12 Central and South America

Coordinating Lead Authors: Edwin J. Castellanos (Guatemala), Maria Fernanda Lemos (Brazil)

Lead Authors: Laura Astigarraga (Uruguay), Noemí Chacón (Venezuela), Nicolás Cuvi (Ecuador), Christian Huggel (Switzerland), Liliana Miranda (Peru), Mariana Moncassim Vale (Brazil), Jean Pierre Ometto (Brazil), Pablo L. Peri, (Argentina), Julio C. Postigo (USA/Peru), Laura Ramajo (Chile/Spain), Lisandro Roco (Chile), Matilde Rusticucci (Argentina).

Contributing Authors: Júlia Alves Menezes (Brazil), Pedro Borges (Venezuela), Jhonattan Bueno (Venezuela), Francisco Cuesta (Ecuador), Fabian Drenkhan (Peru), Alex Guerra (Guatemala), Valeria Guinder (Argentina), Isabel Hagen (Switzerland), Jorgelina Hardoy (Argentina), Stella Hartinger (Peru), Gioconda Herrera (Ecuador), Cecilia Herzog (Brazil), Bárbara Jacob (Chile), Thais Kasecker (Brazil), Andrea Lampis (Colombia/Brazil), Izabella Lentino (Brazil), Luis C. S. Madeira Domingues (Brazil), José Marengo (Brazil), David Montenegro Lapola (Brazil), Ana Rosa Moreno (Mexico), Julia de Niemeyer Caldas (Brazil), Eduardo Pacay (Costa Rica/Guatemala), Roberto Pasten (Chile), Matias Piaggio (Uruguay), Osvaldo Rezende (Brazil), Alfonso J. Rodriguez-Morales (Colombia), Marina Romanello (Argentina/UK), Sadie J. Ryan (USA/UK), Anna Stewart-Ibarra (USA/Ecuador), María Valladares (Chile/Spain)

Review Editors: Carlos Méndez (Venezuela), Avelino Suarez (Cuba)

Chapter Scientist: María Valladares (Chile/Spain)

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Executive Summary

Vulnerability and observed impacts:

Central and South America (CSA) are highly exposed, vulnerable and strongly impacted by climate change, a situation amplified by inequality, poverty, population growth and high population density, land use change particularly deforestation with the consequent biodiversity loss, soil degradation, and high dependence of national and local economies on natural resources for the production of commodities (*high confidence*[1]). Profound economic, ethnic and social inequalities are exacerbated by climate change. High levels of widespread poverty, weak water governance, unequal access to safe water and sanitation services and lack of infrastructure and financing reduce adaptation capacity, increasing and creating new population vulnerabilities (*high confidence*). {12.1.1, 12.2, 12.3, 12.5.5, 12.5.7, Figure 12.2}

The Amazon forest, one of the world's largest biodiversity and carbon repositories, is highly vulnerable to drought (*high confidence*). The Amazon forest was highly impacted by the unprecedented droughts and higher temperatures observed in 1998, 2005, 2010 and 2015/2016, which are attributed partly to climate change. This resulted in high tree mortality rates and basin-wide reductions in forest productivity, momentarily turning pristine forest areas from a carbon sink into a net source of carbon to the atmosphere (*high confidence*). Other terrestrial ecosystems in CSA have been impacted by climate change, through persistent drought or extreme climatic events. The combined effect of anthropogenic land use change and climate change increases the vulnerabilities of terrestrial ecosystems to extreme climate events and fires (*medium confidence*). {12.3, 12.4, Figure 12.7, Figure 12.9, Figure 12.10}

The distribution of terrestrial species has changed in the Andes due to increasing temperature (*very high confidence*). Species have shifted upslope, leading to range contractions for highland species and range contractions and expansions for lowland species, including crops and vectors of diseases (*very high confidence*). {12.3.2.4}

Ocean and coastal ecosystems in the region, such as coral reefs, estuaries, salt marshes, mangroves and sandy beaches, are highly sensitive and negatively impacted by climate change and derived hazards (*high confidence*). Observed impacts include the reduction in coral abundance, density and cover in Central America (CA), northwestern South America (NWS) and northeastern South America (NES) and an increasing number of coral bleaching events in CA and NES; other observed impacts are changes in the plankton community and in ocean and coastal food web structures, loss of vegetated wetlands and changes in macrobenthic communities in CA, NWS, northern South America (NSA) and southeastern South America (SES). {12.3, 12.5.2, Figure 12.8, Figure 12.9, Table SM12.3}

Global warming has caused glacier loss in the Andes from 30% to more than 50% of their area since the 1980s. Glacier retreat, temperature increase and precipitation variability, together with land use changes, have affected ecosystems, water resources and livelihoods through landslides and flood disasters (*very high confidence*). In several areas of the Andes, flood and landslide disasters have increased, and water availability and quality and soil erosion have been affected by both climatic and non-climatic factors (*high confidence*). {12.3.2, 12.3.7, Figure 12.9, Figure 12.13, Table SM12.6}

The scientific evidence since the IPCC's Fifth Assessment Report (AR5) increased the confidence in the synergy among fire, land use change, particularly deforestation, and climate change, directly impacting human health, ecosystem functioning, forest structure, food security and the livelihoods of resource-dependent communities (*medium confidence*). Regional increases in temperature, aridity and drought increased the frequency and intensity of fire. On average, people in the region were more exposed to high fire danger between 1 and 26 additional days depending on the sub-region for the years 2017–2020 compared to 2001–2004 (*high confidence*). {12.2, 12.3, Figure 12.9, Figure 12.10, Table 12.5}

Changes in the timing and magnitude of precipitation and extreme temperatures are impacting agricultural production (*high confidence*). Since the mid-20th century, increasing mean precipitation has positively impacted agricultural production in SES, although extremely long dry spells have become more frequent, affecting the economies of large cities in southeastern Brazil. Conversely, reduced precipitation and altered rainfall at the start and end of the rainy season and during the mid-summer drought (MSD) is impacting rainfed subsistence farming, particularly in the Dry Corridor in CA and in the tropical Andes, compromising food security (*high confidence*). The crop growth duration for maize in those regions was reduced by at least 5% between 1981–2010 and 2015–2019. {12.3.1, 12.3.2, 12.3.6, Table 12.4}

Climate change affects the epidemiology of climate-sensitive infectious diseases in the region (*high confidence*). Examples are the effects of warming temperatures on increasing the suitability of transmission of vector-borne diseases, including endemic and emerging arboviral diseases such as dengue fever, chikungunya and Zika (*medium confidence*). The reproduction potential for the transmission of dengue increased between 17% and 80% for the period 1950–1954 to 2016–2021, depending on the sub-region, as a result of changes in temperature and precipitation (*high confidence*). {12.3.1, 12.3.2, 12.3.3, 12.3.5, 12.3.6, Table 12.1}

The Andes, northeastern Brazil and the northern countries in CA are among the more sensitive regions to climatic-related migrations and displacements, a phenomenon that has increased since AR5 (*high confidence*). Climatic drivers interact with social, political, geopolitical and economic drivers; the most common climatic drivers for migration and displacements are droughts, tropical storms

1 In this report, the following summary terms are used to describe the available evidence: limited, medium and robust; and for the degree of agreement: low, medium and high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high; they are typeset in italics, for example, *medium confidence*. Different confidence levels can be assigned to evidence and agreement statements, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

and hurricanes, heavy rains and floods (*high confidence*). {12.3.1.4, 12.3.2.4, 12.3.3.4, 12.3.5.4, 12.5.8.4}

The impacts of climate change are not of equal scope for men and women (*high confidence*). Women, particularly the poorest, are more vulnerable and are impacted in greater proportion. Often they have less capacity to adapt, further widening structural gender gaps (*high confidence*). {12.3.7.3, 12.5.2.4, 12.5.2.5, 12.5.7.3, 12.5.8.1, 12.5.8.3, 12.5.8.4}

Current adaptation responses:

Ecosystem-based adaptation is the most common adaptation strategy for terrestrial and freshwater ecosystems (*high confidence*). There is a focus on the protection of native terrestrial vegetation through the implementation of protected areas and payment for ecosystem services (PES), especially those related to water provision. The adaptation measures in place, however, are insufficient to safeguard terrestrial and freshwater ecosystems in the CSA from the negative impacts of climate change (*high confidence*). {12.5.1, 12.5.3, 12.6}

Adaptation initiatives in ocean and coastal ecosystems mainly focus on conservation, protection and restoration) (*high confidence*). The main adaptation measures are ocean zoning, the prohibition of productive activities (e.g., fisheries, aquaculture, mining and tourism) on marine ecosystems, the improvement of research and education programmes and the creation of specific national policies (*high confidence*). {12.5.2}

Adaptive water management has mainly centred on enhancing the quantity and quality of water supply, including large infrastructure projects, which, however, are often contested and can exacerbate water-related conflicts (*high confidence*). Inclusive water regimes that overcome social inequalities and approaches including nature-based solutions, such as wetland restoration and water storage and infiltration infrastructure, with synergies for ecosystem conservation and disaster risk reduction, have been found to be more successful for adaptation and sustainable development (*high confidence*). {12.5.3, 12.6.1, 12.6.3}

Adaptation strategies for agricultural production are increasing in the region as a response to current and projected changes in climate (*high confidence*). The main observed adaptation strategies in agriculture and forestry are soil and water management conservation, crop diversification, climate-smart agriculture, early-warning systems (EWSs), upward shifting for plantations to avoid warming habitat and pests and improved management of pastures and livestock. Adaptation requires governance improvements and new strategies to address the changing climate; nevertheless, barriers limiting adaptive capacity persist such as lack of educational programmes for farmers, adequate knowledge of site-specific adaptation and institutional and financial constraints (*high confidence*). {12.5.4}

Urban adaptation in the region includes solutions on regulation, planning, urban water management and housing (*high confidence*). Regulation, planning and control systems are central tools for reducing risk associated with the security of buildings and their location and the proper supply of basic urban services and transport (*high confidence*). The adoption of nature-based solutions (e.g., urban agriculture and river restoration) and hybrid (grey-green) infrastructure is still in the early stages, with weak connections to poverty and inequality reduction strategies (*medium confidence*). Focusing on risk reduction encompasses upgrading informal and precarious settlements, built environments and housing conditions, which offer an important but still limited contribution to urban adaptation (*high confidence*). {12.5.5, 12.5.7, 12.6.1}

Adaptation initiatives for the health sector are mainly focused on the development of climate services such as integrated climate-health surveillance and observatories, forecasting climate-related disasters and vulnerability maps (*high confidence*). Climate services for the health sector are largely focused on epidemic forecast tools and associated EWSs for vector-borne diseases and heat and cold waves. Political, institutional and financial barriers reduce the feasibility of implementing these tools (*high confidence*). {12.5.6, Table 12.9, Table 12.11}

Indigenous knowledge and local knowledge (IKLK) are crucial for the adaptation and resilience of social-ecological systems (*high confidence*). IKLK can contribute to reducing the vulnerability of local communities to climate change (*medium confidence*). {12.5.1, 12.5.8, 12.6.2}

What are the projected impacts and key risks?

Climate change is projected to convert existing risks in the region into severe key risks (*medium confidence*). Key risks are assessed as follows: 1. Risk of food insecurity due to droughts; 2. Risk to people and infrastructure due to floods and landslides; 3. Risk of water insecurity due to declining snow cover, shrinking glaciers and rainfall variability; 4. Risk of increasing epidemics, particularly of vector-borne diseases; 5. Cascading risks surpassing public service systems; 6. Risk of large-scale changes and biome shifts in the Amazon; 7. Risks to coral reef ecosystems; and 8. Risks to coastal socioecological systems due to sea level rise (SLR), storm surges and coastal erosion. {12.3, 12.4, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

Impacts on rural livelihoods and food security, particularly for small and medium-sized farmers and Indigenous peoples in the mountains, are projected to worsen, including the overall reduction of agricultural production, suitable farming area and water availability (*high confidence*). Projected yield reductions by 2050 under the A2 scenario are as follows: beans 19%, maize 4–21%, rice 23% in CA with seasonal droughts projected to lengthen, intensify and increase in frequency. Small fisheries and farming of seafood will be negatively affected as El Niño Southern Oscillation (ENSO) events become more frequent and intense and ocean warming and acidification continues (*medium confidence*). {12.2, 12.3, 12.4, Figure 12.9, Figure 12.11, Table 12.4}

Extreme precipitation events, which result in floods, landslides and droughts, are projected to intensify in magnitude and frequency due to climate change (*medium confidence*). Floods and landslides pose a risk to life and infrastructure; a 1.5°C increase would

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result in an increase of 100–200% in the population affected by floods in Colombia, Brazil and Argentina, 300% in Ecuador and 400% in Peru (*medium confidence*). {12.3, Figure 12.7, Figure 12.9, Table SM12.5}

Increasing water scarcity and competition over water are projected (*high confidence*). Disruption in water flows will significantly degrade ecosystems such as high-elevation wetlands and affect farming communities, public health and energy production (*high confidence*). {12.3, Figure 12.3, Figure 12.9, Figure 12.11}

In coming decades, endemic and emerging climate-sensitive infectious diseases are projected to increase (*medium confidence*). This can happen through expanded distribution of vectors, especially viral infectious diseases of zoonotic origin in transition areas between urban and suburban, or rural settings, and upslope in the mountains (*medium confidence*). {12.3.2, 12.3.5, 12.3.7, Figure 12.5, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

The positive feedback between climate change and land use change, particularly deforestation, is projected to increase the threat to the Amazon forest, resulting in the increase of fire occurrence, forest degradation (*high confidence*) and long-term loss of forest structure (*medium confidence*). The combined effect of both impacts will lead to a long-term decrease in carbon stocks in forest biomass, compromising Amazonia's role as a carbon sink, largely conditioned on the forest's responses to elevated atmospheric CO_2 (*medium confidence*). The southern portion of the Amazon has become a net carbon source to the atmosphere in the past decade (*high confidence*). {12.3.3, 12.3.4, Figure 12.9, Figure 12.11, Table 12.6, Table SM12.5}

Up to 85% of natural systems (plant and animal species, habitats and communities) evaluated in the literature for biodiversity hotspots in the region are projected to be negatively impacted by climate change (*medium confidence*). Available studies focus mainly on vertebrates and plants of the Atlantic Forest and Cerrado in Brazil and in CA, with a large knowledge gap on freshwater ecosystems {12.3, 12.5.1, CCP1}

Ocean and coastal ecosystems in the region will continue to be highly impacted by climate change (*high confidence*). Coral reefs are projected to lose their habitat, change their distribution range and suffer more bleaching events driven by ocean warming. In the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios, by 2050, virtually every coral reef will experience at least one severe bleaching event per year (*high confidence*). Under all RCP scenarios of climate change, there will be changes in the geographical distribution of marine species and ocean and coastal ecosystems such as mangroves, estuaries and rocky shores, as well as those species held in fisheries (*medium confidence*). {Figure 12.9, Table SM12.3, Table SM12.4}

Contribution of adaptation to solutions and barriers to adaptation

Policies and actions at multiple scales and the participation of actors from all social groups, including the most exposed and vulnerable populations, are critical elements for effective adaptation (*high confidence*). Engaging social movements and local actors in policymaking and planning for adaptation generate positive synergies and better results. Adaptation policies and programmes that consider age, socioeconomic status, race and ethnicity are more efficient because these factors determine vulnerability and potential benefits of adaptation. Socioeconomic and political factors that provide some level of safety and continuity of policies and actions are critical enablers of adaptation (*high confidence*). {12.5.1, 12.5.2, 12.5.7, 12.5.8, 12.6.4}

The knowledge and awareness of climate change as a threat have been increasing since AR5 due to the increasing frequency and magnitude of extreme weather events in the region, information available and climate justice activism (*high confidence*). Conflicts in which the direct biophysical impacts of climate change play a major role can unleash protests and strengthen social movements (*medium confidence*). {12.5.8, 12.6.4}

Research approaches that integrate IKLK systems with natural and social sciences have increased since AR5 (*high confidence*) and are helping to improve decision-making processes in the region, reduce maladaptation and foster transformational adaptation through the integration with ecosystem-based adaptation and community-based adaptation (*high confidence*). {12.5.1, 12.5.8, 12.6.2}

The most widely reported obstacle to adaptation in terrestrial, freshwater, ocean and coastal ecosystems is financing (*high confidence*). There is also a significant gap in identifying limits to adaptation and weak institutional capacity for implementation. This hinders the development of comprehensive adaptation programmes, even under adequate funding. {12.5.1, 12.5.2}

The use of climate-smart agriculture technologies strengthening synergies among productivity and mitigation is rising as an important adaptation strategy in the region (*high confidence*). Pertinent information for farmers provided by climate information services is facilitating the understanding of the role of climate compared with other drivers in perceived productivity changes. Index insurance builds resilience and contributes to adaptation by protecting farmers' assets in the face of major climate shocks, by promoting access to credit and by the adoption of improved farm technologies and practices. {12.5.4}

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Institutional instability, fragmented services and poor water management, inadequate governance structures, insufficient data and analysis of adaptation experience are barriers to addressing the water challenges in the region (*high confidence*). {12.5.3}

Inequality, poverty and informality shaping cities in the region increase vulnerability to climate change, while policies, plans or interventions addressing these social challenges with inclusive approaches represent opportunities for adaptation (*high confidence*). Initiatives to improve informal and precarious settlement, guaranteeing access to land and decent housing, are aligned with comprehensive adaptation policies that include the development and reduction of poverty, inequality and disaster risk (*medium confidence*). {12.5.5, 12.5.7}

Adaptation policies often address climate impact drivers, but seldom include the social and economic underpinnings of vulnerability. This narrow scope limits adaptation results and compromises their continuity in the region (high confidence). In a context of unaddressed underdevelopment, adaptation policies tackling poverty and inequality are marginal, underfunded and not clearly included at national, regional or urban levels. Dialogue and agreement that include multiple actors are mechanisms to acknowledge trade-offs and promote dynamic, site-specific adaptation options (medium confidence). {12.5.7}

12.1 Introduction

12.1.1 Central and South America Region

Central and South America (CSA) is a highly diverse region, both culturally and biologically. It has one of the highest levels of biodiversity on the planet (Hoorn et al., 2010; Zador et al., 2015; IPBES, 2018a) (Cross-Chapter Paper [CCP] 1: Biodiversity Hotspots) and a wealth of cultural diversity resulting from more than 800 Indigenous Peoples who share the territory with European and African descendants and more recent Asian migrants (CEPAL, 2014). Moreover, it is one of the most urbanised regions in the world, with some of the most populated metropolitan areas (UNDESA, 2019). Several countries in the region have experienced sustained economic growth in recent decades, making important advances in reducing poverty in the area. Yet it is a region of substantial social inequality including the highest inequality in land tenure, where a large percentage of the population remains below the poverty line, unequally distributed between rural and urban areas and along aspects like gender and race; these groups are highly vulnerable to climate change and natural extreme events that frequently affect the region (*high confidence*) (ECLAC, 2019b; Busso and Messina, 2020; Poveda et al., 2020).

Land use changes in the region, particularly deforestation, are significant, mostly due to agricultural production for export purposes, one of the main sources of income for the area (Salazar et al., 2016) (Figure 12.2c). Additional pressure on the land comes from illegal activities, pollution and induced fires. These changes exacerbate the impacts of climate change and make the region a key player in the future of the world economy and food production (IPBES, 2018a). The region boasts the largest tropical forest on the planet and other important biomes of high biodiversity on mountains, lowlands and coastal areas. It can potentially continue its agricultural expansion and development at the expense of substantially reducing the areas of natural biomes. Indigenous Peoples and smallholder families are lacking adequate climate policies combined with institutions to protect their property rights; this could result in a more sustainable process of agricultural expansion, without substantially increasing greenhouse gas (GHG) emissions and the vulnerability of those populations (*high confidence*) (Sá et al., 2017).

CSA is divided into eight climatic sub-regions by Working Group (WG) I (Figure 12.1). Though the southern part of Mexico is included in the climatic sub-region South Central America (SCA) for WGI, Mexico is assessed in Chapter 14 (North America). In this chapter, we refer to this sub-region as CA because it excludes southern Mexico. The climate-change literature for the region occasionally includes Mexico, and in those cases, our assessment makes reference to Latin America but when only southern Mexico is included, the term Mesoamerica is used. Figure 12.2 and Table SM12.1 summarise relevant characteristics of the sub-regions included in this chapter.

Geographical scope of Central and South America

Poligon delineations represent the boundaries used for the regional synthesis of historical trends and future climate change projections used in the Assessment Reports of the IPCC WGI.

(a) Central America (CA)*

(b) Northwestern South America (NWS)

(c) Northern South America (NSA)

(d) South America Monsoon (SAM)

(e) Northeastern South America (NES)

(f) Southwestern South America (SWS)

(g) Southeastern South America (SES)

(h) Southern South America (SSA)

* Different from the WGI South Central America (SCA) which includes the southern part of Mexico.

