions; biomass increases between 20 and 70% were projected for Arctic and subarctic divisions with lower historical landings (Bryndum-Buchholz et al., 2020).
Multiple	Multiple species					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Assuming status quo management, declines are projected in multiple groundfish species in the EBS due to climate effects on fish and food webs with most groups near or below recent historical (1991–2017) biomass levels by 2080 (Whitehouse and Aydin, 2020).
Multiple	Multiple species					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Under RCP8.5, end-of-century (2080–2100 average) community spawner stock biomass, catches and mean body size decreased by 36% (±21%), 61% (±27%) and 38% (±25%), respectively. Climate variability drove uncertainty in projections for 85% of species (Reum et al., 2020).
Multiple drivers	Shellfish					Climate change will shift fisheries poleward and to depth.	Shifting distributions poleward and changes to access, including decreases in access to shellfisheries in CA-QC, are projected (Wilson et al., 2020).
Multiple drivers	All	Climate change has altered the distribution of fish and fisheries.	Species distributions have shifted poleward and phenology has shifted earlier with the strongest effects on bony fish (Poloczanska et al., 2016; Miller et al., 2018).	*Very high*	*High*		
Multiple drivers	Shellfish					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Declines in landings are twice as high under RCP8.5 as RCP2.6 and include 54, 48 and 42% declines in landings of lobster, sea scallop and northern shrimp, respectively, under RCP8.5 by 2090. Total shellfish landings (primarily that of snow crab) are projected to decline in CA-QC and CA-QT, and increase after 2050; declines under RCP8.5 are double those of RCP2.6 (Wilson et al., 2020). Climate change reduced the probability of observing recovery in simulations of blue king crab in the Bering Sea (Reum et al., 2019).

Climate driver	Type	Summary	Observed change	Evidence	Agreement	Summary	Projected changes
Multiple drivers (O_2, temperature, NPP)	Multiple					Climate change will reduce the yield and productivity of fish and shellfish with greater impacts at RCP8.5 than RCP2.6.	Projected declines of global catch of 3 mt $^{\circ}C^{-1}$ of GMWL with disparities in magnitude and direction across North American regions and the strongest benefits of RCP2.6 relative to RCP8.5 (>30%) along the coasts of Mexico; species turnover is more than halved between RCP8.5 and RCP2.6 (Cheung et al., 2016). Using the same modelling approach (DBEM), increases of 70% in catch potential in the Canadian Arctic were projected under RCP8.5 versus minimal increases under RCP2.6; however, the present catch potential is more than tenfold higher than actual catch and estimates are sensitive to model assumptions (Tai et al., 2019).
Multiple drivers (SLR, warming, OA)	Fisheries and fisheries Management					Climate change will increase fishery management challenges.	Multiple effects of climate change on fisheries (e.g., fish distributions, productivity, declines in catch, novel opportunities for new fisheries, changes in fish growth) can result in increased conflict drivers including changes in fishery yields, more or less fishers, opportunistic exploration, food insecurity, resource allocation trade-offs, changing fishery locations and changes to fishing livelihoods (Mendenhall et al., 2020).
Multiple drivers (temperature, OA)	Shellfish					OA will negatively impact future fisheries catch.	Climate change reduces the probability of observing recovery in projection simulations of blue king crab in the Bering Sea (Reum et al., 2019).
Ocean and lake acidification	Shellfish	OA has reduced yield and impacted fish and shellfish fisheries.	Survival of larval and juvenile red king crab (RKC) in the lab decreased 97–100% with decreasing pH (Long et al., 2013; Swiney et al., 2017).	*Limited*	*Medium*	OA will negatively impact future fisheries catch.	Ocean acidification reduces maximum sustainable yield, catch and profits of EBS Tanner crab in projection simulations, with projected declines >50% over 20 years due to OA impacts on larval hatching and survival (Punt et al., 2016). Projected economic impacts of OA on Bering Sea RKC fisheries are sensitive to assumptions around OA effects and global RKC prices (Seung et al., 2015); OA declines projected for some shellfisheries but are less than impacts of temperature (Wilson et al., 2020).
Ocean and lake acidification	Mollusc			*Limited*	*Medium*	OA will negatively impact future fisheries catch.	Projected OA conditions under RCP8.5 are anticipated to reach critical risk thresholds for mollusc harvests earlier in northern regions than southern areas, that is, between present day and 2030 in northern regions of North America (US-AK, US-NW and northern US-NE) and after 2099 in the Gulf of Mexico and Hawaiian Islands; combined risk is highest in the N-CC (Ekstrom et al., 2015).
Ocean and lake acidification	Groundfish	OA has reduced yield and impacted fish and shellfish fisheries.	There are no appreciable effects of pH on larval growth of walleye pollock in the lab (Hurst et al., 2013)	*Limited*	*Low*	OA will negatively impact future fisheries catch.	Population declines of 17% were projected due to temperature, while an additional 1% decline in Arctic cod populations by 2100 under RCP8.5 was due to the effects of OA (Steiner, 2019); OA influenced biological reference points used for setting target harvest limits for northern rock sole (Punt et al., 2021). Projected declines of flatfish declined up to 20–80% in California Current ecosystem projections with OA due to loss of shelled prey items.
Temperature	Shellfish					Climate change will shift fisheries poleward and to depth.	Projected increases in suitable thermal habitat for American lobster in Nova Scotia (CA-QC) are greater under RCP2.6 than RCP8.5 (note different base models used for each projection) (Greenan et al., 2019).
Temperature	Multiple species						

Climate driver	Type	Summary	Observed change	Evidence	Agreement	Summary	Projected changes
Temperature	Multiple species					Climate change will shift fisheries poleward and to depth.	Poleward shifts of ~20.6 km per decade are projected for multiple North American fisheries based on changes in thermal habitat under RCP2.6 and RCP8.5; changes were greater under RCP8.5 than RCP2.6 and largest along the west coast of North America (Morley et al., 2018).
Multiple drivers	Fish and shellfish		Seafood is an important source of nutrients and protein for Indigenous Peoples in CA-BC (Section 14.5.6; Marushka, 2019). Polices that incorporate nutrition in fisheries management are limited in North America (Kohen, 2021).	*Robust*	*High*	Climate change poses a risk to the health and nutrition of Indigenous Peoples in North America.	Projected climate change (2050) reduces essential nutrient intake by Indigenous Peoples in CA-BC by 21 and 31% under RCP2.6 and RCP8.5, respectively. Substitution of seafood with selected alternative non-traditional foods did not meet nutritional needs (Marushka et al., 2019); In CA-BC, projected declines in abundance of key Indigenous subsistence resources (e.g., salmon, halibut, herring, rockfish and shellfish) are greater for RCP8.5 than RCP2.6 (–20.8 to 15.0%, respectively) (Weatherdon et al., 2016).