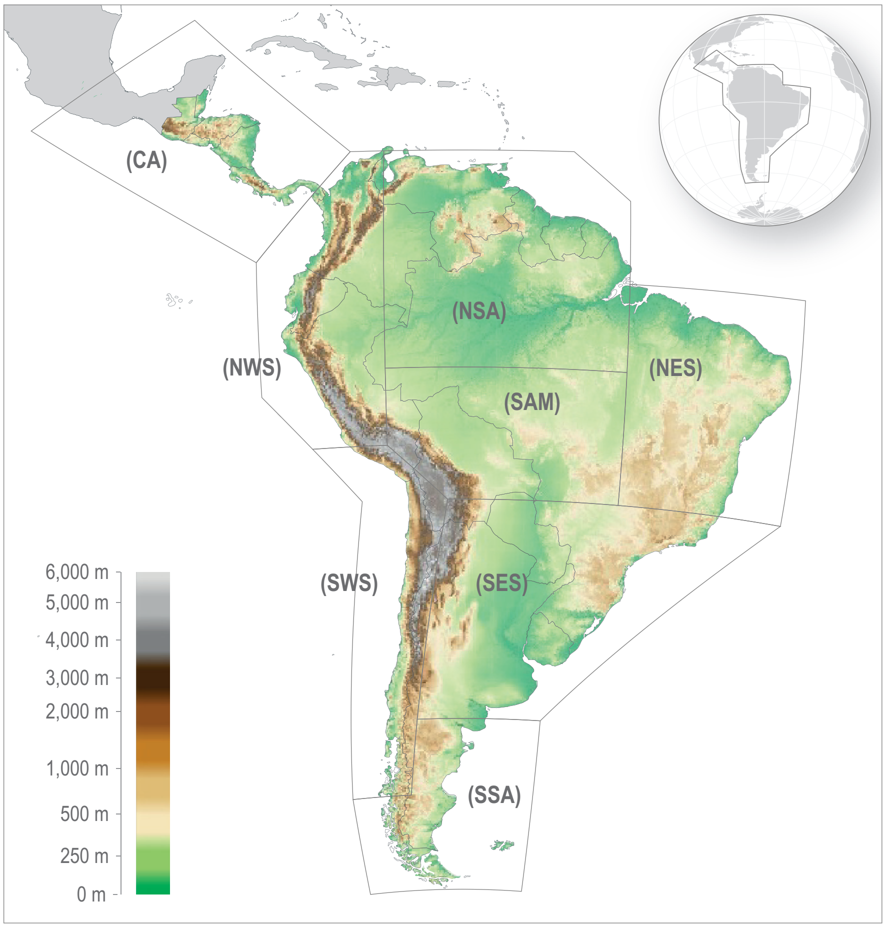

Figure 12.1 | Sub-regions included in CSA region. Note that the WGI climatic sub-region SCA corresponds to CA in this chapter, as southern Mexico is included in Chapter 14. Small islands in the region are covered in Chapter 15 in more detail.

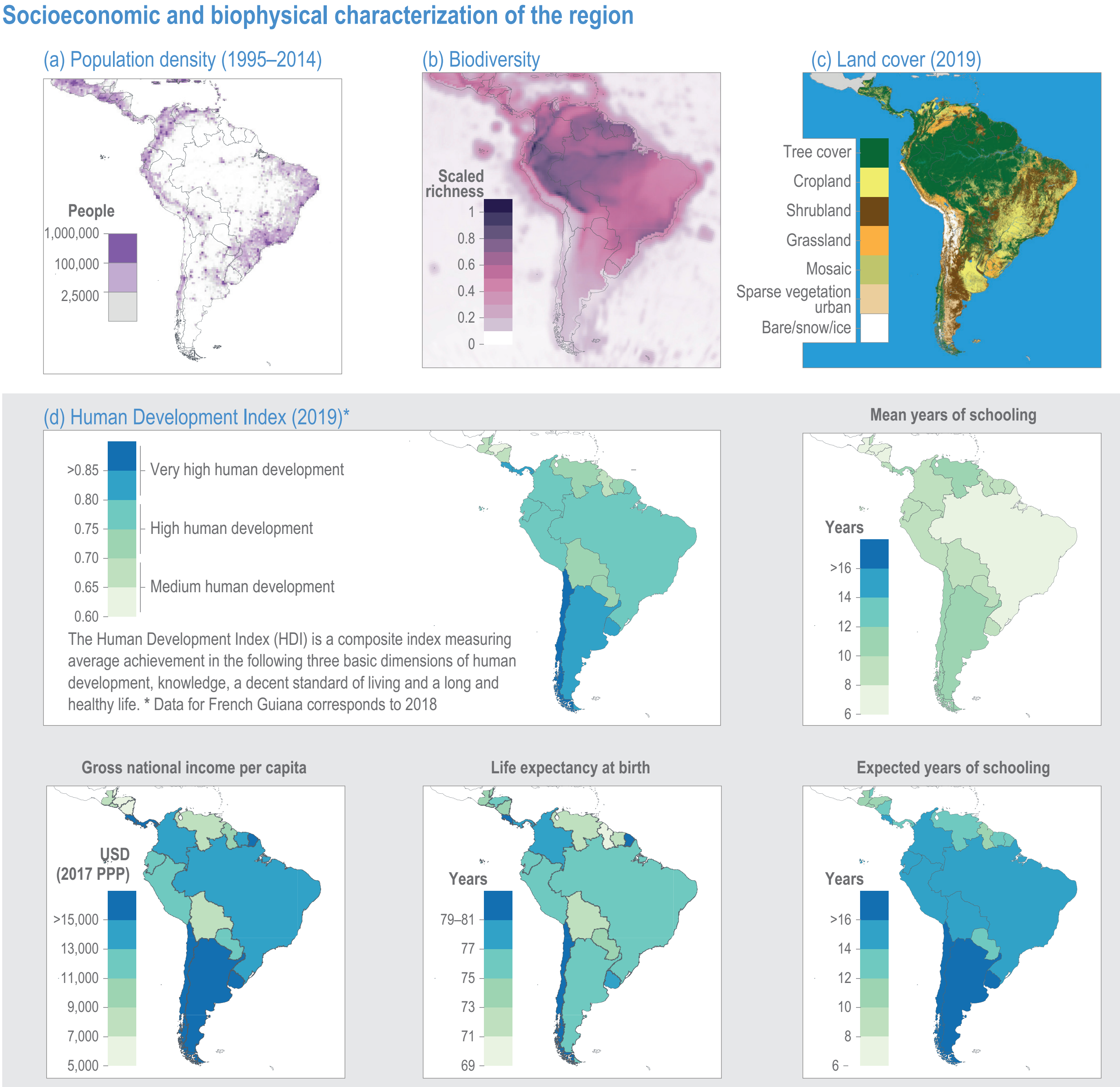

Figure 12.2 | Characterisation of the region. Population data from ISIMIP (2021) after Klein Goldewijk et al. (2017). Biodiversity expressed as marine and terrestrial species richness adapted from Gagné et al. (2020). Land cover data from ESA (2018). Human Development Index (HDI) and its components from UNDP (2020). HDI and components for French Guiana from Global Data Lab (2020).

12.1.2 Approach and Storyline for the Chapter

The chapter is divided into two main sections. The first section follows an integrative approach in which hazards, exposure, vulnerability, impacts and risks are discussed following the eight climatically homogeneous sub-regions described in WGI AR6 (Figure 12.1). The second section assesses the implemented and proposed adaptation practices by sector; in doing so, it connects to the WGII AR6 cross-chapter themes. The storyline is then a description of the hazards, exposure, vulnerability and impacts providing as much detail as is available in the literature at the sub-regional level, followed by the identification of risks as a result of the interaction of those aspects. This integrated sub-regional approach ensures a balance in the text, particularly for countries that are usually underrepresented in the literature but that show a high level of vulnerability and impacts, such as those observed in CA. The sectoral assessment of adaptation that follows is useful for policymakers and implementers, usually focused and organised by sectors, government ministries or secretaries that can easily locate the relevant adaptation information for their particular sector. To ensure coherence in the chapter, a summary of the assessed

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adaptation options by key risks is presented, followed by a feasibility assessment for some relevant adaptation options. The chapter closes with case studies and a discussion of the knowledge gaps evidenced in the process of the assessment.

12.2 Summary of AR5 and Recent IPCC Special Reports

CSA shows increasing trends of climatic change and variability and extreme events severely impacting the region, exacerbating problems of rampant and persistent poverty, precarious health systems and water and sanitation services, malnutrition and pollution. Inadequate governance and lack of participation escalates the vulnerability and risk to climate variability and change in the region (*high confidence*) (WGII AR5 Chapter 27) (Magrin et al., 2014).

Increasing trends in precipitation had been observed in SES (Figure 12.1), in contrast to decreasing trends in CA and central-southern Chile (*high confidence*) (WGII AR5 Chapter 27) (Magrin et al., 2014). The frequency and intensity of droughts have increased in many parts of SA (IPCC, 2019c). Warming has been detected throughout CSA, except for a cooling trend reported for the ocean off the Chilean coast.

Climate projections indicate increases in temperature for the entire region by 2100 for RCP4.5 and RCP8.5, but rainfall changes will vary geographically, with a notable reduction of –22% in northeastern Brazil and an increase of +25% in SES. Significant dependency on rainfed agriculture (>30% in Guatemala, Honduras and Nicaragua) indicates high sensitivity to climatic variability and change and represents a challenge for food security (*high confidence*) (SRCCL Chapter 5, Mbow et al., 2019). Undernutrition has worsened since 2014 in CSA (SRCCL Chapter 5, Mbow et al., 2019). Evidence of climate-change impacts on food security is emerging from IKLK studies in SA. Municipalities in CA with a high proportion of subsistence crops tend to have fewer resources for adaptation and more vulnerable to climate change (SRCCL Chapter 5, Mbow et al., 2019). Rising temperature and decreased rainfall could reduce agricultural productivity by 2030, threatening the food security of the poorest populations (WGII AR5 Chapter 27, Magrin et al., 2014). Though reduced suitability and yield for beans, coffee, maize, plantain and rice are expected in CA (SRCCL Chapter 5, Mbow et al., 2019), limiting the warming to 1.5°C, compared with 2°C, are projected to result in smaller net reductions in yields of maize, rice, wheat and other cereal crops for CSA (*high confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). The heat stress is expected to reduce the suitability of Arabica coffee in Mesoamerica, but it can improve in high-latitude areas in SA (SRCCL Chapter 4, Olsson et al., 2019). There is *limited evidence* that these declines in crop yields may result in significant population displacement from the tropics to the sub-tropics (SR15 Chapter 3, Hoegh-Guldberg et al., 2018).

There is a *high confidence* that heatwaves will increase in frequency, intensity and duration, becoming, under high emission scenarios, extremely long, over 60 d in duration in SA; the risk of wildfires will also increase significantly in SA (SRCCL Chapter 2, Jia et al., 2019). These processes are leading and will continue to lead to increased desertification that will cost between 8% and 14% of gross agricultural product in many CSA countries (SRCCL Chapter 3, Mirzabaev et al., 2019). Distinguishing climate-induced changes from land use changes is challenging, but 5–6% of biomes in SA are expected to change by 2100 due to climate change (SRCCL Chapter 4, Olsson et al., 2019).

Changes in weather and climatic patterns are negatively affecting human health in CSA, in part through the emergence of diseases in previously non-endemic areas (WGII AR5 Chapter 27, Magrin et al., 2014). Projections of potential impacts of climate change on malaria confirm that weather and climate are among the drivers of geographic range, intensity of transmission, and seasonality; the changes of risk become more complex with additional warming (*very high confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). There is *high confidence* that constraining the warming to 1.5°C would reduce risks for unique and threatened ecosystems safeguarding the services they provide for livelihoods and sustainable development (food, water) in CA and Amazon (SR15 Chapter 5, Roy et al., 2018).

Observed changes in streamflow and water availability affect vulnerable regions (WGII AR5 Chapter 27, Magrin et al., 2014). Glacier mass changes in the Andes in recent decades are among the most negative ones worldwide (SROCC Chapter 2, Hock et al., 2019). This reduction has modified the frequency, magnitude and location of related natural hazards, while the exposure of people and infrastructure has increased because of growing population, tourism and economic development (*high confidence*) (SROCC Chapter 2, Hock et al., 2019).

The negative impacts of climate change in the region are exacerbated by deforestation and land degradation attributed mainly to expansion and intensification of agriculture and cattle ranching, usually under insecure-tenure land. This conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss and is an important source of GHG emissions (*high confidence*) (WGII AR5 Chapter 27, Magrin et al., 2014).

The combination of continued anthropogenic disturbance, particularly deforestation, with global warming may result in dieback of forest in the region (*medium confidence*) (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). Losses of biomass as high as 40% are projected in CA with a warming of 3°C–4°C, and the Amazon may experience a significant dieback at similar warming levels (SR15 Chapter 3, Hoegh-Guldberg et al., 2018). Advances in second-generation bioethanol from sugarcane and other feedstock will be important for mitigation. However, agricultural expansion results in large conversions in tropical dry woodlands and savannahs in SA (Brazilian Cerrado, Caatinga and Chaco) (*high confidence*) (SRCCL Chapter 1, Arneth et al., 2019). The expansion of soybean plantations in the Amazonian state of Mato Grosso in Brazil reached 16.8% yr^{-1} from 2000 to 2005; and oil palm, a significant biofuel crop, is also linked to recent deforestation in tropical CA (Costa Rica and Honduras) and SA (Colombia and Ecuador), although lower in magnitude compared to deforestation from soybean and cattle ranching (WGII AR5 Chapter 27, Magrin et al., 2014).

Ocean and coastal ecosystems in the region already show important changes due to climate change and global warming (SROCC Chapter 5, Bindoff et al., 2019).

Adaptation to future climate change starts by reducing the vulnerability to the present climate considering the deficient welfare of people in the region. Generalising to the region cases of synergies among development, adaptation and mitigation planning requires a governance model where development needs, vulnerability reduction and adaptation strategies are intertwined (WGII AR5 Chapter 27, Magrin et al., 2014).

12.3 Hazards, Exposure, Vulnerabilities and Impacts

12.3.1 Central America Sub-region

12.3.1.1 Hazards

Since the mid-20th century, extreme warm temperatures have increased and extreme cold temperatures have decreased in the region (*medium confidence*). The magnitude and frequency of extreme precipitation events have increased, but droughts have mixed signals (*low confidence*) (WGI AR6 Table 11.13, Table 11.14, Table 11.15, Seneviratne et al., 2021). Spatially variable trends have been detected for the MSD timing, the amount of rainy-season precipitation, the number of consecutive and total dry days and extreme wet events at the local scale since the 1980s. At the regional scale, a positive trend in the duration, but not the magnitude, of the MSD was found (Anderson et al., 2019).

Significant increases in tropical cyclone (TC) intensification rates in the Atlantic basin, highly unusual compared to model-based estimates of internal climate variations, have been observed (Bhatia et al., 2019). TCs contributed approximately 10% of the annual precipitation (Khouakhi et al., 2017). During the TC season more TC-driven events of extreme sea level exceed a 10-year return period (Muis et al., 2019).

Massive heatwave events and increase in the frequency of warm extremes are projected at the end of the 21st century (*high confidence*). When comparing 2.0°C with 1.5°C of warming, the longest annual warm wave is projected to increase more than 60 d (Taylor et al., 2018).

General decrease in the magnitude of heavy precipitation extremes (Chou et al., 2014; Giorgi et al., 2014) (in 1.5°C projection) but increase in the frequency of extreme precipitation (R50mm) (Imbach et al., 2018) are projected for both 2°C and 4°C global warming level (GWL). Strong declines in mean daily rainfall are projected for July in Belize (Stennett-Brown et al., 2017; WGI AR6 Table 11.14, Seneviratne et al., 2021) and decreased rainfall through the year for all capital cities except Panama City (*medium confidence: limited evidence, high agreement*) (Pinzón et al., 2017).

The main climate impact drivers like extreme heat, drought, relative SLR, coastal flooding, erosion, marine heatwaves, ocean aridity (*high confidence*) and aridity, drought and wildfires will increase by mid-century (*medium confidence*) (Figure 12.6, WGI AR6 Table 12.6, Ranasinghe et al., 2021).

The rainy season in CA will likely experience more pronounced MSD by the end of this century, with a signal for reduced minimum precipitation by mid-century for the June July August (JJA) and September October November (SON) quarters, and a broader second peak is projected, consistent with the future south displacement of the Intertropical Convergence Zone (ITCZ) (*high confidence*) (Fuentes-Franco et al., 2015; Hidalgo et al., 2017; Maurer et al., 2017; Imbach et al., 2018; Naumann et al., 2018; Ribalaygua et al., 2018; Corrales-Suastegui et al., 2020).

Climate projections indicate a decrease in frequency of TCs in CA accompanied by an increased frequency of intense cyclones (WGI AR6 Section 12.4.4.3, Ranasinghe et al., 2021).

12.3.1.2 Exposure

Of the 47 million Central Americans in 2015, 40% lived in rural areas, with Belize being the least urbanised (54% rural) and Costa Rica the most (21% rural) (CELADE, 2019); 10.5 million lived in the Dry Corridor region, an area recently exposed to severe droughts that have resulted in 3.5 million people in need of humanitarian assistance (FAO, 2016a). Except in Belize and Panama, the majority of the countries' populations—ranging from 56% in Honduras to 95% in El Salvador—were exposed to two or more risks derived from natural extreme events, affecting between 57% and 96% of the GDP of the countries (UNISDR and CEPREDENAC, 2014). CA is one of the regions most exposed to climatic phenomena; with long coastlines and lowland areas, the region is repeatedly affected by drought, intense rains, cyclones and ENSO events (*high confidence*) (ECLAC et al., 2015).

Large urban centres are located on mountains or away from the shore, with the notable exceptions of Panama City, Belmopan and Managua, capital cities housing around 3 million people. Urban development in the capital cities and suburbs has almost tripled in the last 40 years, reaching population densities as high as 11,000 inhabitants/km^2 in Guatemala City and Tegucigalpa, with the spread of poor neighbourhoods in steep ravines and other marginal high-risk areas (Programa Estado de la Nación – Estado de la Región, 2016).

12.3.1.3 Vulnerability

Climate change is exacerbating socioeconomic vulnerability in CA, a region with high levels of socioeconomic, ethnic and gender inequality, high rates of child and maternal mortality and morbidity, high levels of malnutrition and inadequate access to food and drinking water (ECLAC et al., 2015). Disasters from adverse natural events exacerbate CA's economic vulnerability, accounting for substantial human and economic losses (UNISDR and CEPREDENAC, 2014). Vulnerability in most sectors is considered high or very high (*high confidence*) (Figure 12.7).

Approximately 40% of the CA population live in poverty. Guatemala (62%), Honduras (60%), Nicaragua (46%) and Belize (42%, 2009) had the highest poverty rates in CSA in 2018 (ECLAC, 2019b; BCIE, 2020). Rural poverty rates are higher—82% in Honduras and 77% in Guatemala in 2014—as is poverty among Indigenous Peoples, up to 79% in Guatemala. Rural poor are the most sensitive to climate extremes as their main economic activity is based on agriculture in vulnerable terrains (NU CEPAL, 2018). In 2014, all CA countries, except for El Salvador (excluding Belize), had higher GINI coefficients (more inequality) than the average for Latin America (0.473), which in itself is the most unequal region in the world (ECLAC, 2019b); in 2018 the situation remained similar, with El Salvador showing the lowest GINI coefficient (40) and the remaining countries showing values higher than the Latin American average (BCIE, 2020).

12.3.1.4 Impacts

The countries in the region are consistently ranked highest in the world by risk of being impacted by extreme events (*high confidence*). The economic costs of climate-change impacts in 2010 were estimated as being from 2.9% of GDP for Guatemala to 7.7% for Belize (ECLAC et al., 2015). For the period 1992–2011, Honduras, Nicaragua and Guatemala were among the 10 most impacted countries in the world by extreme weather events (UNISDR and CEPREDENAC, 2014). The number of these events has increased 3% annually in the last 30 years (Bárcena et al., 2020a).

Human and economic losses, changing water availability and increasing food insecurity are the most studied impacts of climate change in CA (Figure 12.9) (Harvey et al., 2018; Hoegh-Guldberg et al., 2019). Hydro-meteorological events, such as storm surges and TCs, are the most frequent extreme events and have the highest impact (*high confidence*) (Reyer et al., 2017). From 2005 to 2014, the cumulative impacts were over 3410 people dead, hundreds of thousands displaced and damages estimated around USD 5.8 billion (Ishizawa and Miranda, 2016). One standard deviation in the intensity of a hurricane windstorm leads to a decrease in both the growth of total GDP per capita (0.9% to 1.6%) and total income and labour income by 3%, whereas it increases moderate and extreme poverty by 1.5% in CA (Ishizawa and Miranda, 2016).