Notes:

HAB: harmful algal bloom; NPP: net primary production; SLR: sea level rise; OA: ocean acidification; MHW: marine heatwave; NAFO: Northwest Atlantic Fisheries Organization
See Figure 14.1 for additional acronym definitions.

SM14.3 Supplemental Table of Case Studies for Section 14.6, Figure 14.11

Table SM14.9 | Key risk assessment for North America. Results were used to identify topic areas for burning embers and the full risk assessment of available literature; see corresponding section text for full assessment.

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
KR1		Bolsen and Shapiro (2018)				3			High
		Ding et al. (2011)							High
		Drews and Van den Bergh (2016)				3			High
		Morton et al. (2017)				0			High
		Supran and Oreskes (2017)				3			High
		van der Linden et al. (2015)							High
		Aklin and Urpelainen (2014)							High
KR2	Cities and infrastructure: cities	Castro and De Robles (2019)	Mexico: all		Current	2	3	3	High
	Terrestrial and freshwater: land species	EPA (2017)	USA: all	RCP4.5	2099 (cumulative costs)	3			Med
			USA: all	RCP8.5	2099 (cumulative costs)	3			Med

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
KR3	Health and communities: morbidity	Greene (2018)	California		During the 2012–2016 California drought	3	3	3	High[a]
			California		During the 2012–2016 California drought	3	3	3	High[a]
	Health and communities: mortality	Mach et al. (2019)	Global	RCP8.5	2100	2	2		Undetectable
	Conflict, crime, violence, security	Mach et al. (2019)	Global	RCP4.5	2100	1	1		Undetectable
	Terrestrial and freshwater: land species	Hope et al. (2016)	Canada: Ontario	RCP8.5	2070–2100	3			High
			Canada: Ontario	RCP2.6	2070–2100	1			Low
KR4	Oceans: coastal ecosystem	Vousdoukas et al. (2020)	USA: northwest	RCP4.5	2050				Medium
	Poverty and livelihoods: marine transportation	Smith and Stephenson (2013)	Arctic: all	RCP4.5	2040–2059				Medium
			Arctic: all	RCP8.5	2040–2059				High
KR5	Food and fibre: fisheries and aquaculture	Tables SM14.5–14.7	Potential risk evaluated in Tables 14.5–14.7						High[a]
	Terrestrial and freshwater: land species	Allen et al. (2015)	Global			2	3	3	Very high[a]
		Gauthier et al. (2015)	Canada: Ontario			2	2	3	High
		McIntyre et al. (2015)	USA: southwest			2	3	3	Very high[a]
		Weiskopf et al. (2019)				2	2	2	High[a]
		Zaifman et al. (2017)					2	2	Undetectable
	Terrestrial and Freshwater: Mountain ecosystem	Halofsky et al. (2020)	USA: northwest			2	2	2	High[a]
KR6	Energy resources: fossil resources	Bartos and Chester (2015)	USA: southwest		2040–2060	1	2	3	Medium
	Energy resources: hydro resources	Bartos and Chester (2015)	USA: northwest		2040–2060	1	2	3	Medium
	Terrestrial and freshwater: mountain ecosystem	Fell et al. (2017)	Global		Future	2	3	3	Very high[a]
	Water: freshwater resource	Bonsal et al. (2019)	Canada: all		Current and mid-century	1	1	1	Medium
		Brown et al. (2019)	USA: southwest	RCP4.5	2046–2070 and 2071–2095		2	2	Medium
			USA: southwest	RCP8.5	2046–2070 and 2071–2095		3	3	High
		Cook et al. (2019)	USA: southwest	RCP8.5	2048–2057				Low
		Duran-Encalada et al. (2017)	Mexico: northeast		2010–2080	3	3	3	High[a]
		Li et al. (2017)	USA: southwest	RCP4.5	2100	2	3	2	High

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulner-ability score	Exposure score	Risk assessment
KR6	Water: freshwater resource	Paredes-Tavares et al. (2018)	Mexico: north	RCP4.5	1980–2009 base period as compared with 2075–2099 future	2	3	3	Medium to high[a]
			Mexico: north	RCP8.5	1980–2009 base period as compared with 2075–2099 future	3	3	3	High[a]
		Schwarz (2018)	USA: southwest		2050	2	3	3	High
	Water: water quality	Chapra et al. (2017)	USA: all	RCP8.5	2050 (2040–2059)	3	3	2	Medium
			USA: all	RCP4.5	2090 (2080–2099)	3	3	2	High
			USA: all	RCP8.5	2050 (2040–2059)	2	3	2	Medium
			USA: all	RCP4.5	2090 (2080–2099)	2	3	2	High
		Duran-Encalada et al. (2017)	Mexico: northeast		2010–2080	3	2	2	High
KR7	Health and communities: morbidity	Cunsolo Willox et al. (2012)	Arctic: Canada		Lifetime of community members, conducted 2009–2010	3	2	3	High
		Cunsolo Willox et al. (2013)	Arctic: Canada		Lifetime of community members, conducted 2009–2010	3		3	High
		Dodd et al. (2018)	Arctic: Canada		Lived experiences of the 2014 wildfire season	3		3	High
		Durkalec et al. (2015)	Arctic: Canada			3		3	High
		Greene (2018)	California		During the 2012–2016 California drought	3	3	3	High
		Obradovich et al. (2018)	USA: all	RCP8.5	2002–2012	3		3	High
		Schwartz et al. (2017)	New York		2012–2016	3	3	2	High
		Vida et al. (2012)	Canada: Quebec		1995–2007	3		2	Medium
		Yusa et al. (2015)			1993–2013	3			High

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulner-ability score	Exposure score	Risk assessment
KR7	Health and communities: mortality	Burke et al. (2018)	USA: all	RCP8.5	2000 (reference period) to 2050 (projection time frame)	3		3	High
			Mexico: all	RCP8.5	2000 (reference period) to 2050 (projection time frame)	3		3	High
		Fernández-Arteaga et al. (2016)	Mexico: all		2005–2012	3	3		High
		Ford et al. (2018)	USA: northwest	RCP4.5	2100	3	3	3	High[a]
KR8	Food and fibre: fisheries and aquaculture	Gaichas et al. (2014)	USA: northeast	RCP8.5	2075–2100	2	2	3	High
	Health and communities: morbidity	Dodd et al. (2018)	Arctic: Canada		Lived experiences of the 2014 wildfire season	3		3	High
		Greene (2018)	California		During the 2012–2016 California drought	3	2	3	High
	Health and communities: mortality	Kohler et al. (2014)	USA: southwest		600–1760 CE	1	3	3	High
KR9	Cities and infrastructure: transportation	Espinet et al. (2016)	Mexico: northeast		2031–2050				High
			Mexico: northwest		2031–2050				Low
			Mexico: central		2031–2050				Low
			Mexico: southwest		2031–2050				Medium
			Mexico: southeast		2031–2050				Medium
	Poverty and livelihoods: marine transportation	Smith and Stephenson (2013)	Arctic: Canada	RCP8.5	2075–2100	3	1	2	High
	Poverty and livelihoods: recreation and tourism	Lithgow et al. (2019)	Mexico: all		Current/present	3	3	3	High[a]
KR10	Cities and infrastructure: cities	Dunning et al. (2012)	Mexico: southeast		100–900 CE	2	2	2	Medium
			Mexico: southwest		100–900 CE	2	2	2	Medium
		Hauer et al. (2016)	USA: All		2100	3	2	3	High
	Health and communities: morbidity	Harp and Karnauskas (2018)	Global		1979–2016	2	1	1	Medium
		Mares (2013)	USA: Midwest		1990–2009 monthly	1	1	1	Low
		Ranson (2014)	USA: all		1960–2009	1	2	2	Medium

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulner-ability score	Exposure score	Risk assessment
KR10	Poverty and livelihoods: recreation and tourism	Dundas and Haefen (2020)	USA: all	RCP2.6	2020–2049	1	1	3	Low
			USA: all	RCP4.5	2020–2049	1	1	3	Low
			USA: all	RCP8.5	2020–2049	1	1	3	Low
			USA: all	RCP2.6	2050–2079	1	1	3	Low
			USA: all	RCP4.5	2050–2079	1	1	3	Low
			USA: all	RCP8.5	2050–2079	1	1	3	Low
			USA: all	RCP2.6	2080–2099	1	1	3	Low
			USA: all	RCP4.5	2080–2099	1	1	3	Low
			USA: all	RCP8.5	2080–2099	1	1	3	Low
		Fisichelli et al. (2015)	USA: all	RCP4.5	2041–2060	2	1	3	Medium
			USA: all	RCP8.5	2041–2060	3	1	3	High
		Groulx et al. (2017)	Canada: Prairies			3	3	3	High
		Hestetune et al. (2018)	USA: Midwest	RCP4.5	2035	0	1		Low
		Hestetune et al. (2018)	USA: Midwest	RCP8.5	2035	0	1		Low
		Hewer and Gough (2019)	Canada: Ontario	RCP4.5	2050 (autumn only; September, October, November)	2	1	3	Low
		Jedd et al. (2018)	USA: northwest		Current	1			Low
		Rutty et al. (2015)	Canada: Ontario			3	1	3	Medium
			Canada: Ontario	RCP8.5	2050	3	3	3	High
	Poverty and livelihoods: recreation and tourism (continued)	Scott et al. (2019)	Canada: Ontario	RCP2.6	2050	3	3	3	High
			Canada: Ontario	RCP4.5	2050	3	3	3	High
			Canada: Ontario	RCP8.5	2050	3	3	3	High
			Canada: Ontario	RCP2.6	2080	3	3	3	High
			Canada: Ontario	RCP4.5	2080	3	3	3	High
			Canada: Ontario	RCP8.5	2080	3	3	3	High
		Scott et al. (2020)	Canada: Ontario	RCP4.5	2050	3	3	3	Very high
			Canada: Ontario	RCP8.5	2050	3	3	3	Very high
			Canada: Quebec	RCP4.5	2050	3	3	3	Very high
			Canada: Quebec	RCP8.5	2050	3	3	3	Very high
			USA: northeast	RCP4.5	2050	3	3	3	Very high
			USA: northeast	RCP8.5	2050	3	3	3	Very high
			Canada: Ontario	RCP4.5	2080	3	3	3	Very high

Key risk	Sector	References	Sub-region	Climate scenario	Time period	Hazard score	Vulner-ability score	Exposure score	Risk assessment
KR 10	Poverty and livelihoods: recreation and tourism (continued)	Scott et al. (2020)	Canada: Ontario	RCP8.5	2080	3	3	3	Very high
			Canada: Québec	RCP4.5	2080	3	3	3	High
			Canada: Québec	RCP8.5	2080	3	3	3	High
			USA: northeast	RCP4.5	2080	3	3	3	High
			USA: northeast	RCP8.5	2080	3	3	3	High
		Seekamp et al. (2019)	USA: southeast						Low
		Wilkins et al. (2018)	USA: northeast		2050		1	3	Medium
	Poverty and livelihoods: recreation and tourism (continued)	Wobus et al. (2017)	USA: all	RCP4.5	2050	3	3	3	High
			USA: all	RCP8.5	2050	3	3	3	High
			USA: all	RCP4.5	2090	3	3	3	High
			USA: all	RCP8.5	2090	3	3	3	High
			USA: all	RCP4.5	2050	3	3	3	High
			USA: all	RCP4.5	2090	3	3	3	High
			USA: all	RCP8.5	2050	3	3	3	High
			USA: all	RCP8.5	2090	3	3	3	High

Note:

(a) Weighting of risk assessment is based on confidence assessment of papers (i.e., level of agreement, robustness, quality of methods, etc.).