Food insecurity is a serious impact of climate change in a region where 10% of the GDP depends on agriculture, livestock and fisheries (*very high confidence*) (ECLAC et al., 2015; CEPAL et al., 2018; Harvey et al., 2018; BCIE, 2020). Crop losses largely result from highly variable rainfall and seasonal droughts, which have increased significantly in recent decades (Table 12.3) (CEPAL and CAC-SICA, 2020), particularly the observed changes in the MSD that reduces rainfall at the onset of the rainy season (May–June) (Anderson et al., 2019). Small and subsistence farmers experience the highest impact because they practice rainfed agriculture (Imbach et al., 2017), along with poor neighbourhoods, which face socioeconomic and physical barriers for adapting to climate change (Kongsager, 2017). In 2015, precipitation diminished between 50% and 70% of its historic average, causing a loss of up to 80% of beans and 60% of maize, leaving 2.5 million people food insecure, 1.6 million of whom were in the Dry Corridor of CA (ECLAC et al., 2015; FAO, 2016a). In 2019, the region entered its fifth consecutive drought year, with 1.4 million people in need of food aid. Seasonal-scale droughts are projected to lengthen by 12–30%, intensify by 17–42% and increase in frequency by 21–42% in RCP4.5 and RCP8.5 scenarios by the end of the century (Depsky and Pons, 2021).

Studies have shown that the incidence of some vector-borne and zoonotic diseases in CA is correlated to climatic variables, particularly temperature and rainfall (*high confidence*) (Figure 12.4; Table 12.1). In Honduras, rainfall and relative humidity were positively correlated with the occurrence of haemorrhagic dengue cases (Zambrano et al., 2012). In Costa Rica, temperature and rainfall were correlated to cattle rabies outbreaks and mortality during 1985–2016 (Hutter et al., 2018); incidence of leishmaniasis showed cycles of 3 years related to temperature changes (Chaves and Pascual, 2006); and snakebites were more likely to occur at high temperatures and were significantly reduced after the rainy season for the period 2005–2013 (Chaves et al., 2015). In Panama, rainfall was associated with an increased number of malaria cases among the Gunas, an Indigenous People with high vulnerability living in poverty conditions on small islands affected by SLR (Hurtado et al., 2018). These correlations point to a possible change in disease incidence with climate change; evidence of that change is yet to be reported in the literature because longitudinal studies are lacking in the region.

Heat stress is another health concern in this already warm and humid part of the world (*high confidence*) (Table 12.2); it is an increasing occupational health hazard with potential impacts on kidney disease (Sheffield et al., 2013; Dally et al., 2018; Johnson et al., 2019). SLR exacerbating wave-driven flooding is expected to impact infrastructure and freshwater availability in small islands and atolls off the coast of Belize (Storlazzi et al., 2018). Observed and expected impacts in the coastal and ocean ecosystems of the sub-region are described in Figure 12.9.

Decreasing water availability is another impact of climate change (*high confidence*). Under a climate-change scenario of 3.5°C warming and a 30% reduction in rainfall, a reduction in the production and export of crops and livestock is projected, affecting the wages and decreasing the GDP of Guatemala by 1.2%, thereby increasing food insecurity (Vargas et al., 2018b). By 2100, water availability per capita is projected to decrease 82% and 90% on average for the region under B2 (low emissions) and A2 (high emissions) scenarios respectively (Figure 12.3) (CEPAL, 2010).

Impacts on rural livelihoods, particularly for small and medium-sized farmers and Indigenous Peoples in mountains, include an overall reduction in production, yield (Table 12.4), suitable farming area and water availability (*high confidence*) (Walshe and Argumedo, 2016; Bouroncle et al., 2017; Hannah et al., 2017; Imbach et al., 2017; Harvey et al., 2018; Batzín, 2019; Donatti et al., 2019). Bean production in El Salvador, Nicaragua, Honduras and Guatemala, is projected to decrease, using the Decision Support for Agro-Technology Transfer (DSSAT) under the A2 scenario, by 19% for 2050, whereas maize production, depending on the water retention capacity of soils, will drop between 4% and 21% by 2050 (CEPAL et al., 2018). In Guatemala, the yield of rainfed maize is expected to decrease by 16% by 2050 under RCP8.5 using the Global Gridded Crop Model Intercomparison GGCMI; yields for rainfed sugarcane are expected to drop by 44% and irrigated sugarcane by 36% under the same modelling conditions (Castellanos et al., 2018). Rice production is expected to decrease by 23% under scenario A2 by 2050 (CEPAL and CAC/SICA, 2013).

The extent and quality of suitable areas for basic grains are expected to contract (*high confidence*). The suitable area for maize will experience

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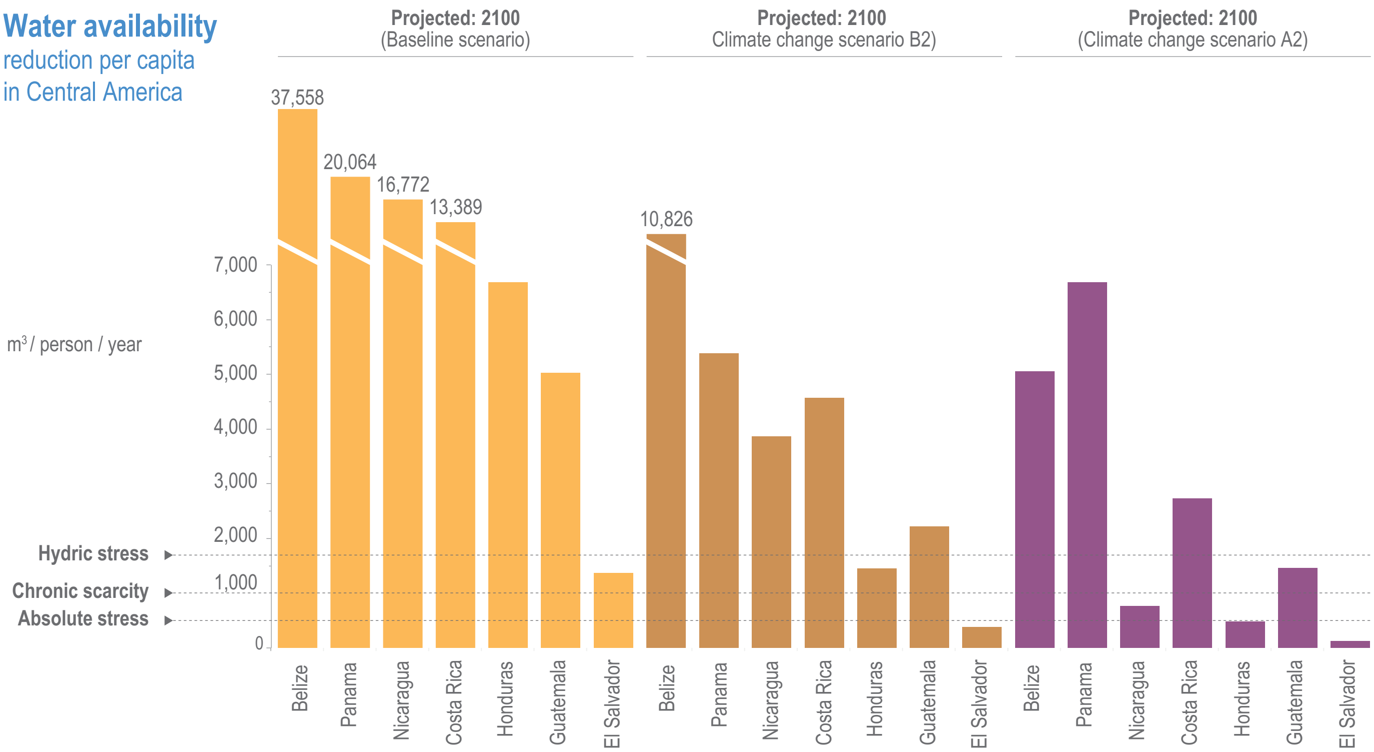

Figure 12.3 | Reduction of water availability per capita projected to 2100 without climate change (baseline scenario) and with two climate-change scenarios (CEPAL, 2010).

a 35% reduction of cultivated area expected by 2100 under the A2 scenario. The area suitable for beans is expected to shrink by 2050. Projections show that suitable areas with excellent capacity under current conditions will decrease by 14%, mainly in Panama (41%) Costa Rica (21%) and El Salvador (20%). The Species Distribution Model, using the IPSL GCM, projects that the suitable zones for cacao and coffee will shrink between 25% and 75% under RCP6.0 (Fernandez-Manjarrés, 2018; Fernández Kolb et al., 2019). Warmer and dryer lower areas will become unsuitable for coffee and will drive its production to higher land (Läderach et al., 2013; Bunn et al., 2015). Under the A2 climate-change scenario, areas with excellent capacity for Arabica coffee will decrease by 12% in CA; coffee yield will decrease in suitable zones whereby the extent of high yield (>0.8 T ha^{-1}) zones is projected to shrink from 34% to 12%, whereas low-yield (<0.3 T ha^{-1}) zones will expand from 14% to 36% by 2100 under the A2 scenario (CEPAL and CAC/SICA, 2014).

Mesoamerica, a biodiversity hotspot spanning across CA and southern Mexico, is a global priority for terrestrial biodiversity conservation, and it is projected to be negatively impacted by climate change, especially through the contraction of distribution of native species as the area becomes increasingly dryer (*high confidence*) (Section CCP1.2.2) (Feeley et al., 2013; Manes et al., 2021). A significant reduction in net primary productivity in tropical forests is expected under both RCP4.5 and RCP8.5 as a result of temperature increase, precipitation reduction and droughts (Lyra et al., 2017; Castro et al., 2018; Stan et al., 2020). Aridity index models show that the dry, sub-humid vegetation of the dry corridor will expand to neighbouring areas and replace the humid forests in the Pacific lowlands and the northern parts of Guatemala by 2050 under RCP4.5 and RCP8.5 scenarios (Pons et al., 2018; CEPAL and CAC-SICA, 2020). A warming of 3°C would shrink the tropical rainforest and replace it with savannah grassland. Wetlands are also expected to be highly affected by climate change in the region (Hoegh-Guldberg et al., 2019).

12.3.2 Northwestern South America Sub-region

12.3.2.1 Hazards

Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Dereczynski et al., 2020; Dunn et al., 2020) were *likely*[2] observed (Figure 12.6; WGI AR6 Table 11.13) (Seneviratne et al., 2021).

Insufficient data coverage and trends in available data are generally not significant for heavy precipitation (*low confidence*) (Dereczynski et al., 2020; Dunn et al., 2020; Sun et al., 2021) (Figure 12.6; WGI AR6 Table 11.14) (Seneviratne et al., 2021).

ENSO is the dominant phenomenon affecting weather conditions in all of CSA and along the Pacific Coast of NWS, causing heavy rains,

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.

storms, floods, landslides, heat and cold waves and extreme SLR (Ashok et al., 2007; Reguero et al., 2015; Wang et al., 2017b; Muis et al., 2018; Rodríguez-Morata et al., 2018; Rodríguez-Morata et al., 2019; Cai et al., 2020). There is *medium confidence* that extreme ENSO will increase long after 1.5°C warming stabilisation according to CMIP5 (Cai et al., 2015, 2018; Wang et al., 2017b). It is *very likely* that ENSO rainfall variability, used for defining extreme El Niño and La Niña, will increase significantly, regardless of amplitude changes in ENSO sea surface temperature (SST) variability, by the second half of the 21st century in scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5 (WGI AR6 Chapter 4) (Lee et al., 2021).

Warming and drier conditions are projected through the reduction of total annual precipitation, extreme precipitation and consecutive wet days and an increase in consecutive dry days (Chou et al., 2014). Heatwaves will increase in frequency and severity in places close to the equator like Colombia (Guo et al., 2018; Feron et al., 2019), with a decrease but strong wetting in coastal areas, pluvial and river flood and mean wind increase (Mora et al., 2014). Models project a *very likely* 2°C GWL increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes. Nevertheless, models project inconsistent changes in the region for extreme precipitation (*low confidence*) (Figure 12.6; WGI AR6 Table 12.14) (Ranasinghe et al., 2021). The main climate impact drivers in the region, like extreme heat, mean precipitation and coastal and oceanic drivers, will increase and snow, ice and permafrost will decrease with *high confidence* (WGI AR6 Table 12.6) (Ranasinghe et al., 2021).

12.3.2.2 Exposure

There is *high confidence* that coastal lowlands are exposed to SLR in the form of coastal flooding and erosion, subsidence and saltwater intrusion (Hoyos et al., 2013). Those hazards can affect settlements, ports, industries and other infrastructures. Mangrove and aquaculture areas are among the most exposed systems (Gorman, 2018). The Eastern Tropical Pacific, particularly Sector Niño 3.4, will see the worst increase in SST, affecting industrial and small-scale fisheries (*very high confidence*) (Castrejón and Defeo, 2015; Reguero et al., 2015; Eddy et al., 2019; Bertrand et al., 2020; Castrejón and Charles, 2020; Escobar-Camacho et al., 2021).

Settlements and agriculture on different scales and hydroelectric infrastructures, especially near big rivers or in plains, are exposed to floods. Exposure and vulnerabilities to precipitation, overflows and related landslides are increasing (Briones-Estébanez and Ebecken, 2017).

The Andean piedmont (500–1200 metres above sea level [MASL]) ecosystems and crops and elevation ranges above the treeline are more exposed to thermal anomalies (*very high confidence*) (Urrutia and Vuille, 2009; Vuille et al., 2015; Aguilar-Lome et al., 2019; Pabón-Caicedo et al., 2020). Temperature rise, combined with precipitation and floods, leaves people more exposed to epidemics (*very high confidence*) (Stewart-Ibarra and Lowe, 2013; Sippy et al., 2019; Petrova et al., 2020). A more significant exposure is related to lower socioeconomic conditions, poor health and marginalisation (Oliver-Smith, 2014).

12.3.2.3 Vulnerability

Local economies reliant on limited and specialised resources, highly dependent on ecosystem services such as water and soil fertility, such as alpaca and llama herders or small-scale fishers, are among the more vulnerable (*very high confidence*) (Hollowed et al., 2013; Postigo, 2013; Glynn et al., 2017; Duchicela et al., 2019), along with the agricultural sector in the face of extreme events (Coayla and Culqui, 2020). Their vulnerabilities increase as a result of unequal chains of value, incomplete transfers of technology and other socioeconomic and environmental drivers (*high confidence*) (Ariza-Montobbio and Cuvi, 2020; Gutierrez et al., 2020).

Informal housing and settlements, usually located in areas exposed to the highest level of risk, exacerbates vulnerability (*very high confidence*) (Miranda Sara and Baud, 2014; Cuvi, 2015; Miranda Sara et al., 2016). The absence of proper drainage systems in urban areas increases this vulnerability, especially to floods. Most cities and infrastructure are considered highly vulnerable to climate change (*high confidence*) (Figure 12.7).

Regions dependent on glacier runoff are particularly vulnerable (Jiménez Cisneros et al., 2014; Mark et al., 2017; Polk et al., 2017). Also biodiversity and water-dependent activities where seasonality and rainfall patterns are changing and where other non-climatic sources of change, such as land use, affect the capacity of ecosystems to provide hydrological services (*very high confidence*) (Cerrón et al., 2019; Molina et al., 2020). The countries in this sub-region (Colombia, Ecuador and Peru) are among the most vulnerable in terms of well-being and health (Figure 12.7; Nagy et al., 2018).

12.3.2.4 Impacts

An increase in the frequency of climate-related disasters has been reported (*high confidence*) (Huggel et al., 2015a; Stäubli et al., 2018) (WGI AR6 Chapter 12) (Ranasinghe et al., 2021). Scale studies indicate an increase of flood risk during the 21st century, consistent with more frequent floods, with the risk being worse in higher emission scenarios (*high confidence*) (Arnell and Gosling, 2013; Hirabayashi et al., 2013; Alfieri et al., 2017; WGI AR6 Chapter 12, Ranasinghe et al., 2021). Those living on riverbanks and in slums built on steep slopes are among the most affected by floods of all kinds (*high confidence*) (Emmer et al., 2016; Emmer, 2017). There is still uncertainty in relation to future drought intensity and frequency (Pabón-Caicedo et al., 2020).

Increased SST, coupled with stronger ENSO events, will affect marine life and fisheries by loss of productive habitat, disruption of nutrient structure, productivity and alteration of species migration patterns, leading to changes in fishing rates, which will impact coastal livelihoods (*high confidence*) (Bayer et al., 2014; Cai et al., 2015; Ding et al., 2017; Mariano Gutiérrez et al., 2017; Bertrand et al., 2020). Figure 12.8 shows other observed sensitivities in several ecosystems and in such places as the Galapagos and Malpelo islands and coastal economic exclusion zones (EEZs).

ENSO events coupled with climate change lead to warmer ocean temperatures, heavy rains, floods and heavy river discharges, which

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Historical changes (1950–59 to 2010–2019)
in suitability for malaria transmission

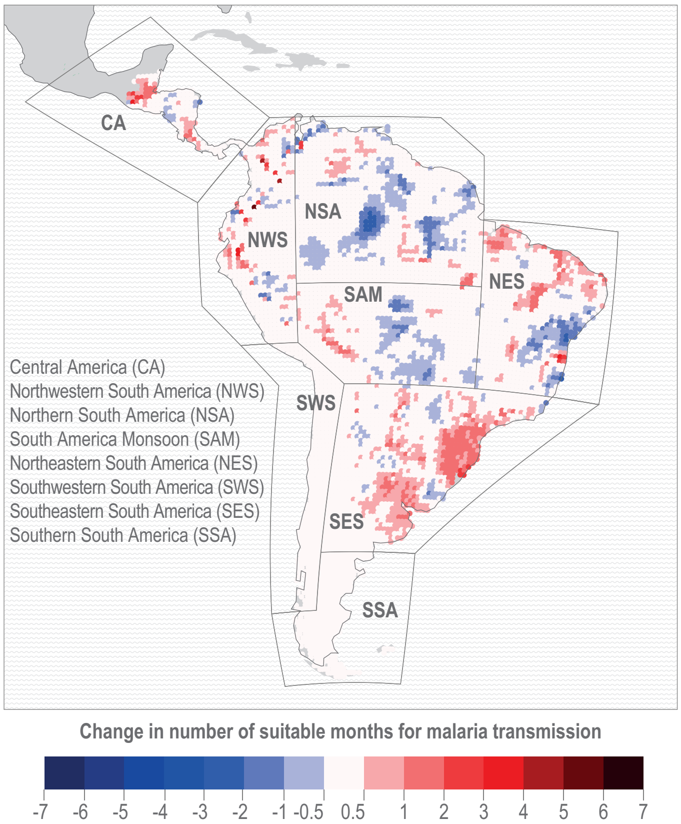

Figure 12.4 | Change in average number of months in a given year suitable for malaria transmission by *Plasmodium falciparum*, from 1950–1959 to 2010–2019. The threshold-based model used incorporates precipitation accumulation, average temperature and relative humidity (Grover-Kopec et al., 2006; Romanello et al., 2021).

will continue to impact several activities, including small-scale fishery infrastructure (*very high confidence*). In Peru alone, wet extremes are estimated to be at least 1.5 times more likely to happen compared to pre-industrial times. The extremely wet ENSO event of 2017 resulted in 6–9 billion USD in monetary losses in that country, 1.7 million inhabitants affected and crops, roads, bridges, homes, schools and health service facilities damaged or destroyed. Distinct types of ENSO events can have differentiated impacts (French and Mechler, 2017; Christidis et al., 2019; Takahashi and Martínez, 2019; Bertrand et al., 2020; Coayla and Culqui, 2020).

Irrigation, potable water, health and education infrastructures, as well as roads, bridges, cities and residential constructions, are frequently damaged or destroyed by extreme precipitation events, which also impact sediment transport, river erosion and annual discharge (*very high confidence*) (Martínez et al., 2017; Morera et al., 2017; Isla, 2018; Rosales-Rueda, 2018; Salazar et al., 2018; Puente-Sotomayor et al., 2021). The increasing variability of precipitation has compromised rainfed agriculture and power generation, particularly in the dry season (*high confidence*) (Bradley et al., 2006; Bury et al., 2013; Buytaert et al., 2017; Carey et al., 2017; Vuille et al., 2018; Orlove et al., 2019). For the Amazon–Andes transition zone, the impacts of hydrological variability and transport of sediments have been noticed in riparian agriculture and biodiversity (*high confidence*) (Maeda et al., 2015; Espinoza et al., 2016; Vauchel et al., 2017; Ronchail et al., 2018; Ayes Rivera et al., 2019; Armijos et al., 2020; Figueroa et al., 2020; Pabón-Caicedo et al., 2020). Changes in seasonality and rain patterns are affecting coffee producers (Lambert and Eise, 2020).