SM14.4 Detailed Methods for Burning Ember Diagrams

The burning embers diagrams in Chapter 14 outline risks associated with climate change as a function of global warming by degrees warming above pre-industrial levels. The first two burning embers, which cover water (Section 14.3) and economic sectors (Section 14.10), focus only on risk by global warming level without adaptation, whereas the third burning ember, which covers tourism activities (Section 14.11), includes risk without adaptation and risk with adaptation. The exclusion of risk with adaptation in the first two embers is due to a lack of available literature that would enable valid assessment. The method used to develop the embers was adapted from Zommers et al. (2020) to include an extensive analysis of key risks and the development of a risk assessment database that helped to reveal appropriate ember focus areas. Once focus areas for ember development were established within the author team, a formal expert elicitation protocol adapted from previous methods outlined in Zommers et al. (2020), Oakley and O'Hagen (2016) and Gosling et al. (2018) was used to develop threshold judgements on risk transitions. Figure SM14.1 outlines the formal five-step process used to generate the burning ember diagrams.

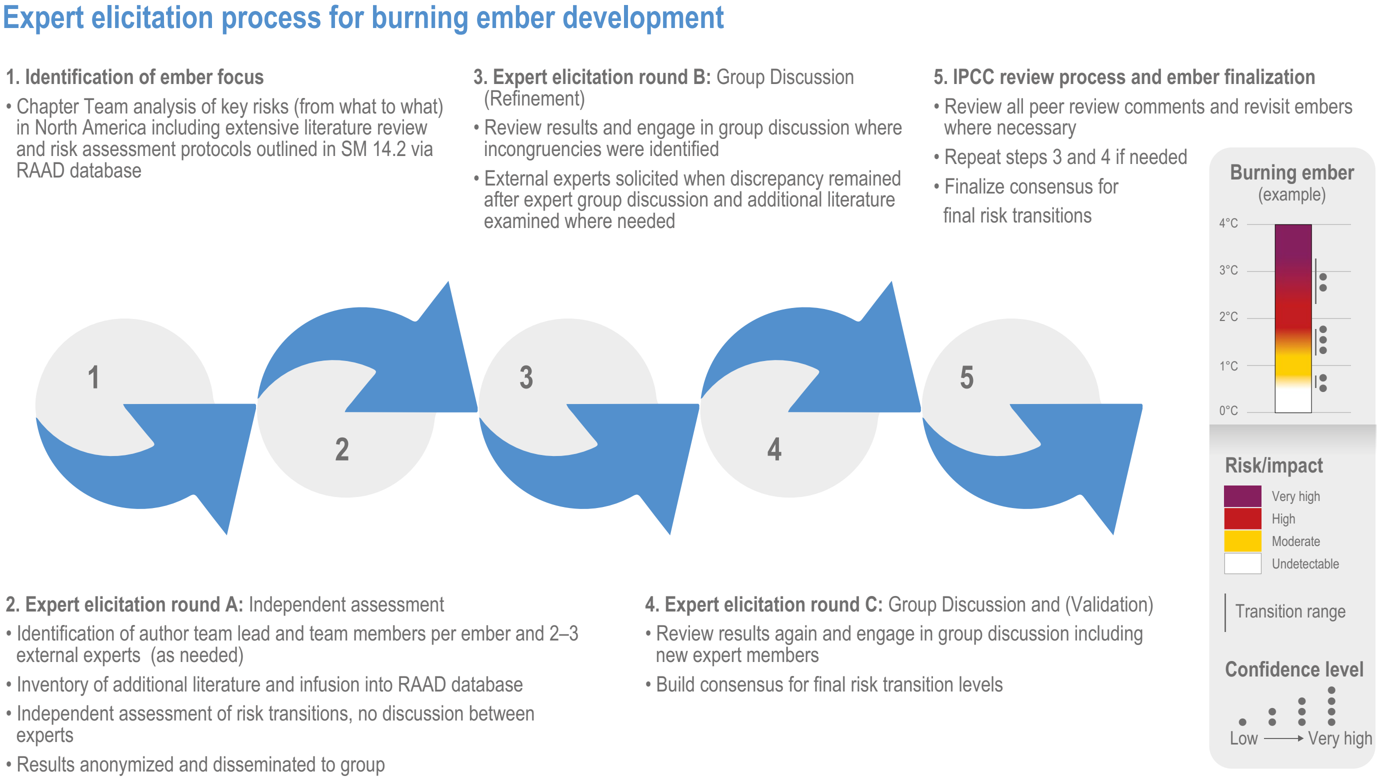
Using the expert opinion of a subset of the Chapter 14 author team (six authors across a range of expertise), we conducted a rapid risk assessment of sectors by WGI hazards in order to identify potential key risks. Authors were asked to identify the risk of a (climate change) caused by increase in a hazard in a given sector for all of North America. These key risks were then evaluated further during the assessment, and results of the rapid assessment are given in Figure 14.11. A subset of case studies from the rapid assessment were evaluated for burning ember diagrams. 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, not detected or positive (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted.

Based on chapter team risk assessment and key risk identification protocols (SM14.3) it was decided that existing literature would enable robust assessments of risks to (a) freshwater, (b) major economic sectors, and (c) key tourism activities across North America. References for the current and past assessments are listed in Table SM14.10 (also see Table SM14.9).

SM14.4.1 Freshwater

SM14.4.1.1 Water Scarcity

There is large literature on projected declines in water availability for portions of North America, primarily in the southwest USA, northern Mexico and the Canadian Prairies. Other research focuses on more widespread increases in water scarcity relative to projected future water demands (Brown et al., 2019). Assessment for this ember considered the latter type of scarcity while focusing primarily on the consequences of increased physical aridification. Papers providing explicit assessments of risks for different climate-change scenarios



Expert elicitation process for burning ember development

1. Identification of ember focus

- Chapter Team analysis of key risks (from what to what) in North America including extensive literature review and risk assessment protocols outlined in SM 14.2 via RAAD database

2. Expert elicitation round A: Independent assessment

- Identification of author team lead and team members per ember and 2–3 external experts (as needed)
- Inventory of additional literature and infusion into RAAD database
- Independent assessment of risk transitions, no discussion between experts
- Results anonymized and disseminated to group

3. Expert elicitation round B: Group Discussion (Refinement)

- Review results and engage in group discussion where incongruencies were identified
- External experts solicited when discrepancy remained after expert group discussion and additional literature examined where needed

4. Expert elicitation round C: Group Discussion and (Validation)

- Review results again and engage in group discussion including new expert members
- Build consensus for final risk transition levels

5. IPCC review process and ember finalization

- Review all peer review comments and revisit embers where necessary
- Repeat steps 3 and 4 if needed
- Finalize consensus for final risk transitions