Increases in vector-borne diseases can be related to increases in rainfall and minimum temperatures during ENSO events (Stewart-Ibarra and Lowe, 2013) and the expansion of the diseases' altitudinal distribution (*high confidence*) (Lowe et al., 2017; Lippi et al., 2019; Portilla Cabrera and Selvaraj, 2020). ENSO events have been related to such diseases as dengue and leptospirosis (Quintero-Herrera et al., 2015; Sánchez et al., 2017; Arias-Monsalve and Builes-Jaramillo, 2019); they can also lead to an increased incidence of chikungunya (Sections 7.2.2.1 and 7.3.1.3). Precipitation, relative humidity and temperature have influenced dengue incidence in recent years (Mattar et al., 2013) (Table 12.1). Dengue cases are predicted to increase in the 1.5°C and the 3.7°C warming scenarios by 2050 and 2100, with increases ranging from 28,900 to 88,800 in Peru, 34,600 to 110,000 in Ecuador, and 97,400 to 317,000 in Colombia, although these scenarios do not consider the potential effects of vaccines or socioeconomic trajectories (Colón-González et al., 2018). Other studies found that *Aedes aegypti* (arbovirus vector) will shift into higher elevations, increasing the populations at risk (Figure 12.5) (Lippi et al., 2019). Climate change will contribute to increased malaria vectorial capacity (*high confidence*) (Section 7.2.2.1) (Laporta et al., 2015). Increases in minimum temperature were associated with historical malaria transmission when taking into consideration disease control interventions and climate factors (Fletcher et al., 2020). Figure 12.4 shows mixed changes in the number of months suitable for malaria transmission, with low-lying areas in coastal regions becoming more suitable. Zoonotic tick-borne diseases and the epidemiology of tuberculosis are also influenced (Garcia-Solorzano et al., 2019; Rodriguez-Morales et al., 2019).

Accelerated warming is reducing tropical glaciers. Glacier volume loss and permafrost thawing will continue in all scenarios (*high confidence*) (Ranasinghe et al., 2021). On average, the tropical Andes have lost about 30% and more of their area since the 1980s (Basantes-Serrano et al., 2016; Mark et al., 2017; Thompson et al., 2017; Rabatel et al., 2018; Vuille et al., 2018; Reinthaler et al., 2019a; Seehaus et al., 2019; Masiokas et al., 2020). In a low-emissions scenario, by the end of the 21st century, Peru will lose about 50% of its present glacier surface, while in a high-emission scenario there will remain very small areas of only about 3–5% on the highest peaks (Schauwecker et al., 2017).

Changing glaciers, snow and permafrost (Figure 12.13), in synergy with land use change, have implications for the occurrence, frequency and magnitude of derived floods and landslides (*high confidence*) (Huggel et al., 2007; Iribarren Anacona et al., 2015; Emmer, 2017; Mark et al., 2017), as well as for landscape transformation through lake formation or drying and for alterations in hydrological dynamics, with impacts on water for human consumption, agriculture, industry, hydroelectric generation, carbon sequestration and biodiversity (*high confidence*) (Michelutti et al., 2015; Carrivick and Tweed, 2016; Kronenberg et al., 2016; Emmer, 2017; Mark et al., 2017; Milner et al., 2017; Polk et al.,

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2017; Reyer et al., 2017; Young et al., 2017; Vuille et al., 2018; Cuesta et al., 2019; Drenkhan et al., 2019; Hock et al., 2019; Motschmann et al., 2020a).

Water flow has decreased in several basins, such as the Shullcas River in the Cordillera Huaytapallana in Peru, and is expected to decrease in the near future in places such as the Cordillera Blanca in Peru (*very high confidence*) (Baraer et al., 2012; Vuille et al., 2018; Somers et al., 2019; Molina et al., 2020). Disruptions in water flows will significantly degrade or eliminate high-elevation wetlands (*high confidence*) (Bury et al., 2013; Dangles et al., 2017; Mark et al., 2017; Polk et al., 2017; Cuesta et al., 2019). Impacts on wetlands are affecting the wild vicuña and the domesticated alpaca (Duchicela et al., 2019). New lakes represent a source of future hazards and water scarcity, as well as opportunities to serve as water reservoirs (Colonia et al., 2017; Drenkhan et al., 2019). The timing and extent of peak water due to glacier shrinkage is spatially highly variable and has passed for a large number of tropical Andes glaciers (Hock et al., 2019). Cities dependent on glacier melt have experienced high variability in domestic water supply (Chevallier et al., 2011; Soruco et al., 2015; Mark et al., 2017), as shown in Case Study 2.7.3, but an increase in demand may also have an effect (Buytaert and De Bièvre, 2012). Water provision is related to socioeconomic issues (Drenkhan et al., 2015). Glacier retreat impacts Andean pastoralists (*high confidence*), as shown in Case Study 2.6.5.4.

NWS houses several global priority areas for biodiversity conservation, including the Tropical Andes and Tumbes-Chocó-Magdalena terrestrial biodiversity hotspots (Section CCP1.2.2; Manes et al., 2021). Biodiversity in the Tropical Andes and Tumbes-Chocó-Magdalena is projected to suffer negative impacts (*medium confidence: medium evidence, high agreement*) (Figure 12.9). Invasive plant species might benefit from climate change in these hotspots (Wang et al., 2017a). Species distribution is changing upslope due to increasing air temperature, leading to range contraction and local extinctions of highland species, whereas lowland species are experiencing range contractions at the rear end and expansions in the front end, including vectors of diseases (*high confidence*) (Crespo-Pérez et al., 2015; Duque et al., 2015; Morueta-Holme et al., 2015; Moret et al., 2016; Aguirre et al., 2017; Cuesta et al., 2017a; Seimon et al., 2017; Fadrique et al., 2018; Tito et al., 2018; Zimmer et al., 2018; Cauvy-Fraunié and Dangles, 2019; Cuesta et al., 2019; Moret et al., 2020; Rosero et al., 2021). Vegetation in summits of the northern Andes is particularly vulnerable because of a high abundance of endemic species with narrow thermal niches and lowland dispersal capacity in comparison to the central Andes (Cuesta et al., 2020).

The upper limit of alpine vegetation (paramo) shifted upslope 500 m in the Chimborazo (Morueta-Holme et al., 2015), yet the upper forest limit (the ecotone between forest and alpine vegetation) is migrating at slower rates or not at all (Harsch et al., 2009; Rehm and Feeley, 2015b), so it is expected to be a major barrier to migration to several montane species, leading to population reductions and biodiversity losses (Lutz et al., 2013; Rehm and Feeley, 2015a). Shifts in tree species distribution may result in decreased above-ground carbon stocks and productivity in tropical mountain forests (*high confidence*) (Feeley et al., 2011; Duque et al., 2015; Fadrique et al., 2018; Duque et al., 2021), a biomass loss that will only be partially offset through increased recruitment and growth of lowland species migrating upslope. Water scarcity can enhance tree mortality and decrease above-ground carbon stocks (Álvarez-Dávila et al., 2017; McDowell et al., 2020). The agricultural frontier of crops, such as potatoes or maize, is moving upwards (*high confidence*), following the freezing level height upward displacement (Morueta-Holme et al., 2015; Skarbø and VanderMolen, 2016; Schauwecker et al., 2017; Vuille et al., 2018). Modelling exercises agree with the observed impacts in species, ecosystem processes, crop impacts and related pests and diseases (*high confidence*) (Cernusak et al., 2013; Tovar et al., 2013; Ramirez-Villegas et al., 2014; Ovalle-Rivera et al., 2015; van der Sleen et al., 2015; Lowe et al., 2017). Agricultural options are changing as a result of intra-seasonal temperature variation (Ponce, 2020). Changes in the timing and amount of precipitation are also impacting agriculture (Table 12.4) (Heikkinen, 2017; Altea, 2020).

Species distribution is changing in dry lowland forests, where deforestation is the more intense driver and climate change is intensely acting (Aguirre et al., 2017; Manchego et al., 2017). Extinctions in amphibians have been related to temperature rises acting in synergy with diseases (Catenazzi et al., 2014). The fungus *Batrachochytrium dendrobatidis* successfully accompanied and caused disease in high-elevation Andean frogs as they expanded their ranges to 5200–5400 m (Seimon et al., 2017). Several groups of freshwater species of the tropical Andes represent 35% of threatened freshwater species in the world (Gardner and Finlayson, 2018). Potential impacts of species turnover in key areas for biodiversity conservation have been identified (Cuesta et al., 2017b).

Climate-change-related hazards could foster rural poverty, and its impacts have led to the modification of agriculture calendars and irrigation adjustments (Postigo, 2014). Livestock populations are diminishing due to rising temperatures, changing water flows and shrinkage of pastures, particularly cattle and pig production (Bayer et al., 2014; Tapasco et al., 2015; Bergmann et al., 2021). In some cases farmers respond to extreme temperatures by increasing use of land and crop intensity (Aragón et al., 2021). Climate change has prompted and will continue to prompt internal and international migrations (Løken, 2019; Bergmann et al., 2021). A change in fire regimes and fire risk is expected in highland ecosystems, although it is difficult to determine the influence of human activities and climate change influence on fire patterns (Oliveras et al., 2014, 2018; Armenteras et al., 2020).

12.3.3 Northern South America Sub-region

12.3.3.1 Hazards

A significant increase in the intensity and frequency of warm extremes and length of heatwaves and a decrease in the frequency of cold extremes (Skansi et al., 2013) were *likely* observed (Figure 12.6) (WGI AR6 Table 11.13) (Donat et al., 2013; Almeida et al., 2017; Seneviratne et al., 2021). Precipitation showed increasing trends in annual and wet season totals over the eastern part and decreasing trends in the dry season (Almeida et al., 2017). An increase in the frequency of anomalous severe floods (Gloor et al., 2015) was observed, but insufficient data coverage for extreme precipitation and trends in the available data

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result in *low confidence* (Avila-Diaz et al., 2020; Dereczynski et al., 2020; Dunn et al., 2020; Sun et al., 2021) (WGI AR6 Table 11.14) (Seneviratne et al., 2021). Droughts presented mixed trends between sub-regions, but evidence indicates an increasing length of dry periods (*low confidence*) (WGI AR6 Tables 11.15 and 12.3) (Skansi et al., 2013; Marengo and Espinoza, 2016; Spinoni et al., 2019; Avila-Diaz et al., 2020; Dereczynski et al., 2020; Dunn et al., 2020; Seneviratne et al., 2021; Ranasinghe et al., 2021).

An overall increase in temperature by the end of the century is projected for all seasons, from 2°C to 6°C depending on the scenario (Chou et al., 2014). Projections also suggest increases in the intensity and frequency of hot extremes and decreases in the intensity and frequency of cold extremes (*very likely* for a 2°C GWL) (WGI AR6 Table 11.13) (López-Franca et al., 2016; Seneviratne et al., 2021). In the entire region, extreme maximum temperature estimates under the RCP4.5 scenario are projected to increase. Major tropical cities are expected to be strongly affected by heatwaves and daily record temperatures (Feron et al., 2019).

A decrease in precipitation over the tropical region but regional changes, such as increases in rainfall amounts in western NSA of up to 40 mm, are expected by mid-century under RCP8.5 (Teichmann et al., 2013; Sánchez et al., 2015). Changes in the dry season in the central part of South America (SA) due to the late onset and late retreat of monsoon, decreases in precipitation over the Amazon and central Brazil are expected (Coppola et al., 2014; Giorgi et al., 2014; Llopart et al., 2014). Further, an increase in the frequency and geographic extent of meteorological drought in the eastern Amazon and the opposite in the west are expected with *medium confidence* (Duffy et al., 2015). A decrease in the total annual precipitation but an increase in heavy precipitation (Seiler et al., 2013; Chou et al., 2014) are projected for a 2°C GWL (Figure 12.6; WGI AR6 Table 11.15) (Seneviratne et al., 2021).

Mean precipitation will decrease, and heavy precipitation, aridity and drought are projected to increase with *medium confidence*, whereas mean temperature, extreme heat, fire weather and coastal and oceanic climate impact drivers will all increase with *high confidence* (WGI AR6 Table 12.6 and Figure 12.8) (Sun et al., 2019; Ranasinghe et al., 2021).

12.3.3.2 Exposure

In NSA the percentage of the national population living in low elevation coastal zones (LECZs) and exposed to SLR is 68% for Suriname, 56% for Guyana and 6% for Venezuela (Nagy et al., 2019). In these countries, the exposure of populations, land areas and built capital to coastal floods is projected to continue and increase (Neumann et al., 2015; Reguero et al., 2015).

In the Amazon basin, approximately 80% of the population is concentrated in cities due to migrations in search of improvements in education, job opportunities, health and goods and services (Eloy et al., 2015; Pinho et al., 2015). These populations settle in areas prone to flooding combined with various levels of sanitation due to limited economic access to areas of lower risk (Pinho et al., 2015; Mansur et al., 2016; Andrade and Szlafsztein, 2018; Parry et al., 2018). In these areas, poor urban planning and high population densities increase exposure levels (Mansur et al., 2016). In this context, 41% of the total population of urban centres of the Amazon delta and estuary (ADE) are exposed to flooding (Mansur et al., 2016), while in Santarem, population and infrastructure are highly exposed to floods and flash floods (Andrade and Szlafsztein, 2018).

Exposure of the Brazilian Amazon to severe to extreme drought has increased from 8% in 2004/2005 to 16% in 2009/2010 and 16% in 2015/2016 (Anderson et al., 2018b); a similar trend is reported in other regions (Table 12.3). During the extreme drought of 2015/2016 in the Amazonian forests, 10% or more of the area showed negative anomalies of the minimum cumulative water deficit (Anderson et al., 2018b). This extreme drought also caused an increase in the occurrence and spread of fires in the basin (*medium confidence: medium evidence, high agreement*) (Aragão et al., 2018; Lima et al., 2018; Silva Junior et al., 2019; Bilbao et al., 2020). Exposure to anomalous fires in ecosystems such as savannahs, which are more fire-prone, increases the exposure and vulnerability of adjacent forest ecosystems not adapted to fire, such as seasonally flooded forests (Bilbao et al., 2020; Flores and Holmgren, 2021).

12.3.3.3 Vulnerability

NSA is one of the most vulnerable sub-regions in the region, after CA, as evidenced by its very high vulnerability in four of the six sectors assessed (Figure 12.7). The LECZ of Venezuela, Guyana and Suriname are highly vulnerable to climate change due to SLR (*high confidence*) (CAF, 2014; Mycoo, 2014; Reguero et al., 2015; Villamizar et al., 2017; Nagy et al., 2019). In Guyana, the combined effect of increased rainfall intensity and SLR has caused flooding over the past two decades, increasing the vulnerability of the agricultural sector (Tomby and Zhang, 2019).

The unprecedented extreme events of floods (2009, 2012 and 2014) and drought (2010) in the Amazon basin led to increased societal vulnerability (*medium confidence*: *medium evidence, high agreement*) (Mansur et al., 2016; Debortoli et al., 2017; Marengo et al., 2018; Menezes et al., 2018). The disruption of the region's natural hydrology dynamics as a consequence of extreme events increases the sensitivity of the food and transport systems of the Indigenous Peoples and rural resource-dependent communities (Pinho et al., 2015).

Migration by Indigenous Peoples and rural resource-dependent communities to cities has increased due to urbanisation, development of extractive activities, agroindustry and infrastructure. Upon migrating, they are forced to abandon their livelihoods in order to acquire temporary jobs and to live in poverty and exclusion conditions on the periphery of the city (Cardoso et al., 2018). Between 60% and 90% of the population in the urban centres of ADE live in conditions of moderate to high degree of vulnerability (Mansur et al., 2016) (Figure 12.7). Amazon populations located in remote urban centres with limited or non-existent roads are more vulnerable to extreme events in relation to more connected urban centres (Parry et al., 2018). These highly risky circumstances reduce the adaptive capacity of these populations (Cardoso et al., 2018). Nevertheless, the dynamics of the adaptive capacity of Indigenous Peoples and rural resource-dependent communities is a complex issue. There is a robust and growing body of literature showing that resource-dependent communities located in remote areas address climate anomalies by reducing the vulnerability of socioecological systems through IKLK (*high confidence*) (Mistry et al., 2016; Vogt et al., 2016; Bilbao et al., 2019, 2020; Camico et al., 2021).

Amazonian forests constitute one of the major carbon (C) sinks on Earth (Pan et al., 2011), playing a pivotal role in the climate system and regional balance of C and water (Marengo et al., 2018; Molina et al., 2019). Deforestation, temperature increase and any factor affecting forest ecosystem dynamics will have an impact on atmospheric CO_2 concentrations and, hence, on the global climate (Ruiz-Vásquez et al., 2020; Sullivan et al., 2020).There is robust scientific evidence of the high vulnerability of Amazon rainforests to increasing temperature and repeated extreme drought events (*high confidence*) (Figure 12.7) (Brienen et al., 2015; Olivares et al., 2015; Feldpausch et al., 2016; Zhao et al., 2017; Anderson et al., 2018b; Anjos and De Toledo, 2018; Yang et al., 2018; Barkhordarian et al., 2019; Sampaio et al., 2019; Rammig, 2020; Sullivan et al., 2020).

12.3.3.4 Impacts

Suriname has experienced coastal erosion and flooding, which causes damage to infrastructure, agriculture and ecosystems, while Georgetown has suffered a significant number of floods (CAF, 2014). In Guyana, coastal flooding has negatively impacted agricultural activity (Tomby and Zhang, 2018) (Figure 12.9). Sugarcane production has been one of the most impacted cash crops. The impact on sugar production has affected Guyana's sugar industry (Tomby and Zhang, 2019). Among the main impacts observed in the sugar industry are an increase in production costs, greater use of pesticides and fertilizers and a reduction in worker income (Tomby and Zhang, 2018).

Indigenous Peoples and resource-dependent rural communities in the Amazon have been impacted over the last decade by extreme drought and flood events in various dimensions of their livelihoods (Pinho et al., 2015). Food security has been strongly impacted since it is based on fishing and small-scale agriculture, two sectors highly vulnerable to climate change. During extreme events, fishing decreases due to limited access to fishing grounds (*medium confidence*: *low evidence, high agreement*) (Figure 12.9) (Pinho et al., 2015; Camacho Guerreiro et al., 2016. Overfishing, deforestation and dam construction are a threat to fishing in the sub-region (Lopes et al., 2019) and therefore contribute to exacerbating the impacts of climate change. Small-scale agriculture practices (e.g., floodplain agriculture and slash and burn) are highly coupled with natural hydrological cycles and therefore severely affected by extreme events (Figure 12.9) (Cochran et al., 2016). Livelihoods are also impacted by disruptions in land and river transport, restrictions in drinking water access, increased incidence of forest fires and disease outbreaks (*medium confidence*: *medium evidence, high agreement*) (Figure 12.9) (Marengo et al., 2013; Pinho et al., 2015; Marengo and Espinoza, 2016; Marengo et al., 2018). In addition, flood events have caused losses of homes and disruption of public and commercial services (Figure 12.9) (Parry et al., 2018).

Several vector-driven diseases such as malaria and leishmaniasis are endemic in the Amazon region; however, socio-environmental changes are altering their natural dynamics (Confalonieri et al., 2014b). An important relationship between the outbreak of infectious diseases and changes in climatic events (e.g., droughts, floods, heat waves, ENSO) or environmental events (e.g., deforestation, dam construction and habitat fragmentation) has been found to exist for the Brazilian Amazon (*medium confidence*: *medium evidence, high agreement*) (Pan et al., 2014; Filho et al., 2016; Nava et al., 2017; Ellwanger et al., 2020). These impacts are more severe in poor populations with limited access to health services (Pan et al., 2014; WHO and UNFCCC, 2020). In the case of Venezuela, the impact of climate change on the epidemiology of malaria has been studied, showing significant influence on transmission in the Amazonia area of the country (Figure 12.4) (Laguna et al., 2017). Other studies from Venezuela have documented the role of ENSO in dengue outbreaks (Vincenti-Gonzalez et al., 2018). Table 12.1 shows the changes observed in reproduction potential for dengue in the different sub-regions due to changes in rainfall and temperature. Forest fires pose a major threat to public health in the region because they relate to an increase in hospital admissions due to respiratory problems, mainly among children and the elderly (Figure 12.5). The amount of air pollutants detected is sometimes higher than that observed in large urban areas, especially during dry seasons when biomass burning increases (Aragão et al., 2016; de Oliveira Alves et al., 2017; Paralovo et al., 2019).