Figure SM14.1 | Expert elicitation protocol for burning ember development

informed the calculations of risk transitions with respect to changes in global average temperatures. For Mexico, Paredes-Tavares et al. (2018) project increasing water-shortage conditions in the Rio Bravo basin over the 21st century, while Molina-Navarro et al. (2016) project roughly a 60% decline in streamflow by the end of the century for the Guadalupe River basin. For the Canadian Prairies, Bonsal et al. (2020) used multiple general circulation models (GCMs) and emissions scenarios to estimate projected increases in the frequency of severe droughts, and Dibike et al. (2017) assessed changes in the summer water balance (P-PET) across western Canadian river basins, further supporting projections of greater drought severity. Material for the USA includes an analysis of climate-change impacts on the major multi-purpose water projects operated by the US Bureau of Reclamation across the 17 western states (Bureau of Reclamation, 2021). Projections of aridification in the US-SW are summarised by Overpeck and Udall (2020). A study of the Missouri River basin documents the increasing role of extreme heat and higher evapotranspiration in driving low flows (Martin et al., 2020b), and an analysis by Prein et al. (2016) uses the observed relationship between specific weather types and droughts in the US-SW to support GCM projections of future US-SW drying due to poleward extension of the subtropical dry zones leading to increasing anticyclonic conditions.

SM14.4.1.2 Snow/Ice Decline, Streamflow and Summer Water

Many North American rivers are characterised by strong streamflow seasonality that is driven by the accumulation of snow and ice over the winter season, followed by spring and summer melting. Water use and management are tuned to this natural cycle. The likelihood of both early-season riverine flooding and low summer water availability will increase as warming erodes natural snow and ice reservoirs. This presents difficult challenges for management of human-constructed reservoirs that are operated for both winter flood protection and summer water deliveries. The risk assessment for this ember reflects these dual risks while following the available literature in emphasising the significance of low summer streamflows in areas heavily dependent on irrigated agriculture. Earlier snowmelt runoff is projected to harm small communities relying on traditional irrigation systems (acequias) in the US-SW by reducing the availability of both irrigation water and upland forage (Bai et al., 2019). Milly and Dunne (2020) evaluated the combined impacts of changes in snow albedo, precipitation and temperature on Upper Colorado River flows, to estimate annual flow reductions of 5–24% by mid-century under RCP4.5. Ray (2020) uses a decision scaling approach in combination with GCM projections to evaluate the likely future performance of California's Central Valley Water System across a range of potential future climate conditions. The approach finds a 93% likelihood of diminished water exports through the Sacramento–San Joaquin Delta to cities and farms in central and southern California by 2050. Ullrich (2018) assessed how a mid-century (2042–2046) drought in California would differ if the same dynamic conditions emerged as those for the 2012–2016 drought, finding much larger losses in snow water storage and total water availability. Bonsal (2020) evaluated the impacts of earlier snowmelt and declining glacier mass on seasonal streamflow patterns and water availability in western Canada. Late-century impacts under RCP4.5 are projected to include 60% summer streamflow declines on Vancouver Island, while winter flows will possibly double for the Fraser and Columbia rivers.

Table SM14.10 | Authors and references associated with the burning embers figures in Chapter 14

Burning ember	Main authors involved	Key references[a]
Freshwater	Kathleen Miller, Linda Mortsch, Dave Gutzler	Scarcity: Molina-Navarro et al. (2016); Prein et al. (2016); Dibike et al. (2017); Paredes-Tavares et al. (2018); Brown et al. (2019); Bonsal et al. (2020); Martin et al. (2020b); Overpeck and Udall (2020); Bureau of Reclamation (2021)
		Snow/ice decline, streamflow and summer water: Schwarz (2018); Ullrich et al. (2018); Bai et al. (2019); Bonsal et al. (2020); Milly and Dunne (2020); Ray et al. (2020)
		Pluvial and flash flooding: Emanuel (2017); Mahoney, et al. (2018); Prein, et al. (2017); Thistlethwaite, et al. (2018); Wobus, et al. (2019)
		Water quality: Chapra et al. (2017); Lee et al. (2018); Ballard et al. (2019); Coffey et al. (2019)
Economic sectors	Jackie Dawson, Libby Jewett, Kirstin Holsman, Michelle Rutty, Jeff Hicke	Energy and mining: Cruz and Krausmann (2013); Kinniburgh et al. (2015); Leong and Donner (2015); McFarland et al. (2015); Clark et al. (2017)
		Construction: Kinniburgh et al. (2015); Rogers et al. (2015); Schulte et al. (2016); Hsiang et al. (2017)
		Forestry: Brecka et al. (2018); D'Orangeville et al. (2018); Chaste et al. (2019)
		Agriculture: Lant et al. (2016); Janssens et al. (2020b)
		Fisheries: Beaugrand et al. (2015); Lam et al. (2016); Holsman et al. (2020)
		Transportation: EPA (2017); Palko and Lemmen (2017); Chinowsky et al. (2019); Koks et al.); Lemmen et al. (2021)
Tourism activities	Jackie Dawson, Michelle Rutty, Chris Lemieux	Nordic skiing and snowmobiling: Wobus et al. (2017); Chin et al. (2018)
		Alpine skiing: Dawson et al. (2009); Rutty et al. (2017); Scott et al. (2019); Scott et al. (2020)
		Beach tourism and coral reef snorkelling: EPA (2017); Groulx et al. (2017); Atzori et al. (2018); Lithgow et al. (2019); Seekamp et al. (2019)
		Parks and protected areas visitation: Fisichelli et al. (2015); Lemieux et al. (2015); Hestetune et al. (2018); Jedd et al. (2018); Wilkins et al. (2018); Hewer and Gough (2019); Dundas and Haefen (2020)

Notes:

(a) The North America risk assessment RAAD database also was utilised for all risk transition assessments (SM14.3; Table SM14.9). A summary of analysis is provided below. Other analysis notes are also available upon request.