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Table 12.1 | Environmental suitability for transmission of dengue by *Aedes aegypti* as modelled by the influence of temperature and rainfall on vectorial capacity and vector abundance; this is overlaid on human population density data to estimate the reproduction potential for these diseases (R_0, expected number of secondary infections resulting from one infected person). The southwestern South America (SWS) and southern South America (SSA) sub-regions are not presented because the vector is not abundant in these areas and the estimated R_0 is lower than 0.01. Data were derived from Romanello et al. (2021).

Sub-region	Average R_0 1950–1954	Average R_0 2016–2020	Absolute change in R_0 from 1950–1954 to 2016–2020	Percentage change in R_0 from 1950–1954 to 2016–2021
Central America (CA)	3.00	3.53	0.53	18%
Northwestern South America (NWS)	1.85	2.40	0.55	30%
Northern South America (NSA)	1.31	2.05	0.74	56%
South America Monsoon (SAM)	0.93	1.67	0.74	80%
Northeastern South America (NES)	2.11	2.47	0.36	17%
Southeastern South America (SES)	0.64	0.81	0.17	26%

Climate-change impacts have also been observed in the oceans, coastal ecosystems (coral reefs and mangroves), EEZs and saltmarshes in NSA; further impacts are expected in coral reefs, estuaries, mangroves and EEZs in the sub-region (Figure 12.9). Species in freshwater ecoregions (e.g., the Orinoco and Amazon Rivers and their flooded forests) are predicted to suffer a decrease in range and climatic suitability (*medium confidence: low evidence, high agreement*) (Section CCP1.2.3; Manes et al., 2021). A significant decrease in climate refugia (90%) for multiple vertebrate and plant species in the region has been projected for a 4°C scenario, with considerable benefits of mitigation and reducing risks to 40% for a 2°C scenario (Warren et al., 2018).

Droughts in 2009/2010 and 2015/2016 increased tree mortality rate in Amazon forests (Doughty et al., 2015; Feldpausch et al., 2016; Anderson et al., 2018b), while productivity showed no consistent change; some authors reported a drop in productivity (Feldpausch et al., 2016), while others found no significant changes (Brienen et al., 2015; Doughty et al., 2015). Nevertheless, the combined effect of increasing tree mortality with variations in growth results in a long-term decrease in C stocks in forest biomass, compromising the role of these forests as a C sink (*high confidence*) (Brienen et al., 2015; Rammig, 2020; Sullivan et al., 2020) (Figure 12.9). Under the RCP8.5 scenario for 2070, drought will increase the conversion of rainforest to savannah (*medium confidence*: *medium evidence, high agreement*) (Anadón et al., 2014; Olivares et al., 2015; Sampaio et al., 2019). The transformation of rainforest into savannah will bring forth biodiversity loss and alterations in ecosystem functions and services (*medium confidence*: *medium evidence, high agreement*) (Anadón et al., 2014; Olivares et al., 2015; Sampaio et al., 2019). In the Amazon basin, the synergistic effects of deforestation, fire, expansion of the agricultural frontier, infrastructure development, extractive activities, climate change and extreme events may exacerbate the risk of savannisation (*medium confidence*: *medium evidence, high agreement*) (Nobre et al., 2016b; Bebbington et al., 2019; Sampaio et al., 2019; Rammig, 2020).

12.3.4 South America Monsoon Sub-region

12.3.4.1 Hazards

Temperature extremes have *likely* increased in the intensity and frequency of hot extremes and decreased in the intensity and frequency of cold extremes (Donat et al., 2013; Bitencourt et al., 2016) (WGI AR6 Table 11.13, Seneviratne et al., 2021). In a vast transition zone between the Amazon and the Cerrado Biomes within the region, analysis of seasonal precipitation trends suggested that almost 90% of the observational sites showed a reduction in the length of the rainy season in the region (Debortoli et al., 2015), in the period 1971–2014 (Marengo et al., 2018), confirming the growth in length of the dry season. Changes in the hydrological and precipitation regimes, characterised by a reduction in rainfall in southern Amazonia, in contrast to an increase in northwestern Amazonia, and overall increases in extreme precipitation and in the frequency of consecutive dry days have been reported by several authors (Fu et al., 2013; Almeida et al., 2017; Marengo et al., 2018; Espinoza et al., 2019a) with *low confidence* (WGI AR6 Table 11.14) (Seneviratne et al., 2021) due to insufficient data coverage and trends in available data generally not significant.

The Amazon has been identified as one of the areas of persistent and emergent regional climate-change hotspots in response to various representative concentration pathways (Diffenbaugh and Giorgi, 2012). In Bolivia, CMIP3/5 models projected an increase in temperature (2.5°C–5.9°C), with seasonal and regional differences. In the lowlands, both ensembles agreed on less rainfall (–19%) during drier months (June–August and September–November), with significant changes in interannual rainfall variability, but disagreed on changes during wetter months (January–March) (Seiler et al., 2013). As a consequence of higher temperatures and reduced rainfall, an increased water deficit would be expected in the Brazilian Pantanal (Marengo et al., 2016; Bergier et al., 2018; Llopart et al., 2020) with *high confidence*. The largest increases in warmer days and nights, and aridity, drought and significant increases in fire occurrence are calculated over the Amazon area (Huang et al., 2016). Over the entire region, by mid-century (RCP4.5) there is *medium confidence* of increases in river and pluvial floods, aridity and mean wind speed, and extreme heat, fire weather and drought are projected to increase with *high confidence* (WGI AR6 Table 12.6; Ranasinghe et al., 2021).

12.3.4.2 Exposure

A large expansion in cropland area (soybean, corn and sugarcane) was observed in the past two decades in SAM, in response to increased local and global demand for biofuels and agricultural commodities (*high confidence*) (Lapola et al., 2014; Cohn et al., 2016). Feedbacks to the climate system resulting from such land use changes are intricate. The clear-cutting of Amazon forest and Cerrado savannah in the region led to a local warming due to an increase in the energy balance and evapotranspiration (Malhado et al., 2010); in contrast, the replacement of pasture by agriculture have led to a local cooling effect, due to changes in the surface albedo (*medium confidence: medium evidence, medium agreement*). Deforestation of the Amazon for pastures and soybean have decreased evapotranspiration during drought months and caused a localised lengthening of the dry season in northwestern SAM by 6.5 (± 2.5) d since 1979 (*medium confidence: medium evidence, medium agreement*) (Fu et al., 2013).

It is not surprising, therefore, that while SAM is the region in CSA that experienced the highest temperature increase in the last century, it is where most of the fire spots in the sub-continent are located, owing also to the prevalent use of fires in pasturelands (*medium confidence: medium evidence, high agreement*) (Bowman et al., 2009). Recently, da Silva Junior et al. (2020) reported 6,708,350 and 6,188,606 fire foci in Cerrado and Amazonia, between 1999 and 2018, corresponding to 80% of the total observed in Brazil. The occurrence of extreme droughts has affected the carbon and water cycles in large areas of the Amazon rainforest (*high confidence*) (Lapola et al., 2014; Agudelo et al., 2019), in particular in its southern and eastern portions, where deforestation rates are higher. The loss of carbon in the Amazon region considering the combined effect of land use change in the southern portion of the region bordering Cerrado and Pantanal and global carbon emission scenarios can be as high as 38% at 4°C of warming, but limited to 8% if the Paris Agreement limit of 1.5°C is achieved (*medium confidence, medium evidence, high agreement*) (Burton et al., 2021), driving the region to be a net carbon source to the atmosphere (Gatti et al., 2021). A recent extreme drought was estimated to affect the photosynthetic capacity of 400,000 km^2 of the forest (Anderson et al., 2018b); nevertheless, there are considerable uncertainties regarding the effects of CO_2 fertilisation in tropical forests and ecosystems (*medium confidence: medium evidence, high agreement*) (Sampaio et al., 2021). Extreme drought events increase forest vulnerability to fire, directly affecting the biodiversity and the forest structure and its plant species distribution (*high agreement*) (Brando et al., 2014). Production sectors are also exposed. SAM is pointed out as a region where agricultural production will be especially impacted by climate change, affecting the production of annual crops, fruits and livestock (*medium confidence: medium evidence, high agreement*) (Lapola et al., 2014; Zilli et al., 2020).

12.3.4.3 Vulnerability

The largest expanses of remaining vegetation in the Cerrado biome are located in SAM, but the region has a small number of protected areas (only 7.5% of Cerrado vegetation occurs inside protected areas), which will leave fauna and flora with little room for moving across the landscape in the face of climate change. Protected areas—Indigenous lands included—have significantly reduced forest clear-cutting in the Amazon deforestation arc (most of which is inside SAM) (*high confidence*) (Nolte et al., 2013). However nearly 100 protected areas in the Amazon, Cerrado and Pantanal biomes inside SAM have been identified as highly or moderately vulnerable to future climate change and demand serious adaptation interventions (*medium confidence: medium evidence, high agreement*) (Feeley and Silman, 2016; Lapola et al., 2019b). Yet the maintenance of these protected areas or even the halting of deforestation may do little to impede a large-scale persistent ecosystem shift to an alternative state (crossing a tipping point) of the Amazon rainforest or even more subtle changes caused by climate change in the region (*medium confidence: medium evidence, high agreement*) (Aguiar et al., 2016a; Boers et al., 2017; Lapola et al., 2018; Lovejoy and Nobre, 2018).

The agriculture in the region is highly dependent on the climate (*high confidence*), responsible for three-fourths of the variability in agricultural yields in the region (Table 12.4). Irrigation is an important strategy for agricultural production in part of the region, but it accounts for no more than 8% of the total agricultural area in SA and 7% in CA (OECD and FAO, 2019). This practice faces potential impacts from reductions in surface water availability in future climate scenarios (Ribeiro Neto et al., 2016; Zilli et al., 2020), enhanced by non-climate drivers such as land use changes (*medium confidence: medium evidence, high agreement*) (Spera et al., 2020). The remaining fluctuation in yields relates to issues of infrastructure, market, economy, policy and social aspects. Good infrastructure, transport logistics, quality of roads and storage strongly influence the vulnerability of the agricultural sector (Figure 12.7).

The combined effects of extreme climate events and ecosystem fragmentation, for example, by deforestation or fire, lead to changes in forest structure, with the death of taller trees and reduction in diversity of plant species, loss of productivity and carbon storage (*high agreement*) (Brando et al., 2014; Reis et al., 2018). The rise of a large-scale soybean agroindustry in the early 2000s led to a faster increase in human development indicators in some regions, tightly linked to the agricultural production chain (*high confidence*) (Richards et al., 2015). Such a development also came at considerable cost to the environment (e.g., Neill et al. 2013) and the regional climate, even though a moratorium implemented in 2006 on new soy plantations on deforested areas reduced deforestation by a factor of five (*high confidence*) (Macedo et al., 2012; Kastens et al., 2017). The same sort of supply chain interventions along with incentive-based public policies applied to the beef supply chain could minimise the need for agricultural expansion in the SAM deforestation frontier (*medium confidence: medium evidence, high agreement*) (Nepstad et al., 2014; Pompeu et al., 2021).

SAM has a low population density, and the majority of the population is located in cities. The populations of some of these cities are reported as being highly vulnerable considering the enormous social inequalities embedded in these cities (*high confidence*) (Filho et al., 2016). Inequalities and uneven access to infrastructure, housing and healthcare increase populations' vulnerability to atmospheric pollution and drier conditions (*high confidence*) (Rodrigues et al., 2019; IPAM, 2020; Machado-Silva et al., 2020).

12.3.4.4 Impacts

The Amazon and the Cerrado are among the largest and unique phytogeographical domains in SA. The Brazilian Cerrado is one of the most diverse savannah in the world, with more than 12,600 plant species, with 35% being endemic (*high confidence*) (Forzza et al., 2012). Historic land cover change and concurrent climate change in the region strongly impacted the biodiversity and led to the extinction of 657 plant species for the Cerrado, which is more than four times the global recorded plant extinctions (*high confidence*) (Strassburg et al., 2017; Green et al., 2019). The effects of climate change, expressed by drought and heatwaves, lead to plant stress, compromising growth and increasing mortality (Yu et al., 2019). The fauna dependent on dew water was strongly impacted by the 1.6°C temperature rise that occurred from 1961 to 2019 (*medium confidence: medium evidence, medium agreement*) (Hofmann et al., 2021). Modelling outcomes project impacts in forest ecosystems in the region, with persistent warming and significant moisture reduction (Anjos et al., 2021), leading to a potential change in the ecosystem structure and distribution in the region (*medium confidence: medium evidence, medium agreement*) (Government of Brazil, 2020).

The observed impact on plant species in SAM is projected to worsen in a warmer world (Warszawski et al., 2013). An increasing dominance of drought-affiliated genera of tree species has been reported in the southern part of the Amazon rainforest in the last 30 years (*medium confidence: medium evidence, medium agreement*) (Esquivel-Muelbert et al., 2019). Due to the tight relationship between drought and fire occurrence, an increase of 39% to 95% of burned area is modelled to impact the Cerrado region under RCP4.5 and RCP8.5, while under RCP2.6, a 22% overshoot in temperature is estimated to impact the area in 2050 decreasing to 11% overshoot by 2100 (Silva et al., 2019d), leading to a high impact on agricultural production (*high confidence*).

SAM hosts the headwaters of important South American rivers, such as the Paraguay, Madeira, Tocantins-Araguaia and Xingu. The impact from

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Table 12.2 | Average change in mean number of days exposed to heatwaves (defined as a period of at least 2 d where both the daily minimum and maximum temperatures are above the 95th percentile for their respective climatologies) in the over-65 population in 2016–2020 relative to 1986–2005. Temperature data taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 data set; calculations were derived from Romanello et al. (2021).

Country	Number of additional days of heatwave exposure in 2016–2020 relative to 1986–2005
Argentina	4.9
Belize	8.8
Bolivia	2.2
Brazil	3.1
Chile	3.3
Colombia	9.3
Costa Rica	0.8
Ecuador	7.6
El Salvador	2.2
Guatemala	8.4
Guyana	8.2
Honduras	11.2
Nicaragua	2.2
Panama	2.6
Paraguay	2.6
Peru	3.6
Suriname	15.2
Uruguay	2.7
Venezuela	8.5

climate change is expressed differently in several sub-regions. Extreme floods in the southern Amazon and Bolivian Amazon floodplains were described and related to the exceptionally warm sub-tropical South Atlantic ocean (*high confidence*) (Espinoza et al., 2014), causing high economic impacts (losses in crop and livestock production and infrastructure) and number of fatalities (*very high confidence)* (Ovando et al., 2016). In contrast, declines in stream flow, particularly in the dry season, expressed by the ratio of runoff to rainfall, are observed for the southern part of the Amazon basin (*high evidence*) (Molina-Carpio et al., 2017; Espinoza et al., 2019b; Heerspink et al., 2020). Observed precipitation reduction in the Cerrado region impacted main water supply reservoirs for important cities in the Brazilian central region, leading to a water crisis in 2016/2017 (Government of Brazil, 2020) and affecting hydropower energy generation (Ribeiro Neto et al., 2016). Modelling studies project decreases in the river discharge rate on the order of 27% for the Tapajós basin and 53% for the Tocantins-Araguaia basin for the end of the century, which may affect freshwater biodiversity, navigation and generation of hydroelectric power (*medium confidence: medium evidence, high agreement*) (Marcovitch et al., 2010; Mohor et al., 2015). This region also holds one of the largest floodplains in the world, the Pantanal. The climatic connection of Pantanal regions to the Amazon, and the influence of deforestation in local precipitation (Marengo et al., 2018) has implications for conservation of ecosystem services and water security in Pantanal (*high confidence*) (Bergier et al., 2018). Impacts of extreme drought, with increasing numbers of dry days and the peak of fire foci, were recently reported (*robust evidence*) (Lázaro et al., 2020; Garcia et al., 2021). The projected impacts of climate change will lead to profound changes in the annual flood dynamics for Pantanal wetlands, altering ecosystem functioning and severely affecting biodiversity (*high confidence*) (Thielen et al., 2020; Marengo et al., 2021).

Soybean and corn yields in the Cerrado region will suffer one of the strongest negative impacts under the estimates of the RCP4.5 and RCP8.5 scenarios and will require high levels of investment in adaptation should they continue to be cultivated in the same areas as currently (*high confidence*) (Oliveira et al., 2013; Camilo et al., 2018). Changes in precipitation patterns are related to reductions in agricultural productivity and revenues in the southern portion of the Amazon region (*medium confidence: medium evidence, high agreement*) (Costa et al., 2019; Leite-Filho et al., 2021). Thus, the future socioeconomic vigour of the region will be, to a large extent, connected to an unlikely stability of the regional climate and eventual fluctuations of global markets potentially affecting the agricultural supply chain (*high confidence*) (Nepstad et al., 2014).

Observations from recent past droughts in SAM indicate how the incidence of respiratory diseases may worsen under a drier and warmer climate. Northwest SAM had an approximately 54% increase in the incidence of respiratory diseases associated with forest fires during the 2005 drought compared to a no-drought 10-year mean (*high confidence*) (Ignotti et al., 2010; Pereira et al., 2011; Smith et al., 2014). It is estimated that more than 10 million people are exposed to forest fires in the deforestation arc, a region comprising several Brazilian states in the southern and western parts of the Amazon rainforest, with several impacts on human health including potential exacerbation of the COVID-19 crisis in Amazonia (*medium confidence: medium evidence, high agreement*) (de Oliveira et al., 2020) (Table 12.5). Increases in hospital admissions, asthma, DNA damage and lung cell death due to the inhalation of fine particulate matter represent an increase in public health system costs (*high confidence*) (Ignotti et al., 2010; Silva et al., 2013; de Oliveira Alves et al., 2017; Machin et al., 2019). The patchy landscape created by forest clearing contributes to a rising risk of zoonotic disease emergence by increasing interactions between wildlife, livestock and humans (*medium confidence: low evidence, medium agreement*) (Dobson et al., 2020; Tollefson, 2020). Recent studies also suggest an influence of climate change in zoonotic diseases, such as *Orthohantavirus* and *Chapare* viral infections, rodent-borne diseases, in some areas of Bolivia (Escalera-Antezana et al., 2020a; Escalera-Antezana et al., 2020b). Extreme fluctuations in Amazon River levels were associated with a significant increase in the incidence of diarrhoea, leptospirosis and dermatitis (de Souza Hacon et al., 2019; Government of Brazil, 2020). According to a comprehensive characterisation of future heatwaves and alternative RCPs scenarios, Brazilian urban areas in the SAM region are projected to face increasing related mortality from 400% to 500% in the period 2031–2080 compared to the period 1971–2020, under the highest emission scenario and high-variant population scenario (*medium confidence: low evidence, medium agreement*) (Guo et al., 2018). Table 12.2 shows the increase in days of exposure to heatwaves already observed in the region.

The high risk of floods (high-frequency and costly damage) is centred in the Brazilian states of Acre, Rondônia, Southern Amazonas and Pará

(Andrade et al., 2017). Global-scale studies indicate an increase of flood risk for the SAM region during the 21st century (consistent with floods that are more frequent) (*high confidence*) (Hirabayashi et al., 2013; Arnell et al., 2016; Alfieri et al., 2017). Higher emission scenarios result in substantially higher flood risks than low emission scenarios (Alfieri et al., 2017).

12.3.5 Northeastern South America Sub-region

12.3.5.1 Hazards

The region has *likely* experienced an increase in temperature, with significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Donat et al., 2013) (WGI AR6 Table 11.13, Seneviratne et al., 2021).

A decrease in the frequency and magnitude of extreme precipitation was observed, but with *low confidence*, due to insufficient data coverage and trends in available data being generally insignificant. An increase in drought duration was observed with *high confidence* but *medium confidence* with respect to the increase of drought intensity (WGI AR6 Table 11.14, Seneviratne et al., 2021). Table 12.3 shows the estimates of changes in land area per sub-region affected by drought events; NES sub-region presented the highest changes in CSA.

The projected warming for the extreme annual maximum temperatures (TXx) over NES is +2°C for the 1.5°C scenario and about +2.5°C for the 2°C scenario (Hoegh-Guldberg et al., 2018). An increased number of tropical nights with minimum temperatures exceeding the 20°C threshold is projected (Orlowsky and Seneviratne, 2012). In general, extreme heat will increase and cold spells decrease with *high confidence*. A decrease in total precipitation is projected with *high confidence*, with an increase in heavy precipitation events and an increase in dryness (*medium confidence*). Increases in drought severity due to the combination of increased temperatures, less rainfall and lower atmospheric humidity (5 to 15% relative humidity reduction) create water deficits, which are projected for the entire region after 2041 (3–4 mm d^{-1} reduction), particularly over western NES and over the semiarid region (Marengo and Bernasconi, 2015; Marengo et al., 2017). Fire will significantly increase (*high confidence*) (Figure 12.6).

12.3.5.2 Exposure

NES is home to about 60 million people (estimate for 2019 fromIBGE [2020]]), with >70% living in urban areas (data for 2010 from IBGE [2020]; Silva et al. [2017]) and high poverty levels (>50%, data for 2003 fromIBGE [2020]]). People are exposed to intense drought and famine (*high confidence*), and about 94% of the region has moderate to high susceptibility to desertification (Marengo and Bernasconi, 2015; Spinoni et al., 2015; Vieira et al., 2015; Mariano et al., 2018; Tomasella et al., 2018; Marengo et al., 2020c). The most severe dry spell of 2012–2013 affected about 9 million people, who were exposed to water, food and energy scarcity (Marengo and Bernasconi, 2015).

People, infrastructure and economic activities are exposed to SLR in the 3800 km of coastline (*medium confidence*). The high concentration of cities on the coast is a concern (Martins et al., 2017), with all state capital cities but one on the coast, totalling almost 12 million vulnerable people (estimate for 2019 fromIBGE [2020]]). The ports of São Luís, Recife and Salvador are important exporters of Brazilian commodities, and the beaches in the sub-region are an international touristic destination, generating considerable revenues (Pegas et al., 2015; Ribeiro et al., 2017).

Natural systems in NES are also exposed to climate change. In terrestrial ecosystems, 913,000 km^2 of NES' dry forest Caatinga vegetation (Silva et al., 2017) is exposed to predicted increases in dryness. Despite what has been previously suggested, the Caatinga has high biodiversity and endemism (Silva et al., 2017), which vulnerable to habitat reduction due to climate change and agricultural expansion (Silva et al., 2019b). Fifty-two percent of the freshwater fish (203 species) are endemic (Lima et al., 2017) and are exposed to predicted reduction in river flow due to climate change (Marengo et al., 2017; de Jong et al., 2018). The coastal waters contain a separate marine ecoregion due to its uniqueness (Spalding et al., 2007). The region is responsible for 99% of Brazilian shrimp production, which is exposed to SLR and increases in ocean temperature and acidification (Gasalla et al., 2017). Most coral reefs in the Southern Atlantic Ocean are along NES's coast (Leão et al., 2016), increasing its conservation and touristic value. The 685 km^2 of coral reefs along NES's coast (likely an underestimate [Moura et al. 2013; UNEP-WCMC et al. 2018]) are exposed to increased sea temperatures.

Table 12.3 | Change in percentage of land area affected by extreme drought in 2010–2019, in relation to 1950–1959 using Standardised Precipitation-Evapotranspiration Index (SPEI); extreme drought is defined as SPEI ≤ –1.6 (Federal Office of Meteorology and Climatology MeteoSwiss, 2021). Data were derived from Romanello et al. (2021).

	Average change in percentage of land area in drought in 2010–2019 with respect to 1950–1959		
Sub-region	**At least 1 month in drought**	**At least 3 months in drought**	**At least 6 months in drought**
Central America (CA)	38.8%	17.6%	6.1%
Northwestern South America (NWS)	51.8%	25.3%	7.0%
Northern South America (NSA)	52.5%	18.3%	2.5%
South America Monsoon (SAM)	48.0%	34.4%	12.2%
Northeastern South America (NES)	64.5%	38.4%	12.0%
Southeastern SouthAmerica (SES)	16.4%	6.7%	0.4%
Southwestern South America (SWS)	20.5%	13.9%	7.5%
Southern South America (SSA)	–23.5%	–8.8%	—

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12.3.5.3 Vulnerability

NES is the world's most densely populated semiarid land and its population is highly vulnerable to droughts (*high confidence*), which have well-documented impacts on water and food security, human health and well-being in the region (e.g., Confalonieri et al. 2014a; Marengo et al. 2017; Bedran-Martins et al. 2018) (Figure 12.7). The region's relatively low economic development and poor social and health indicators increase vulnerability, especially that of poor farmers and traditional communities (Confalonieri et al., 2014a; Bech Gaivizzo et al., 2019). In state capital cities, about 45% of the population live in poverty (data for 2003 fromIBGE [2020]]), often in slums with already deficient water supply and sewage systems and poor access to health and education. Climate change will increase pressures on water availability, threatening water, energy and food security (Marengo et al., 2017).

Natural systems in NES are also vulnerable (Figure 12.7). The Caatinga vegetation is particularly sensitive to variations in water availability and climate change (Seddon et al., 2016; Rito et al., 2017; Dantas et al., 2020). It has already lost about 50% of its original vegetation cover (Souza et al., 2020), with only about 2% of the remaining vegetation within fully protected areas (CNUC and MMA, 2020). Caatinga's high vulnerability to climate change is further increased by the extensive conversion of native vegetation (*high confidence*) (Rito et al., 2017; Silva et al., 2019b, c).

Studies with terrestrial animals show that habitat loss increases the vulnerability of species to climate change (*high confidence*) (de Oliveira et al., 2012; Arnan et al., 2018; da Silva et al., 2018b). NES's coral reefs have shown some resilience to bleaching, but vulnerability is intensified by the synergy between chronic heat stress caused by increased SST (Teixeira et al., 2019) and other well-documented stressors, such as coastal runoff, urban development, marine tourism, overexploitation of reef organisms and oil extraction (*high confidence*) (Figure 12.8) (Leão et al., 2016).

12.3.5.4 Impacts

The impacts of intense drought have been reported in NES since 1780, with severe losses in agricultural production, livestock death, increase in agricultural prices and human death (Figure 12.9) (Marengo et al., 2017, 2020c; Martins et al., 2019; Government of Brazil, 2020; Silva et al., 2020). The rural population already suffers from natural water scarcity in the countryside. The drought in 2012 was responsible for reducing up to 99% of the corn production in Pernambuco state (Government of Brazil, 2020). A predicted increase in drought, coupled with inadequate soil management practices by small farmers and agribusiness, increases the region's susceptibility to desertification (Spinoni et al., 2015; Vieira et al., 2015; Mariano et al., 2018; Tomasella et al., 2018; Marengo et al., 2020c). In NES, 70,000 km^2 have reached a point at which agriculture is no longer possible (Government of Brazil, 2020). Intense droughts have triggered migration to urban centres within and outside NES (Confalonieri et al., 2014a; Government of Brazil, 2020). More than 10 million people have been impacted by the drought of 2012/2014 in the region, which was responsible for water shortage and contamination, increasing death by diarrhoea (Marengo and Bernasconi, 2015; Government of Brazil, 2020).

There is growing evidence of the impacts of climate change on human health in NES, mostly linked to food and water insecurity caused by recurrent long droughts (e.g., gastroenteritis and hepatitis) (*high confidence*) (Figure 12.9) (Sena et al., 2014; de Souza Hacon et al., 2019; Marengo et al., 2019; Government of Brazil, 2020; Salvador et al., 2020). From 2071 to 2099, thermal conditions in NES might improve for vectors of dengue, chikungunya and Zika (de Souza Hacon et al., 2019). Additionally, a high risk of mortality associated with climatic stress in the period of 2071–2099 is expected in the São Francisco river basin (de Oliveira et al., 2019; de Souza Hacon et al., 2019).

Recent studies predict strong negative impacts of climate change on NES's agriculture (*high confidence*) (Ferreira Filho and Moraes, 2015; Nabout et al., 2016; Gateau-Rey et al., 2018) (Figure 12.9; Table 12.4). NES concentrates the bulk of the predicted loss of regional gross domestic product (GDP) associated with agriculture in Brazil (Ferreira Filho and Moraes, 2015; Forcella et al., 2015). Although agriculture makes a modest contribution to the region's economy, its drop could have a severe impact on the poorest rural household by shrinking the agricultural labour market and increasing food prices (Ferreira Filho and Moraes, 2015; Government of Brazil, 2020). The expected increase in dryness is also predicted to impact the region's hydroelectric power generation (Marengo et al., 2017; de Jong et al., 2018). SLR has also been reported to impact coastal cities such as Salvador, destroying urban constructions (Government of Brazil, 2020). SLR, increased ocean temperature and acidification may also negatively impact NES's shrimp aquaculture production (Figure 12.8) (Gasalla et al., 2017). Along with climate change, overfishing has driven exploited marine fish species to collapse (Verba et al., 2020).

Biodiversity in NES is severely threatened by climate change in terrestrial (*medium confidence: medium evidence, high agreement*) and freshwater (*low confidence: low evidence, high agreement*) ecosystems (Figure 12.9). There are few studies projecting the likely impact of climate change on NES's biodiversity, especially its endemic freshwater fish. Recent studies have already reported the reduction in several endemic plant species affecting pollination and seed dispersal (Bech Gaivizzo et al., 2019; Cavalcante and Duarte, 2019; Silva et al., 2019b). Studies with terrestrial animals predict that most groups will be negatively impacted by climate change (de Oliveira et al., 2012; Arnan et al., 2018; da Silva et al., 2018b; Montero et al., 2018). Changes in the abundance of coral reef community and extreme reduction in coral cover have been observed in NES (de Moraes et al., 2019; Duarte et al., 2020). A number of observed coral bleaching events associated with an abnormal increase in sea temperatures have occurred in NES (Krug et al., 2013; Leão et al., 2016; de Oliveira Soares et al., 2019) (Figure 12.8), but thus far mortality has remained low and corals have been able return to normal values or remain stable following sea water temperature rise (*medium confidence: medium evidence, high agreement*) (Leão et al., 2016). Mangroves in the region have shown increased mortality, but they have also expanded their range inland (Figure 12.6) (Godoy and Lacerda, 2015; Cohen et al., 2018). Future projections include mangrove landward expansion and lower migration rates by 2100 (Cohen et al., 2018).

12.3.6 Southeastern South America Sub-region

12.3.6.1 Hazards

An increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes were observed with *high confidence* (Rusticucci et al., 2017; Wu and Polvani, 2017) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). There is *low confidence* that the decrease in hot extremes over SES is related to an increase in extreme precipitation (Wu and Polvani, 2017).

Over SES most stations have registered an increase in annual rainfall, largely attributable to changes in the warm season; this is one of few sub-regions where a robust positive trend in precipitation and significant intensification of heavy precipitation have been detected since the early 20th century (*high confidence*) but with *medium confidence* in a reduction of hydrological droughts (Vera and Díaz, 2015; Saurral et al., 2017; Lovino et al., 2018; Avila-Diaz et al., 2020; Carvalho, 2020; Dereczynski et al., 2020; Dunn et al., 2020; Marengo et al., 2020a; Olmo et al., 2020) (WGI AR6 Table 11.14) (Seneviratne et al., 2021). A higher observed frequency of extratropical cyclones in the region has been detected (Parise et al., 2009; Reboita et al., 2018) with three cyclogenetic foci: south-southeastern Brazil, extreme south of Brazil and Uruguay, and southeastern Argentina.

In Montevideo, mean sea levels have increased over the past 20 years, reaching 11 cm from 1902 to 2016, and a recent accelerating trend has been observed (Gutiérrez et al., 2016b). A value of water level rise and its acceleration for Buenos Aires was calculated from a record of annual mean water levels obtained from hourly levels (1905–2003). Annual mean water level showed a trend of $+1.7 \pm 0.05$ mm yr^{-1} and an acceleration of $+0.019 \pm 0.005$ mm yr^{-2} (D'Onofrio et al., 2008).

Increasing trends in mean air temperature and extreme heat and decreasing cold spells are projected (*high confidence*) (WGI AR6 Table 12.6) (Ranasinghe et al., 2021). The increase in the frequency of warm nights is larger than that projected for warm days, consistent with observed past changes that have been related to changes in cloud cover that affect daytime temperatures differently than nighttime temperatures (López-Franca et al., 2016; Menéndez et al., 2016; Feron et al., 2019).

Increases in mean precipitation (*high confidence*), pluvial floods and river floods are projected (*medium confidence*) (Nunes et al., 2018) (WGI AR6 Table 12.6) (Ranasinghe et al., 2021). Droughts in the River Plate basin will be more frequent in the medium term (2011–2040) and the distant future (2071–2100) (with respect to the 1979–2008 period), but also shorter and more severe, for the more extreme emission scenario (RCP8.5) (*low confidence*) (Carril et al., 2016).

Negative trends in the annual number of cyclone events in the long term of 3.6% to 6.5% (2070–2098) are projected and showed an increase of 3% to 11% (2080–2100 for the A1B scenario) (Grieger et al., 2014; Reboita et al., 2018). All coastal and oceanic climate impact drivers (relative sea level, coastal flood and erosion, marine heatwaves and ocean aridity) are expected to increase by mid-century in the RCP8.5 scenario (*high confidence*) (WGI AR6 Table 12.6) (Ranasinghe et al., 2021).

12.3.6.2 Exposure

Higher temperatures and SLR, changes in rainfall patterns, and an increased frequency and intensity of extreme weather events could generate risks to the energy and infrastructure sectors and to the mining and metals industry. In the River Plate basin, urban floods have become more frequent, causing infrastructure damage and sometimes substantial mortality (*high confidence*) (Barros et al., 2015; Zambrano et al., 2017; Nagy et al., 2019; Mettler-Grove, 2020; Morales-Yokobori, 2021; Oyedotun and Ally, 2021). A large increase in landslides and flash floods is also predicted for the Brazilian portion of SES, where they are responsible for the majority of deaths related to disasters in the country (*high confidence*) (Debortoli et al., 2017; Haque et al., 2019; Saito et al., 2019; Marengo et al., 2020d; da Fonseca Aguiar and Cataldi, 2021). Due to uncontrolled urban growth, 21.5 million people living in the large Brazilian cities of São Paulo, Rio de Janeiro and Belo Horizonte (estimate for 2019 fromIBGE [2020]]) are expected to be exposed to water scarcity, despite widespread water availability in the region (*medium evidence, medium agreement*) (Marengo et al., 2017, Marengo et al., 2020b; Lima and Magaña Rueda, 2018).

The expected increase in temperature will also expose the populations in large cities to extreme heat. Urban heat islands are already a reality in large cities in the region, such as Buenos Aires (*high confidence*) (Wong et al., 2013; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019; Mettler-Grove, 2020), Rio de Janeiro (*high confidence*) (Ceccherini et al., 2016; Neiva et al., 2017; Geirinhas et al., 2018; Peres et al., 2018; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019; de Farias et al., 2021) and São Paulo (*high confidence*) (Mishra et al., 2015; Barros and Lombardo, 2016; Ceccherini et al., 2016; Vemado and Pereira Filho, 2016; de Azevedo et al., 2018; Lima and Magaña Rueda, 2018; Ferreira and Duarte, 2019; Lapola et al., 2019a; Sarricolea and Meseguer-Ruiz, 2019; Wu et al., 2019), with reported impact on human health in the latter (*medium confidence: medium evidence, medium agreement*) (e.g., Araujo et al. 2015; Son et al. 2016; Diniz et al. 2020). These cities alone represent 22 million people exposed to increased heat (estimate for 2019 fromIBGE [2020]] and from INDEC [2010]).

The sub-region presents a high frequency of occurrence of intense severe convection events (Section 12.3.6.1). Because of this situation, strong winds from the south or southeast and high water levels affect the whole Argentine coast, as well as the River Plate shores, Uruguay and southern Brazil (Isla and Schnack, 2009). The coast of the River Plate is subject to flooding when there are strong winds from the southeast (sudestadas). As sea level rises as a result of global climate change, storm surge floods will become more frequent in this densely populated area, particularly in low-lying areas (*high confidence*) (Figure 12.8) (D'Onofrio et al., 2008; Nagy et al., 2014a; Santamaria-Aguilar et al., 2017; Nagy et al., 2019 impacts and adaptation in Central and South America coastal areas; Cerón et al., 2021).

The region's natural systems are also exposed to climate change. The SES region is home to two important biodiversity hotspots, with high levels of species endemism: the Cerrado and the Atlantic Forest, where about 72% of Brazil's threatened species can be found (PBMC, 2014).

12.3.6.3 Vulnerability

The River Plate basin and the city of Buenos Aires are highly vulnerable to recurring floods, and the increasing number of newcomers to the area reduce the collective cultural adaptation developed by older neighbours (*high confidence*) (Barros, 2006; Nagy et al., 2019; Mettler-Grove, 2020; Morales-Yokobori, 2021; Oyedotun and Ally, 2021). Extreme events, including storm surges and coastal inundation/flooding, cause injuries and economic/environmental losses on the urbanised coastline of Southern Brazil (States of São Paulo and Santa Catarina) (*high confidence*) (Muehe, 2010; Khalid et al., 2020; Ohz et al., 2020; de Souza and Ramos da Silva, 2021; Quadrado et al., 2021; Silva de Souza et al., 2021).

Cities like Rio de Janeiro and São Paulo are overpopulated, where most people live in poor conditions of inadequate housing and sanitation, such as slums, with little and no trees and high temperatures. These people have low access to sanitation, public health and residential cooling and are vulnerable to the effects of heat islands on human comfort and health (Figure 12.7). These include cardiopulmonary, vector-borne diseases and even death (*medium confidence: medium evidence, medium agreement*) (Araujo et al., 2015; Mishra et al., 2015; Geirinhas et al., 2018; Peres et al., 2018). Heat stress is known to worsen cardiovascular, diabetic and respiratory conditions (Lapola et al., 2019a). In connection with the heat island effect, these people are also vulnerable to injuries and casualties due to increased thunderstorms, causing economic losses and other social problems (Vemado and Pereira Filho, 2016).

12.3.6.4 Impacts

Despite the observed increase in rainfall in the region, between 2014 and 2016 Brazil endured a water crisis that affected the population and economy of major capital cities in the SES region (Blunden and Arndt, 2014; Nobre et al., 2016a). Extremely long dry spells have become more frequent in southeastern Brazil, affecting 40 million people and the economies in cities such as Rio de Janeiro, São Paulo and Belo Horizonte, which are the industrial centres of the country (*medium confidence: medium evidence, medium agreement*) (PBMC, 2014; Nobre et al., 2016a; Cunningham et al., 2017; Marengo et al., 2017, 2020b; Lima and Magaña Rueda, 2018). They have also impacted agriculture, affecting food supply and rural livelihoods, especially in Minas Gerais (Nehren et al., 2019). Agricultural prices increased by 30% in some cases, and harvest yields of sugar cane, coffee and fruits suffered a reduction of 15–40% in the region. The number of fires increased by 150%, and energy prices increased by 20–25%, as most electricity comes from hydroelectric power (Nobre et al., 2016a). In Argentina, projected changes in the hydrology of Andean rivers associated with glacier retreat are predicted to have negative impacts on the region's fruit production (*low evidence, medium agreemen*t) (Barros et al., 2015).

Heat islands affect ecosystems by increasing the energy consumption for cooling, the concentration of pollutants and the incidence of fires (*high confidence*) (Wong et al., 2013; Akbari and Kolokotsa, 2016; Singh et al., 2020b; Ulpiani, 2021). It also affects human health, as well increasing the incidence of respiratory and cardiovascular diseases (*medium confidence: medium evidence, medium agreement*) (Araujo et al., 2015; Barros and Lombardo, 2016; de Azevedo et al., 2018; Geirinhas et al., 2018).

Warming temperatures have been implicated in the emergence of dengue in temperate latitudes, increasing populations of *Aedes aegypti* (*high confidence*) (Natiello et al., 2008; Robert et al., 2019, 2020; Estallo et al., 2020; López et al., 2021) (Table 12.1), and field studies have demonstrated the role of local climate in vector activity (Benitez et al., 2021). Figure 12.5 shows the modelled transmission suitability for dengue for two climate-change scenarios. Future increases in the number of months suitable for transmission of dengue will be highest in SES (see SM12.8 for additional information). There is additional evidence of the spread of arbovirus into southern temperate latitudes (Basso et al., 2017); however, a longer historical time series is needed to understand climate–disease interactions, given the relatively recent emergence of arborvirus in this region.

SLR impacts the port complex in Santa Catarina, which during the last 6 years has interrupted its activities 76 times due to strong winds or big waves, with estimated losses varying between USD 25,000 and 50,000 for each 24 idle hours (Ohz et al., 2020). Historically, extratropical cyclones associated with frontal systems cause storm surges in the city of Santos. Although there are no fatality records, these events cause several socioeconomic losses, especially in vulnerable regions, including the Port of Santos, the largest port in Latin America (São Paulo). In an 88-year time span (1928–2016), the frequency of storm surge events was three times greater in the last 17 years (2000–2016) than in the previous period of 71 years (1928–1999) (Souza et al., 2019).

There are many projected impacts of climate change on natural systems. The impacts of SLR are habitat destruction and the invasion of exotic species, which affect biodiversity and the provision of ecosystem services (Figure 12.8) (Nagy et al., 2019).