SM14.4.1.3 Pluvial and Flash Flooding

Heavier precipitation events are projected for many parts of North America, increasing the potential for flooding, including flash flooding in areas distant from existing stream channels. Papers estimating projected damages from flooding and/or changes in precipitation intensity as a function of climate change were used to inform construction of this ember. Emanuel (2017) presents projections of end-of-century changes in the frequency of heavy precipitation events over the Houston, Texas, metropolitan area for the RCP8.5 scenario. Results indicate that the current 100-yr return frequency event would increase to a 1 in 5-yr frequency, while the frequency of extremely destructive rainfall akin to that produced by Hurricane Harvey would increase from an estimated 1 in 2000 year to a 1 in 100-year event. Thistlethwaite (2018) used an existing insurance-industry catastrophe model for Halifax, Canada, to estimate changes in damages that would be produced by increasingly heavy rainfall events. The study found that: '…average annual losses could increase by 137% by mid-century and 300% by late-century due to climate change alone. But increasing exposure and value of capital at risk could more than double those figures'. Prein (2017) examines future changes in total rain volume delivered by mesoscale convective systems (MCS) over North America, finding that increases in MCS size and maximum precipitation rates will combine to result in large increases in total rainfall and potential for flooding. Wobus (2019) calculates current and projected future expected annual flood damages (EAD) for hydrological basins across the continental USA (CONUS) based on current-day exposed assets and projected changes in return intervals for floods of various magnitudes. Increased expected damages occur in all regions, with the largest impacts in US-NE, US-MW, US-SP and US-NP: 'EAD from flooding typically increases by 25–50% under a 1°C warming scenario and in most regions more than double under a 3°C warming scenario'. Gaur and Simonovic (2018) assessed changes in the return frequency of major fluvial floods across Canada, focusing on current 100- and 250-year events based on multiple end-of-century GCM projections. They found increased frequencies for northern Canadian river basins, with current 100-year events becoming 1 in ~50-year events, while estimated frequencies tended to decrease for southern Canadian basins. A survey of methods for estimating probable maximum precipitation (PMP) for dam safety is presented by Mahoney (2018), concluding that: 'Multiple modeling studies have produced results…showing increases of 15 to 50% in PMP later in the 21st century'

SM14.4.1.4 Water Quality

The majority of the papers published on the impacts of climate change on water quality focus on the USA with results for individual and regional watersheds, and CONUS (see synthesis by Coffey et al., 2019; Paul et al., 2019). Coffey et al. (2019) provide an authoritative survey of the effects of climate drivers (e.g., temperature increase and more intense precipitation) on water quality (i.e., increase in issues related to nutrients, algal blooms, sediments, pathogens) and summarises climate-change assessments (primarily SRES scenarios and some RCPs) into maps of impacts for much of CONUS. This research provides a strong foundation for the linkage between current observed and modelled climate as well as the relationship to water quality and future impact-assessment modelling based on scenarios. Sinha (2019) produced an assessment of projected increase in nitrogen loading for CONUS for mid-century (2031–2060) and end of century (2071–2100). Results, given as the percentage of change in mean total nitrogen flux from the base period 1976–2005 (Figure SM14.1), were based on climate scenarios (all four RCPs) interacting with historical land use, and show the mean percentage increase in nutrient flux mid-century (5–9%) and end of century (9–15%). Chapra (2017) addressed the issue of harmful algal blooms (HABs) and reported on current conditions (i.e., the strong relationship between cyanobacteria growth and temperature) and assessed future impacts using RCP4.5- and RCP8.5-based scenarios from five GCMs. The 100,000 cells ml^{-1} threshold (WHO guidance) represents a 'very high' risk of harmful consequences to people. This assessment for CONUS (300 reservoirs and 10 natural lakes important for recreation) reported a projected increase from 0 d for the base period 1986–2005 to 10.4 d (RCP4.5) and 11.2 d (RCP8.5) for 2050, and for 2090 11 d (RCP4.5) and 18.2 d (RCP8.5). Wagena and Easton (2018) used multi-model climate scenarios to assess the effect on water quality in the Susquehanna River basin for the base period 1990–2014 and future scenario periods (2041–2065 and 2075–2099). Compared with the historical baseline and with no conservation practices, there were increases in flow and surface runoff linked with increases in mid-century total nitrogen export of 9% (4–14%) and sediment of 26% (9–60%), and late-century total nitrogen of 12% (5–20%) as well as sediment of 31% (14–72%). Average nitrate, dissolved phosphorus and total phosphorus export decreased–not a consistent finding across modelling assessments in the literature; see Coffey et al. (2019)–but reflects local hydrology, geology and land use. The water quality burning ember was developed using the studies discussed above, all using RCP scenarios with three of five based on CONUS assessments.

SM14.4.2 Economic Sectors

Risks to economic sectors and activities were sometimes assessed across all of North America within specific regions, and for specific crops or species (corn and soybean, cod and pollock). The assessment is informed by literature on economic damage projections (see Box 14.6; Cross-Working Group Box ECONOMIC in Chapter 16). However, these risks are not translated into estimates of economic damages and do not address interactions between sectors nor adjustments due to future shifts in demand that could amplify or moderate economic impacts across an economy. The economic impact of the changes in any given sector depends on the relative importance of that sector to a national, regional or local economy.

SM14.4.2.1 Energy and mining

Analysis was focused on several case studies (observed and modelled) in remote regions of operational mines (onshore oil fields in Mexico as well as Texas, Kansas and Oklahoma in the USA, Athabasca oil sands and mines in the northern and Prairie regions in Canada) (Cruz and Krausmann, 2013; Leng, 2015; OCCIAR 2015; Clark, 2017) and urban and rural regions of energy generation and transmission (northwest, northeast and southeast USA) (Kinniburgh et al., 2015; McFarland et al., 2015). Increased average temperature will lead to an increase in cooling degree days (which will outweigh the decrease in heating degree days), creating more pressure on energy systems to meet peak demands (*high confidence*). In turn, costs will increase (both in terms of production and supply, transmission and energy prices for consumers) *(high confidence*). Changes in hydrological regimes will have negative implications (e.g., decreased streamflow, flooding, storm surges, SLR) for energy infrastructure and generation in the future (*medium confidence*). Elevated temps diminish thermal power plant efficiency and capacity (including transmission lines) (*medium confidence*).

SM14.4.2.2 Construction

Existing literature is mostly focused on the USA and suggests that warming temperatures will reduce labour productivity (*medium confidence*) (Kinniburgh et al., 2015; Rogers et al., 2015; Schulte et al., 2016) and could negatively impact the health and well-being of workers (Hsiang et al., 2017) especially in the southern USA and Mexico (*medium confidence*) (also see Dong et al., 2019).