SES is a global priority for terrestrial biodiversity conservation and is home to two important biodiversity hotspots—the Atlantic Forest and Cerrado—which are among the world's most studied biodiversity hotspots in connection with climate-change impact on biodiversity, especially for terrestrial vertebrates (Section CCP1.2.2; Manes et al., 2021). An increasing number of studies show that the Atlantic Forest and Cerrado are at risk of biodiversity loss, largely due to projected reductions of species' geographic distributions in many different taxa (e.g., Loyola et al. 2012, 2014; Ferro et al. 2014; Hoffmann et al. 2015; Martins et al. 2015; Aguiar et al. 2016b; Vale et al. 2018; Borges et al. 2019; Braz et al. 2019; Vale et al. 2021). Cerrado savannahs are projected to be the hotspot most negatively impacted by climate change within SA, mostly though range contraction of plant species (*very high confidence*), while the Atlantic Forest is projected to be highly impacted especially though the contraction of the distribution of endemic species (*very likely*) (Section CCP1.2.2; Figure 12.10) (Manes et al., 2021). Reductions in species' distribution are also projected in the River Plate basin for sub-tropical amphibians (Schivo et al., 2019) and the river tiger (*Salminus brasiliensis*), a keystone fish of economic value (Ruaro et al., 2019). Farming of mussels and oysters in the region is predicted to be negatively impacted by climate change, particularly SLR, and ocean warming and acidification (Gasalla et al., 2017). Some more localised habitats are also at risk of losing area due to climate

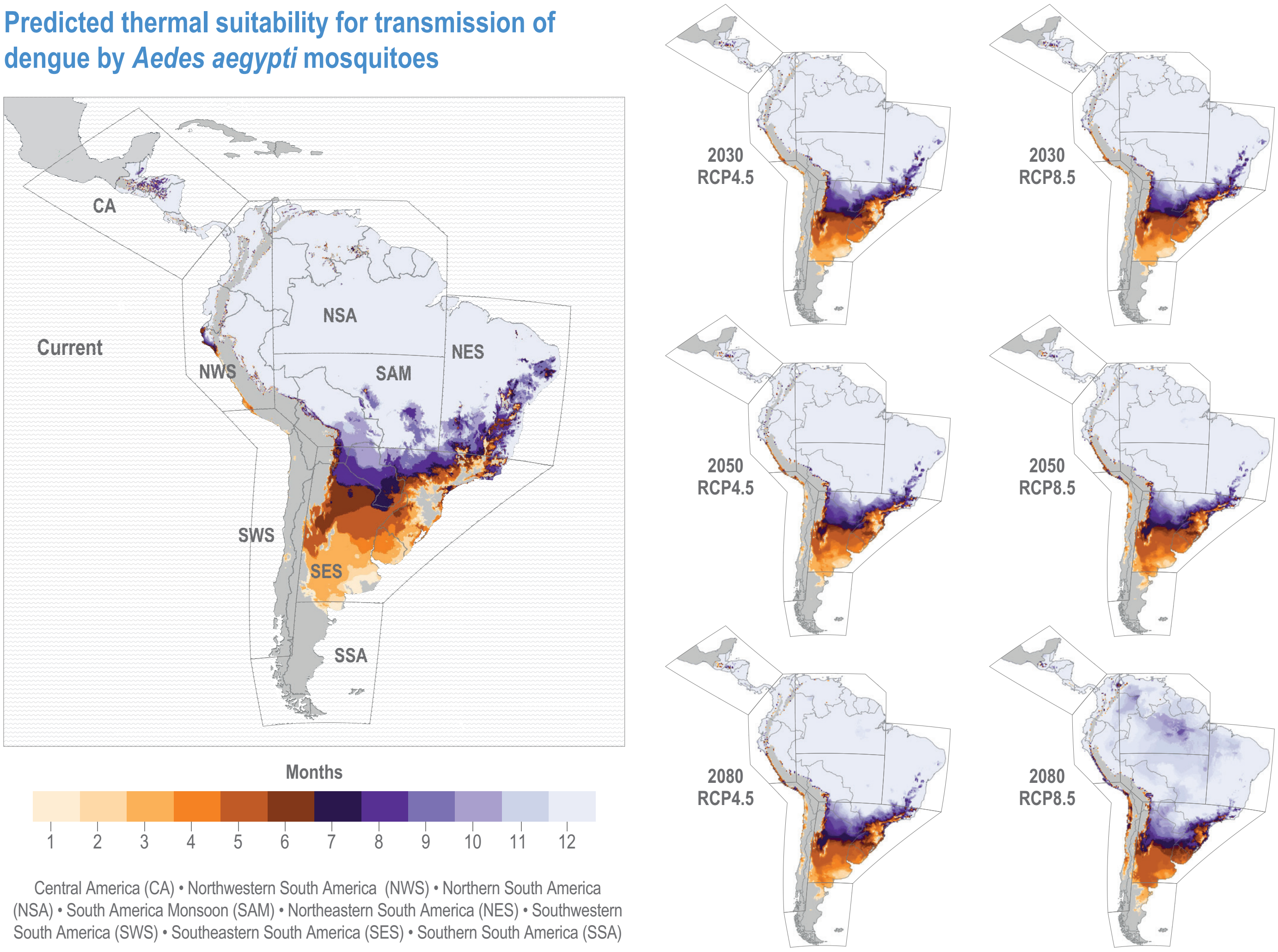

Figure 12.5 | Predicted thermal suitability for transmission of dengue by *Aedes aegypti* mosquitoes, mapped as the number of months of the year suitable under baseline or current conditions (2015), and in 2030, 2050 and 2080 under RCP4.5 and RCP8.5. Adapted from Ryan et al. (2019). See SM12.8 for additional data on population at risk for dengue and Zika in the sub-regions and methodological details.

change, such as the meadows of northwestern Patagonia (Crego et al., 2014) and mangroves of southern Brazil (Godoy and Lacerda, 2015). Predicted changes in global climate along with agricultural expansion will strongly affect South American wetlands, which comprise around 20% of the continent and bring many benefits, such as biodiversity conservation and water availability (Junk, 2013).

12.3.7 Southwestern South America Sub-region

12.3.7.1 Hazards

Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes have *likely* been observed for the region (Skansi et al., 2013; Ceccherini et al., 2016; Meseguer-Ruiz et al., 2018; Vicente-Serrano et al., 2018; Dereczynski et al., 2020; Dunn et al., 2020; Olmo et al., 2020) (WGI AR6 Table 11.13) (Seneviratne et al., 2021). In particular, a significant increment in the duration and frequency of heatwaves mainly in central Chile from 1961 to 2016 has been observed (Piticar, 2018).

A robust drying trend for Chile (30°S–48°S) has been recorded (*medium confidence*) (Saurral et al., 2017; Boisier et al., 2018). However, inconsistent trends over the region in the magnitude of precipitation extremes with both decreases and increases (Chou et al., 2014; Giorgi et al., 2014; Heidinger et al., 2018; Meseguer-Ruiz et al., 2018) (WGI AR6 Table 11.14) (Seneviratne et al., 2021) have been observed (*low confidence*). The glacier equilibrium line altitude has presented an overall increase over central Chilean Andes (Barria et al., 2019).

For central Chile, a significant increase (5% to 20% in the last 60 years) in wave heights in the sea has been observed (Martínez et al., 2018). From 1982 to 2016, sea levels at central Chile have increased 5 mm yr^{-1}, where El Niño events of 1982–1983 and 1997–1998 caused an extreme increase of 15 to 20 cm in the mean sea level (Campos-Caba, 2016; Martínez et al., 2018).

From 1946 to 2017, the number of fires and areas burned have increased significantly in Chile (*high confidence*) (González et al., 2011; Jolly et al., 2015; Úbeda and Sarricolea, 2016; de la Barrera et al., 2018; Urrutia-Jalabert et al., 2018). Fires are attributed to changes in temperature regimes (González et al., 2011; de la Barrera et al., 2018; Gómez-González et al., 2018) and precipitation regimes (*medium confidence*) (Gómez-González et al., 2018; Urrutia-Jalabert et al., 2018).

The glaciers of the southern Andes (including the SWS and SSA regions) show the highest glacier mass loss rates worldwide (*high confidence*) contributing to SLR (Jacob et al., 2012; Gardner et al., 2013; Dussaillant et al., 2018; Braun et al., 2019; Zemp et al., 2019). Since 1985, the glacier area loss in the sub-region is in a range of 20 up to 60% (Braun et al., 2019; Reinthaler et al., 2019b).

Four sets of downscaling simulations based on the Eta Regional Climate Model forced by two global climate models (Chou et al., 2014) projected warmer conditions (more than 1°C) for the entire sub-region by 2050 under the RCP4.5 scenario (*medium confidence*). Extremely warm December–January–February days as well as the number of heatwaves per season are expected to increase by 5–10 times in northern Chile (Feron et al., 2019), *likely* increasing in the intensity and frequency of hot extremes over the entire region (WGI AR6 Table 11.13) (Seneviratne et al., 2021). Drier conditions (*medium confidence*), by means of a decrease in total annual and extreme precipitation, are expected to increase for southern Chile, but inconsistent changes are expected in the sub-region (*low confidence*) (Chou et al., 2014) (WGI AR6 Table 11.14) (Seneviratne et al., 2021) with *high confidence* upon an increase in fire weather and a decrease in permafrost and snow extent (WGI AR6 Table 12.6, Ranasinghe et al., 2021).

Regional sea-level change for the region predicted by 2100 shows that total mean SLR along the coast will lie between 34 and 52 cm for the RCP4.5 scenario and between 46 and 74 cm for the RCP8.5 scenario with *high confidence* (Albrecht and Shaffer, 2016; WGI AR6 Table 12.6, Ranasinghe et al., 2021).

12.3.7.2 Exposure

There is *high confidence* that age and socioeconomic status are key factors determining health exposure and quality of life in SWS, where low-income areas show an insufficient number of public spaces to provide acceptable environmental quality in comparison with the high-income areas (Romero-Lankao et al., 2013; Fernández and Wu, 2016; Paz et al., 2016; Hystad et al., 2019; Smith and Henríquez, 2019; Jaime et al., 2020; Pino-Cortés et al., 2020).

Profound social inequalities, urban expansion and inadequate city planning (e.g., drainage network) increase exposure to flooding events and landslides (*high confidence*) (Müller and Höfer, 2014; Rojas et al., 2017; Lara et al., 2018), heat hazards such as heatwaves (*high confidence*) (Welz et al., 2014; Qin et al., 2015; Inostroza et al., 2016; Welz and Krellenberg, 2016; Krellenberg and Welz, 2017) and the loss and fragmentation of green infrastructure (GI) (Hernández-Moreno and Reyes-Paecke, 2018). SWS cities show the highest levels of air pollution of CSA (*medium confidence: medium evidence*, *high agreement*) (Pino et al., 2015; Huneeus et al., 2020; González-Rojas et al., 2021), where state air quality alerts have limited effect on protective health behaviours, since public perceptions about air pollution vary widely among the population (Boso et al., 2019). In particular, human communities living in coastal cities show a negative safety perception about the performance of the infrastructure and coastal defences to flood events (*low confidence*) (González and Holtmann-Ahumada, 2017; Igualt et al., 2019).

Although climate change is critically important for the current and future status of mining activity in SWS (Odell et al., 2018), and SWS areas subjected to mining activities are highly exposed to water risk (Northey et al., 2017), to date there is *low evidence* of climate change impacting mining activities (Corzo and Gamboa, 2018; Odell et al., 2018).

12.3.7.3 Vulnerability

Rapid changes in temperature and precipitation regimes make terrestrial ecosystems highly vulnerable to climate change (*high confidence*) (Salas et al., 2016; Fuentes-Castillo et al., 2020) (Figure 12.7). Terrestrial ecosystems dominated by exotic species (e.g., pine) with lower landscape heterogeneity and degraded soils and that are close to settlements and roads are highly vulnerable to wildfires in comparison to forests dominated by native trees (*high confidence*) (Altamirano et al., 2013; Castillo-Soto et al., 2013; Cóbar-Carranza et al., 2014; Salas et al., 2016; Bañales-Seguel et al., 2018; Gómez-González et al., 2018; Sarricolea et al., 2020). Changes in land use, artificial forestation, deforestation, agricultural abandonment and urbanisation have provoked a permanent degradation of old-growth forests, putting at risk the biodiversity, recreation and ecotourism (*medium confidence: medium evidence, high agreement*) (Rojas et al., 2013; Nahuelhual et al., 2014). Marine coastal ecosystems such as dunes, sandy beaches and wetlands show high deterioration, decreasing their ability to mitigate extreme events (*medium confidence: low evidence*, *high agreement*) (González and Holtmann-Ahumada, 2017; Ministerio de Medio Ambiente de Chile, 2019).

The water sector shows a very high vulnerability (*high confidence*) (Figure 12.7) mainly due to weak water governance focused on market aspects (e.g., inter-sectoral water transactions, setting rates, granting concessions, waiving the water right) (*high confidence*) (Hurlbert and Diaz, 2013; Valdés-Pineda et al., 2014; Barría et al., 2019; Hurlbert and Gupta, 2019; Muñoz et al., 2020a; Urquiza and Billi, 2020b). Potable water and adequate sanitation are available in SWS; however, water availability in Chile is unevenly distributed in rural communities (*high confidence*) (Valdés-Pineda et al., 2014; Nelson-Nuñez et al., 2019). Spatial differences in water availability are enhanced by strong population growth, economic development, mining activities and the high dependence of agriculture on irrigation (*high confidence*) (Stathatou et al., 2016; Northey et al., 2017; Fercovic et al., 2019). Droughts in SWS are a major threat to water security (*high confidence*) (Aitken et al., 2016; Núñez et al., 2017) as river streamflows are highly dependent on the interannual to decadal climate conditions, snow melting processes and rainfall events (Boisier et al., 2016) and impacted by land uses and changes in irrigated agriculture (*medium confidence: medium evidence, high agreement*) (Vicuña et al., 2013; Fuentes et al., 2021).

Energy and water needs of large-scale mining activities make this socioeconomic sector particularly vulnerable to climate change;

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additionally, the relative lack of power of resource-poor communities living in areas where such mining makes claims on water and energy resources renders these communities even more vulnerable (Odell et al., 2018). Given new conditions generated by changes in a growing demand and climate change, mining companies will need to increase resilience to extreme events; additionally, the declining concentrations of minerals of interest in raw materials require greater energy input for extraction and processing and new methods to avoid associated emissions are required (Hodgkinson and Smith, 2018).

Urban and agriculture sectors are vulnerable to climate change (*medium confidence: medium evidence, high agreement*) (Figure 12.7), increasing problems and demand for water (*high confidence*) (Monsalves-Gavilán et al., 2013; Meza et al., 2014; Fercovic et al., 2019). Important health problems (e.g., pathogenic infections, changes in vector-borne diseases, heat-related mortality, lower neurobehavioural performance) have been associated with agriculture, mining and thermal power production activities in SWS (*high confidence*) (Muñoz-Zanzi et al., 2014; Valdés-Pineda et al., 2014; Pino et al., 2015; Cortés, 2016; Berasaluce et al., 2019; Muñoz et al., 2019a; Ramírez-Santana et al., 2020).

Large-scale agricultural growth has increased vulnerability to climate change by disfavouring traditional agriculture, the homogenisation of the biophysical landscape and the replacement of traditional crops and native forests with exotic species like pines and eucalyptus (*high confidence*) (Torres et al., 2015), where farmers' perceptions of climate change are highly dependent on educational level and access to meteorological information (*low confidence*) (Roco et al., 2015). Agricultural systems owned by Indigenous Peoples (i.e., Mapuche, Quechua and Aymara farmers) seem to pose a lower level of vulnerability to drought and higher response capacity than non-Indigenous farmers thanks to the use of the traditional knowledge of specific management techniques and the tendency to conserve species or varieties of crops tolerant to water scarcity (*low confidence*) (Montalba et al., 2015; Saylor et al., 2017; Meldrum et al., 2018). Fishery- and aquaculture-related livelihoods are vulnerable to climate and non-climate drivers (*medium confidence: medium evidence, high agreement*), such as sea surface warming and precipitation reduction (Handisyde et al., 2017; Soto et al., 2019; González et al., 2021), changes in upwelling intensity (*low confidence*) (Oyarzún and Brierley, 2019; Ramajo et al., 2020), eutrophication and harmful algal bloom (HAB) events (Almanza et al., 2019), a lack of observational elements and data management (Garçon et al., 2019) and events such as earthquakes and tsunamis (Marín, 2019).

Chile has experienced accelerated economic growth, which has reduced poverty; however, important geographical, economic and educational inequalities remain (Repetto, 2016). The Chilean healthcare system has become more equitable and responsive to the population's needs (e.g., the Bono AUGE healthcare reform programme); however, the high relative inequalities in terms of income (OECD, 2018), education level and rural–urban factors are determinants of quality of care, health system barriers and differential access to healthcare (*high confidence*) (Frenz et al., 2014). Exposure and vulnerability to psychosocial risks in SWS show significant inequalities in times of disasters such as earthquakes according to socioeconomic, geographic and gender factors (*high confidence*) (Labra, 2002; Vitriol et al., 2014; Quijada et al., 2018), which are increased by the absence of local planning and drills and the lack of coordination (Vitriol et al., 2014). Indigenous Peoples have the highest levels of vulnerability in Chile in terms of income, basic needs and access to services to climate change (*low confidence*) (Parraguez-Vergara et al., 2016).

12.3.7.4 Impacts

Increasing temperatures in SWS have impacted temperate forests (*high confidence*) (Peña et al., 2014; Urrutia-Jalabert et al., 2015; Camarero and Fajardo, 2017; Fontúrbel et al., 2018; Venegas-González et al., 2018b; Peña-Guerrero et al., 2020). Increasing temperatures and decreasing precipitation have increased the impacts of wildfires on terrestrial ecosystems (*high confidence*) (Boisier et al., 2016; Díaz-Hormazábal and González, 2016; Martinez-Harms et al., 2017; de la Barrera et al., 2018; Gómez-González et al., 2018; Urrutia et al., 2018; Bowman et al., 2019), creating conditions for future landslides and floods (de la Barrera et al., 2018).

Future projections show important changes in the productivity, structure and biogeochemical cycles of SWS temperate and rainforests (*medium confidence: medium evidence, high agreement*) (Gutiérrez et al., 2014; Correa-Araneda et al., 2020) and their fauna (*low confidence*) (Glade et al., 2016; Bourke et al., 2018). The Chilean Winter Rainfall-Valdivian Forests are a biodiversity hotspot (Manes et al., 2021) (Section CCP1.2.2) projected to suffer habitat change, with loss of vegetation cover in the future due to climate change (*medium confidence: medium evidence, high agreement*) (Jantz et al., 2015; Mantyka-Pringle et al., 2015). Species are projected to suffer changes in their distribution, including a decrease in climatic refugia for vertebrates (*low confidence*) (Cuyckens et al., 2015; Warren et al., 2018).

Increasing temperatures have enlarged the number and areal extent of glacier lakes in the central Andes, northern Patagonia and southern Patagonia (*high confidence*) (Wilson et al., 2018), while decreased rainfall and rapid glacier melting have provoked changes in the environmental, biogeochemical and biological properties of central-southern and Andes Chilean lakes (*low confidence*) (Pizarro et al., 2016).

Increasing glacier lake outburst floods (GLOFs), ice and rock avalanches, debris flows and lahars from ice-capped volcanoes have been observed in SWS (Iribarren Anacona et al., 2015; Jacquet et al., 2017; Reinthaler et al., 2019b). There is *low evidence* on the effects of warming and degrading permafrost on slope instability and landslides in these regions (Iribarren Anacona et al., 2015).

Increasing temperatures, decreasing precipitation regimes and an unprecedented long-term drought have decreased the annual average river streamflows that supply SWS megacities such as Santiago (*high confidence*) (Meza et al., 2014; Muñoz et al., 2020a), with important and negative effects on water quality (Bocchiola et al., 2018; Yevenes et al., 2018), threatening irrigated agriculture activities (*medium confidence: medium evidence, high agreement*) (Yevenes et al., 2018; Oertel et al., 2020; Peña-Guerrero et al., 2020). Large reductions in

Table 12.4 | Average percentage change in crop growth duration for the period 2015–2019. Crop growth duration refers to the time taken in a year for crops to accumulate the reference period (1981–2010) average growing season accumulated temperature total (ATT). As temperatures rise, the ATT is reached earlier (higher negative changes), the crop matures too quickly, and thus yields are lower. "No data" means no data are available for the growth of that crop in the specified region. NP means that the crop is not present in significant areas in that region. Data were derived from Romanello et al. (2021).