SM14.4.2.3 Forestry

Forestry in North America will be disproportionately impacted by geographic region. Analysis here is focused on case studies of the USA, eastern Canada, northern Canada and the Boreal Forest, including changes due to biome shifts, reduced productivity, drought events, insects, elevated ozone levels and fire for forestry. Changes in the quality and quantity of timber yields are expected whereby total yield could potentially increase until 2°C warming in conjunction with increased CO_2 and fertilisation, but the quality could decrease depending on the extent of disturbance from insects, drought and extreme events (*medium confidence*) (Attavanich and McCarl, 2014; Tian et al., 2016; Brecka et al., 2018; D'Orangeville et al., 2018; Chaste et al., 2019). After 2°C warming, most models reveal a reversal of total yield trends and continuation of potential reductions in yield quality exacerbated by reductions in water availability and increased disturbance events from fire, insects and other events (*medium confidence*) (Beach et al., 2015; McKenney et al., 2016; D'Orangeville et al., 2018; Chaste et al., 2019).

Table SM14.11 | Burning ember risk transitions for freshwater resources

	Risk transition	Global mean surface temperature change above pre-industrial levels (°C)		Confidence
Snow and ice decline (seasonal flows)	Undetectable to moderate	Min	0.6	*Medium*
		Max	0.9	
	Moderate to high	Min	1.2	*Medium*
		Max	2	
	High to very high	Min	3.2	*Medium*
		Max	4	
Heavy precipitation (flooding)	Undetectable to moderate	Min	0.9	*Medium*
		Max	1.5	
	Moderate to high	Min	2.5	*Medium*
		Max	3	
	High to very high	Min	3.7	*Medium*
		Max	4	
Water quality impacts	Undetectable to moderate	Min	0.20	*Medium*
		Max	1.30	
	Moderate to high	Min	1.45	*Medium*
		Max	2.90	
	High to very high	Min	2.95	*Medium*
		Max	4.20	

SM14.4.2.4 Agriculture

Similar to forestry in North America, agricultural crop yields and quality will be highly dependent on local geography and vary across the region. Warming temperatures and lack of freshwater availability are key hazards for crop production and can lead to economic loss. Analysis here is focused on corn and soybeans, which are two of the largest crops in North America (Lant et al., 2016). Modelling studies indicate that high risk to the agricultural sector begins just before 2°C warming, which is expected to occur mid-century and beyond (*medium confidence*). The high relative importance of agriculture to the North American economy and the role food exports play in the global food system was considered in the risk transition analysis (see Janssens et al., 2020a).

SM14.4.2.5 Fisheries

Risk transition analysis was focused on cod and pollock species in the Bering Sea under scenarios that include status quo ecosystem-based measures including a limit on total groundfish yields (Holsman et al., 2020). These fisheries represent the largest (pollock), and one of the most valuable (Pacific cod), fisheries in the USA. Warming temperatures and change in sea ice, circulation and shifts in trophic pathways to less energy-efficient food chains (Huntington et al., 2020; Suryan et al., 2021) were used to drive changes in survival (predation), growth and recruitment, as well as subsequent catch, under future scenarios.

SM14.4.2.6 Transportation

The focus of this assessment was on road (including ice roads in the Arctic) and rail and transportation infrastructure such as bridges, airstrips, pipelines and port facilities. Extreme events, warming, storm surge, flooding and SLR are expected to present high risks to transportation infrastructure, especially in coastal and Arctic areas of North America, by 2°C global warming (EPA, 2017; Chinowsky et al., 2019; Koks et al., 2019). North America is a large geographic region that relies heavily on transportation infrastructure for economic sustainability as well as health and well-being. Near-term impacts to transportation infrastructure are expected to be incremental and, albeit expensive to repair, are not anticipated to present irreversible or catastrophic risks. However, in the absence of strong adaptation planning, transportation-related infrastructure will be at high risk before 4°C global warming and could amount to hundreds of billions of USD in needed repairs (EPA 2017; Palko and Lemmen, 2017; Chinowsky et al., 2019; Lemmen et al., 2021; also see Koetse and Rietveld, 2009; Markolf et al., 2019).

SM14.4.3 Tourism Activities (with and without adaptation)

SM14.4.3.1 Nordic Skiing and Snowmobiling

Nordic skiing and snowmobiling are at the highest risk to climate change compared with other tourism activities considering that there are hard limits to adaptation for participating in the activity. Reduction in natural snowfall and increased precipitation events falling as rain

Table SM14.12 | Burning ember risk transitions for economic sectors in North America

Name	Risk transition	Global mean temperature change (°C)		Confidence
Agriculture	Undetectable to moderate	Min	0	*Low*
		Max	1	
	Moderate to high	Min	1	*Medium*
		Max	1.6	
	High to very high	Min	4.2	*Medium*
		Max	6	
Forestry	Undetectable to moderate	Min	0	*High*
		Max	1.5	
	Moderate to high	Min	1.7	*Medium*
		Max	2	
	High to very high	Min	2.2	*Low*
		Max	4	
Tourism	Undetectable to moderate	Min	0.5	*High*
		Max	0.9	
	Moderate to high	Min	1.7	*High*
		Max	2.2	
	High to very high	Min	2.3	*Low*
		Max	3.9	
Transportation	Undetectable to moderate	Min	0.8	*High*
		Max	1.1	
	Moderate to high	Min	1.8	*Medium*
		Max	2.2	
	High to very high	Min	2.5	*Low*
		Max	3.8	
Fisheries	Undetectable to moderate	Min	1.1	*High*
		Max	1.8	
	Moderate to high	Min	2	*Medium*
		Max	2.5	
	High to very high	Min	3	*Medium*
		Max	4.2	
Energy and mining	Undetectable to moderate	Min	0	*Medium*
		Max	1.1	
	Moderate to high	Min	1.5	*Low*
		Max	2.5	
	High to very high	Min		Does not reach this threshold
		Max		
Construction	Undetectable to moderate	Min	0	*Medium*
		Max	1.5	
	Moderate to high	Min		Does not reach this threshold
		Max		
	High to very high	Min		Does not reach this threshold
		Max		

will severely limit nordic skiing and snowmobiling activities. Chin et al. (2018) project the following season length reductions: RCP4.5, 2050s (1.5°C) = 14 d and RCP4.5, 2080s (2°C) = 13 d; RCP8.5, 2050s (1.8°C) = 10 d and RCP8.5, 2080s (4°C) = 5 d. Wobus et al. (2017) project the following snowmobiling season lengths: 139 of 247 (56%) sites would have a snowmobile season of <75 d. RCP4.5, 2050s (1.5°C) = 179 of 247sites (72%) would have <75 d and RCP4.5, 2080s (2°C) = 192 of 247 (78%) sites would have <75 d; RCP8.5, 2050s (1.8°C) = 190 sites of 247 (77%) would have <75 d and RCP8.5, 2080s (4°C) = 228 of 247 (92%) sites would have <75 d.

SM14.4.3.2 Alpine Skiing

There is high agreement that winter/snow-based tourism is already experiencing negative impacts from climate change even with adaptation efforts through machine-made snow. As conditions warm, further impacts are anticipated given the high dependence on natural snowfall and low temperatures (e.g., for snowmaking, snow farming, etc.). High-altitude mountains are not as impacted as low-lying resorts (of which there are more) and we are already seeing impacts (e.g., resort closures, shortened season lengths, etc.). The threshold for economic viability is a 100-d season length in North America (Scott et al., 2020), and this was used to assess overall risk with and without adaptation. Making machine-made snow is economical up to a 5°C temperature increase for 171 ski areas in Ontario, Quebec and the northeast USA, even with advanced snowmaking, as only 29 ski areas in Quebec and high-elevation areas of the northeast USA will be able to maintain a 100-d ski season (Scott et al., 2020).

SM14.4.3.3 Beach Tourism and Coral Reef Snorkelling

Impacts on beach and coral reef tourism are highly location dependent. There is limited literature linking climate change and beach tourism specifically, but many papers outline impacts on coral reefs, coastal regions and tourism generally that can be assessed collectively in order to understand sector risks. Based on this literature, Mexico is at high risk (e.g., coastal squeeze and flooding) (Litgow, 2019), with the USA at risk to coral bleaching. 'Extensive loss of shallow corals is projected by 2050s for major US reef locations [South Florida, Puerto Rico]...near complete loss by 2100...modest loss in Hawaiian coral cover with declines from 38% in 2010 to 11% by 2050 with further declines thereafter' (EPA, 2017). Loss is greater for RCP8.5 compared with RCP4.5. Demand may diminish with proposed adaptation strategies because it can reduce perceived naturalness (e.g., glacier tourism, beach tourism, etc.) (Groulx et al. 2017; Atzori et al., 2018; Seekamp et al., 2019).

SM14.4.3.4 Parks and Protected Areas Visitation

Adaptation options for parks and protected areas are numerous, but it has been found that intrusive structures or infrastructure limiting access to natural environments is undesirable for tourists and therefore may have limited effect in impacting future visitation (Lemieux et al., 2015). The impact of climate change on nature-based tourism (e.g., parks) and outdoor recreation in protected areas is dependent on geographic location. Overall, it is widely agreed that shoulder seasons (spring and autumn) will improve as temperatures warm and increase the tourism season; however, increased precipitation and storm events, particularly in spring, could limit opportunities for longer seasons (e.g., Wilkins et al., 2018; Hewer and Gough, 2019; Dundas and Haefen, 2020). It is also possible that the summer season could be longer and more ideal (particularly in upper-latitude locations) but decline in southern and mid-latitude locations (as it becomes 'too hot') (e.g., Fisichelli et al., 2015) or where there is increased risk for drought (Jedd et al., 2018) and fire (e.g., Hestetune et al., 2018). Time-series analysis of climate and visitation data for US-NW national parks (1991–2012) reveal that visitors are more sensitive to extreme dry (drought) conditions, although findings are mixed (e.g., during a climatically dry season, visitor numbers declined in Yellowstone in 2001 but increased in 2012) (Jedd et al., 2018). Fisichelli (2015) suggests that as temperatures increase, the overall growth in visitor numbers across the parks system is projected to increase (8–23%), noting that visitation strongly declines at temps >25°C (which represents a small portion of parks across the system). Wilkins (2018) showed, through regression analysis between weather variables and tourism spending in Maine (USA), that increasing temperatures is an opportunity for increased tourism spending in summer and autumn.

Table SM14.13 | Burning ember risk transitions for tourism activities in North America

Nordic skiing and snowmobiling				
	Risk transition	Global mean temperature change (°C)		Confidence
Without adaptation	Undetectable to moderate	Min	0.2	*High*
		Max	0.5	
	Moderate to high	Min	0.8	*High*
		Max	1.5	
	High to very high	Min	1.8	*Low*
		Max	2	
With adaptation	Undetectable to moderate	Min	0.2	*High*
		Max	0.5	
	Moderate to high	Min	0.8	*High*
		Max	1.5	
	High to very high	Min	1.8	*Low*
		Max	2	
Alpine skiing				
	Risk transition	Global mean surface temperature change (°C)		Confidence
Without adaptation	Undetectable to moderate	Min	0.5	*High*
		Max	0.8	
	Moderate to high	Min	1.2	*Medium*
		Max	1.8	
	High to very high	Min	2.5	*Medium*
		Max	3	
With adaptation	Undetectable to moderate	Min	0.5	*High*
		Max	1.1	
	Moderate to high	Min	2	*High*
		Max	2.5	
	High to very high	Min	3	*Medium*
		Max	4	
Beach tourism and coral reef snorkelling				
	Risk transition	Global mean surface temperature change (°C)		Confidence
Without adaptation	Undetectable to moderate	Min	0.5	*High*
		Max	1.1	
	Moderate to high	Min	2.5	*Low*
		Max	3	
	High to very high	Min	3.2	*Low*
		Max	5.5	

Nordic skiing and snowmobiling				
With adaptation	Undetectable to moderate	Min	0.8	*High*
		Max	1.1	
	Moderate to high	Min	3	*Medium*
		Max	3.5	
	High to very high	Min	3.5	*Low*
		Max	6	
Parks and protected areas visitation				
	Risk transition	Global mean surface temperature change (°C)		Confidence
Without adaptation	Undetectable to moderate	Min	0.5	*Medium*
		Max	1.1	
	Moderate to high	Min	2	*Low*
		Max	3	
	High to very high	Min	3.5	*Low*
		Max	6	
With adaptation	Undetectable to moderate	Min	0.5	*Medium*
		Max	1.1	
	Moderate to high	Min	2	*Low*
		Max	3	
	High to very high	Min	3	*Low*
		Max	5	

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