Region	Winter wheat	Spring wheat	Rice	Maize	Soybean
Central America (CA)	–4.8%	No data	–1.9%	–5.0%	–4.7%
Northwestern South America (NWS)	–3.8%	–5.2%	–5.2%	–5.6%	–3.1%
Northern South America (NSA)	NP	NP	–0.7%	–3.1%	0.0%
South America Monsoon (SAM)	–5.3%	–0.7%	–1.4%	–2.9%	–1.5%
Northeastern South America (NES)	–1.0%	–1.3%	–0.7%	–3.5%	–2.6%
Southeastern South America (SES)	–2.3%	–3.5%	–2.3%	–2.4%	–2.7%
Southwestern South America (SWS)	–2.3%	–5.2%	–10.0%	–5.2%	No data
Southern South America (SSA)	–0.8%	–6.5%	No data	–1.6%	No data

the availability of groundwater in the SWS region (Meza et al., 2014) and a sustained decrease in the mean annual flows (Ragettli et al., 2016; Bocchiola et al., 2018), especially during the snowmelt season (Vargas et al., 2013), have been observed in SWS. Drought has affected wetlands (*low confidence*) (Zhao et al., 2016; Domic et al., 2018) and desert ecosystems (*medium confidence: medium evidence, high agreement)* (Acosta-Jamett et al., 2016; Neilson et al., 2017; Díaz et al., 2019).

There is *low evidence* on shoreline retreat attributed to climate change (Martínez et al., 2018; Ministerio de Medio Ambiente de Chile, 2019), although increasing wind intensity along the central Chilean coast has caused serious damage in coastal infrastructure and buildings (Winckler et al., 2017) and changes in seawater properties and processes (*low confidence*) (Schneider et al., 2017; Aguirre et al., 2018). Ocean and coastal ecosystems in SWS are sensitive to upwelling intensity, which affects the abundance, diversity, physiology and survivorship of coastal species (*high confidence*) (Anabalón et al., 2016; Jacob et al., 2018; Ramajo et al., 2020) (Figure 12.8). Increasing radiation and temperatures and reduced precipitation, in conjunction with increased nutrient load, have increased HAB events, producing massive fauna mortalities (*high confidence*) (León-Muñoz et al., 2018; IPCC, 2019b, SPM A8.2 and B8.3; Quiñones et al., 2019; Soto et al., 2019; Armijo et al., 2020). Multiple resources subjected to fisheries and aquaculture are highly vulnerable to storms, alluvial disasters, ocean warming, ocean acidification, increasing ENSO extreme events and lower oxygen availability (*high confidence*) (Figure 12.8; García-Reyes et al., 2015; Silva et al., 2015; Duarte et al., 2016, 2018; Lagos et al., 2016; Navarro et al., 2016; Lardies et al., 2017; IPCC, 2019b; Mellado et al., 2019; Ramajo et al., 2019; Silva et al., 2019a; Bertrand et al., 2020). Ocean and coastal ecosystems, especially EEZs, will be highly impacted by climate change in the near and long term (*high confidence*) (Figure 12.8; Table SM12.3; Silva et al., 2015; Silva et al., 2019a).

Changes in temperature and droughts have impacted crops significantly (*medium confidence: medium evidence, high agreement*) (Ray et al., 2015; Zambrano et al., 2016; Lesjak and Calderini, 2017; Ferrero et al., 2018; Piticar, 2018; Haddad et al., 2019; Zúñiga et al., 2021). Table 12.4 shows the changes in crop growth duration, which affects yields. Higher negative numbers then indicate yield reduction for the crop. Increasing temperatures and decreasing precipitation are expected to impact the agriculture sector (i.e., fruits crops and forests) across the entire sub-region, with the largest impacts in the northern and central zone (*high confidence*) (Mera et al., 2015; Zhang et al., 2015; Silva et al., 2016; Lizana et al., 2017; Reyer et al., 2017; Toro-Mujica et al., 2017; Beyá-Marshall et al., 2018; Lobos et al., 2018; O'Leary et al., 2018; Aggarwal et al., 2019; Ávila-Valdés et al., 2020; Fernandez et al., 2020; Melo and Foster, 2021). Observed impacts and future projections warn that increasing temperatures and decreasing precipitation will largely impact water demand by agricultural sectors (*high confidence*) (Novoa et al., 2019; Peña-Guerrero et al., 2020; Webb et al., 2020). Extreme climate events have caused Indigenous Peoples (e.g., Mapuche, Uru and Aymara) to experience water scarcity, a reduction in agricultural production and a displacement of their traditional knowledge and practices (*medium confidence: low evidence, high agreement*) (Parraguez-Vergara et al., 2016; Meldrum et al., 2018; Perreault, 2020).

SWS cities have been largely impacted by wildfires, water scarcity and landslides affecting highways and local roads, as well as potable water supply (Sepúlveda et al., 2015; Araya-Muñoz et al., 2016). Increasing temperature and heat extreme events in cities have increased the demand for water, damage to urban infrastructure (Monsalves-Gavilán et al., 2013) and accelerated ageing and death of trees (*high confidence*) (Moser-Reischl et al., 2019). Increasing temperature will modify energy demand in cities in northern and central Chile (Rouault et al., 2019).

Increasing temperature, heat extreme events and air pollution in SWS have significantly impacted population health (cardiac complications, heat stroke and respiratory diseases) (*high confidence*) (Table 12.2; Leiva G et al., 2013; Monsalves-Gavilán et al., 2013; Pino et al., 2015; Herrera et al., 2016; Henríquez and Urrea, 2017; Ugarte-Avilés et al., 2017; de la Barrera et al., 2018; Johns et al., 2018; Bowman et al., 2019; González et al., 2019; Matus C and Oyarzún G, 2019; Sánchez et al., 2019; Terrazas et al., 2019; Cakmak et al., 2021; Zenteno et al., 2021). There is *low confidence* regarding areal changes in Chagas disease (Tapia-Garay et al., 2018; Garrido et al., 2019) and transmission rates in the future (Ayala et al., 2019).

12.3.8 Southern South America Sub-region

12.3.8.1 Hazards

There were inconsistent trends and insufficient data coverage on extreme temperatures and precipitation (*low confidence*), but an increase in the frequency of meteorological droughts was observed with *medium confidence* (Dereczynski et al., 2020; Dunn et al., 2020; WGI AR6 Tables 11.13, 11.14, 11.15, Seneviratne et al., 2021; WGI AR6 Table 12.3, Ranasinghe et al., 2021). An increase in precipitation in Trelew, no change for Comodoro Rivadavia, both stations located in eastern Patagonia, and negative trends in austral summer rainfall in the southern Andes were observed (Vera and Díaz, 2015; Saurral et al., 2017). Chile's wildfires in Patagonia (fire frequency and intensity) have grown at an alarming rate (Úbeda and Sarricolea, 2016). Decreasing rainfall patterns in Punta Arenas is closely associated with variability at interannual to inter-decadal time scales of the main forcing system of climate in Patagonia. Snow cover extension (SCE) and snow cover duration decreased by an average of approximately 13 ± 2% and 43 ± 20 d respectively from 2000 to 2016, due to warming rather than drying (Rasmussen et al., 2007). In particular, analysis of spatial patterns of SCE indicates a slightly greater reduction on the eastern side (approximately 14 ± 2%) of the Andes Cordillera compared to the western side (approximately 12 ± 3%). According to the longest time series of glacier mass balance data in the Southern Hemisphere, the Echaurren Norte glacier lost 65% of its original area in the period 1955–2015 and disaggregated into two ice bodies in the late 1990s (Malmros et al., 2018; Pérez et al., 2018).

Mean temperatures in the SSA sub-region are projected to continue to rise up to +2.5°C by 2080 with respect to the present climate (Kreps et al., 2012). A rise in temperature means that an isotherm of 0°C will move up mountains, leaving less surface for accumulation of snow (Barros et al., 2015).

An increase in the intensity and frequency of hot extremes and a decrease in the intensity and frequency of cold extremes are projected to be *likely* (WGI AR6 Table 11.13, Seneviratne et al., 2021); CMIP6 models project an increase in the intensity and frequency of heavy precipitation (*medium confidence*).

It is expected that an increase in the intensity of heavy precipitation, droughts and fire weather will intensify through the 21st century in SSA, but mean wind will decrease (*medium confidence*) (Kitoh et al., 2011; WGI AR6 Tables 11.14 and Table 11.15, Seneviratne et al., 2021). The probability of extended droughts, such as the recently experienced mega-drought (2010–2015), increases to up to 5 events/100 yr (Bozkurt et al., 2017). Snow, glaciers, permafrost and ice sheets will decrease with *high confidence* (WGI AR6 Table 12.6, Ranasinghe et al., 2021). The observed area and the elevation changes indicate that the Echaurren Norte glacier may disappear in the coming years if negative mass balance rates prevail (*medium confidence*) (Farías-Barahona et al., 2019).

12.3.8.2 Exposure

Grasslands make a significant contribution to food security in Patagonia by providing part of the feed requirements of ruminants used for meat, wool and milk production. There is a lack of information regarding the combined effects of climate change and overgrazing and the consequences for pastoral livelihoods that depend on rangelands. Temperature and the amount and seasonal distribution of precipitation were important controls of vegetation structure in Patagonian rangelands (Gaitán et al., 2014). They found that over two-thirds of the total effect of precipitation on above-ground net primary production (ANPP) was direct, and the other third was indirect (via the effects of precipitation on vegetation structure). Thus, if evapotranspiration and drought stress increase as temperature increases and rainfall decreases in water-limited ecosystems, a greater exposure of ranchers to a reduction in stocking rate and, therefore, family income would be expected (*medium confidence*). The number of farmers (mainly family enterprises) exposed to climatic hazards (drought) is approximately 70,000–80,000, who have 14–15 million sheep in Argentina (Peri et al., 2021).

The main Argentinian Patagonia cities have developed as a result of oil and gas extraction, which requires massive quantities of water due to fracking and drilling techniques. Vaca Muerta is the major region in SA, where those techniques are used to extract oil and gas, and this will lead to an exacerbation of current water scarcity issues and to competition with irrigated agriculture (Rosa and D'Odorico, 2019), which in the context of drought may exacerbate socioenvironmental conflicts (*medium confidence*).

12.3.8.3 Vulnerability

There are reports related to a decrease in survival, growth and higher vulnerability to drought and fire severity for species of native forests due to climate change and wildfires (*high confidence*) (Mundo et al., 2010; Landesmann et al., 2015; Whitlock et al., 2015; Jump et al., 2017; Camarero et al., 2018; Venegas-González et al., 2018a). A coincidence has been reported between major changes in regional decline in the growth of forests with severe droughts due to climatic variations over northern Patagonia (Rodríguez-Catón et al., 2016). Once the forest decline begins, other contributing factors, such as insects (e.g., defoliator outbreaks), increase forest vulnerability or accelerate the loss of forest health of previously stressed trees (Piper et al., 2015). This region hosts unique temperate rainforests, which are particularly rich in endemic and long-lived conifer species (e.g., *Fitzroya cupressoides*) and which may be vulnerable to declines in soil moisture availability (Camarero and Fajardo, 2017). Patagonia will probably be vulnerable to a decrease in precipitation regimes due to climate change, and consequently many species that rely on meadows in an arid environment will also be impacted (Crego et al., 2014). The floods triggered by strong ENSOs caused significant changes in crop production (Isla et al., 2018).

The development of various human activities and water infrastructure is depleting water sources, changing river basins from exoreic to endoreic and the disappearance of a lake in 2016 (Scordo et al., 2017). Numerous dams for irrigation, some of which are also used for hydropower, have been and are planned to be built despite wind power generation potential (Silva, 2016). Oil and gas have played an important role in the rise of Neuquén-Cipolletti as Patagonia's most populous urban area and in the growth of Comodoro Rivadavia, Punta Arenas and Rio Grande as well.

12.3.8.4 Impacts

The potential impact of climate change is of special concern in arid and semiarid Patagonia, a >700,000 km^2 region of steppe-like plains in Argentina. Thus, melting snow and ice in the glaciers of Patagonia and the Andes will alter surface runoff into interior wetlands. A SLR of 20–60 cm will destroy coastal marshes, and an increase in extreme events, such as storms, floods and droughts, will affect biodiversity in wet grasslands (*medium confidence: low evidence, high agreement*) (after Junk et al. 2013; Joyce et al. 2016). Three species of lizard from Patagonia are at risk of extinction as a result of global warming (Kubisch et al., 2016).

Patagonian ice fields in SA are the largest bodies of ice outside of Antarctica in the Southern Hemisphere. They are losing volume due partly to rapid changes in their outlet glaciers, which end up in lakes or the ocean, becoming the largest contributors to eustatic SLR in the world per unit area (Foresta et al., 2018; Moragues et al., 2019; Zemp et al., 2019). Most calving glaciers in the southern Patagonia ice field retreated during the last century (*high confidence*). Upsala glacier retreat generated slope instability, and a landslide movement destroyed the western edge in 2013. The Upsala Argentina Lake has become potentially unstable and may generate new landslides (Moragues et al., 2019). The climate effect on the summer stratification of piedmont lakes is another issue in connection with glacier dynamics (Isla et al., 2010).

Between 41° and 56° South latitude, the absolute glacier area loss was 5450 km^2 (19%) in the last approximately 150 years, with an annual area reduction increase of 0.25% yr^{-1} for the period 2005–2016 (Meier et al., 2018). The small glaciers in the northern part of the Northern Patagonian Ice Field had over all periods the highest rates of 0.92% a^{-1}. In this sub-region, increased melting of ice is leading to changes in the structure and functioning of river ecosystems and in freshwater inputs to coastal marine ecosystems (*medium confidence: low evidence, high agreement*) (Aguayo et al., 2019). In addition, in the case of coastal areas, the importance of tides and rising sea levels in the behaviour of river floods has been demonstrated (Jalón-Rojas et al., 2018).

Suitable areas for meadows (very productive areas for livestock production) will decrease by 7.85% by 2050 given predicted changes in climate (*low confidence*) (Crego et al., 2014).

A major drought from 1998 to 1999, coincident with a very hot summer, led to extensive dieback in a *Nothofagus* species (Suarez et al., 2004). In another dominant *Nothofagus* species, several periodic droughts have triggered forest decline since the 1940s (Rodríguez-Catón et al., 2016).

Climate-change-impacted ocean ecosystems by reducing kelp coverage, increasing reproductive failure and chick mortality of penguins and spurring the poleward expansion of saltmarshes in the Atlantic Patagonia. SSA houses the Patagonian Steppe Global-200 terrestrial ecoregion, which is a conservation priority on a global scale, but with a clear lack of studies on likely future climate-change impacts (Section CCP1.2.2.2) (Manes et al., 2021). The Patagonian Steppe may suffer pronounced expansion in invasive species' ranges under climate change (*low confidence*) (Wang et al., 2017a).

Fire has been found to promote or halt biological invasions (*medium confidence: medium evidence, high agreement*). For example, an

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Table 12.5 | Change in population-weighted exposure to very high or extremely high wildfire risk. Data were derived from Fire Danger Indices (FDIs) produced by the Copernicus Emergency Management Service for the European Forest Fire Information System (EFFIS) (available at Copernicus Emergency Management Service [2021]). High and very high wildfire danger are defined as FDI ≥ 5. Data were derived from Romanello et al. (2021).

	Population-weighted mean days of exposure to extremely high and very high wildfire danger		
Sub-region	**2001–2004**	**2017–2020**	**Change from 2001–2004 to 2017–2020**
Central America (CA)	30.4	26.9	–3.5
Northwestern South America (NWS)	4.2	4.6	0.5
Northern South America (NSA)	19.7	21.2	1.5
South America Monsoon (SAM)	16.0	27.8	11.8
Northeastern South America (NES)	47.9	53.3	5.4
Southeastern SouthAmerica (SES)	4.2	8.2	4.0
Southwestern SouthAmerica (SWS)	31.9	58.4	26.5
Southern South America (SSA)	88.7	104.9	16.2

Observed and projected hazards in Central and South America

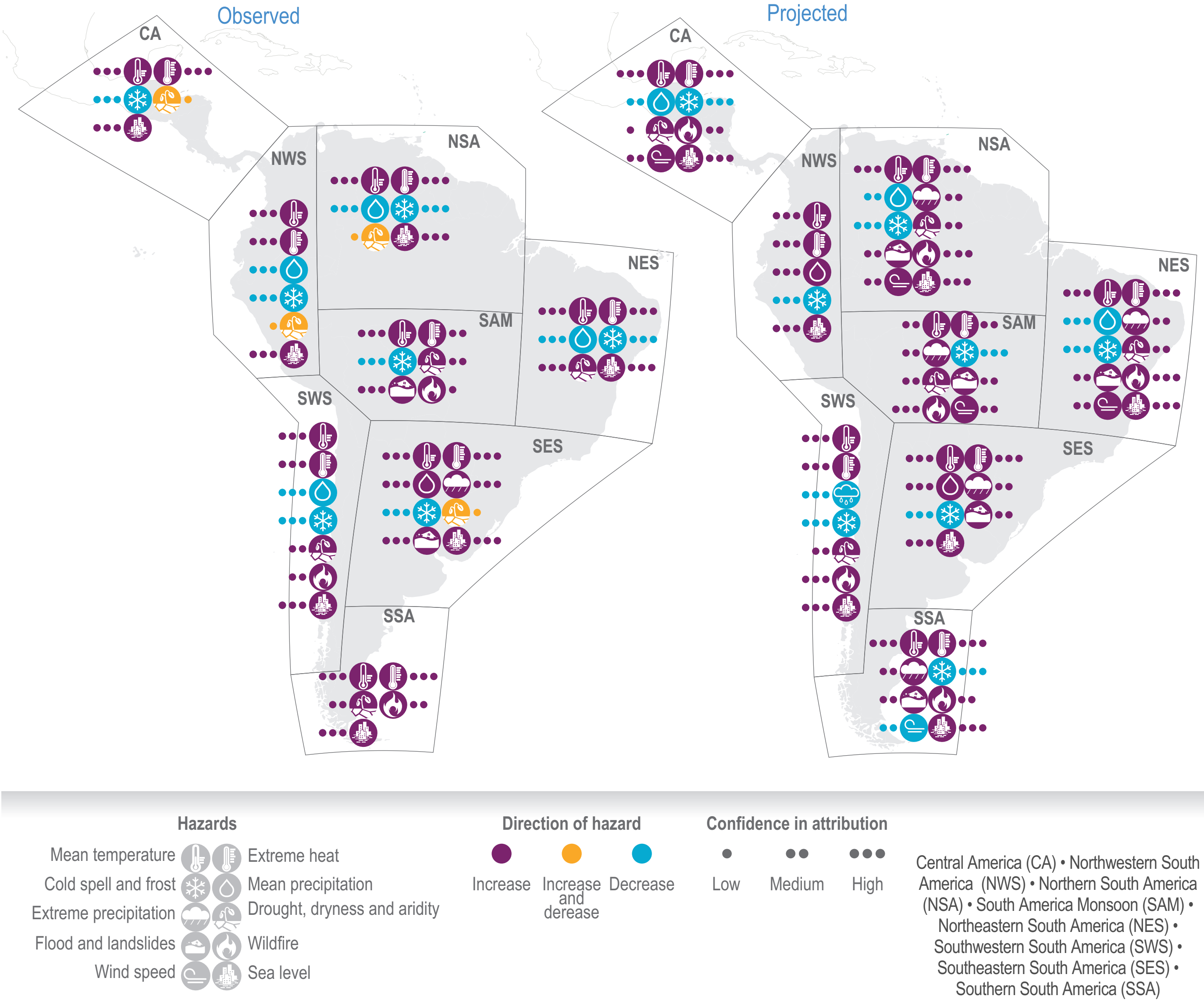

Figure 12.6 | Observed trends (WGI AR6 Tables 11.13, 11.14, 11.15) (Seneviratne et al., 2021) and summary of confidence in direction of projected change in climatic impact drivers, representing their aggregate characteristic changes for mid-century for RCP4.5, SSP3-44 4.5 and SRES A1B scenarios, or above within each AR6 region, approximately corresponding (for CIDs that are independent of SLR) to global warming levels between 2°C and 2.4°C (WGI AR6 Table 12.6) (Ranasinghe et al., 2021).

analysis of *Pinus* spread following wildfires in Patagonia revealed a high risk that pines will become invasive if ignition frequency increases as a result of climate change (Raffaele et al., 2016). According to Inostroza et al. (2016), the Magellan Region is one of the most fragile regions in Patagonia, and despite its low population densities, it is undergoing a silent process of anthropogenic alteration where between 53.1% and 68.1% of the area needs to be considered to be influenced by humans who are occupying pristine ecosystems, even some with extensive conservation designations (Inostroza et al., 2016). Fire exposure can result in several health problems for human populations; Table 12.5 shows that SSA is the region with the highest exposure to wildfire danger.

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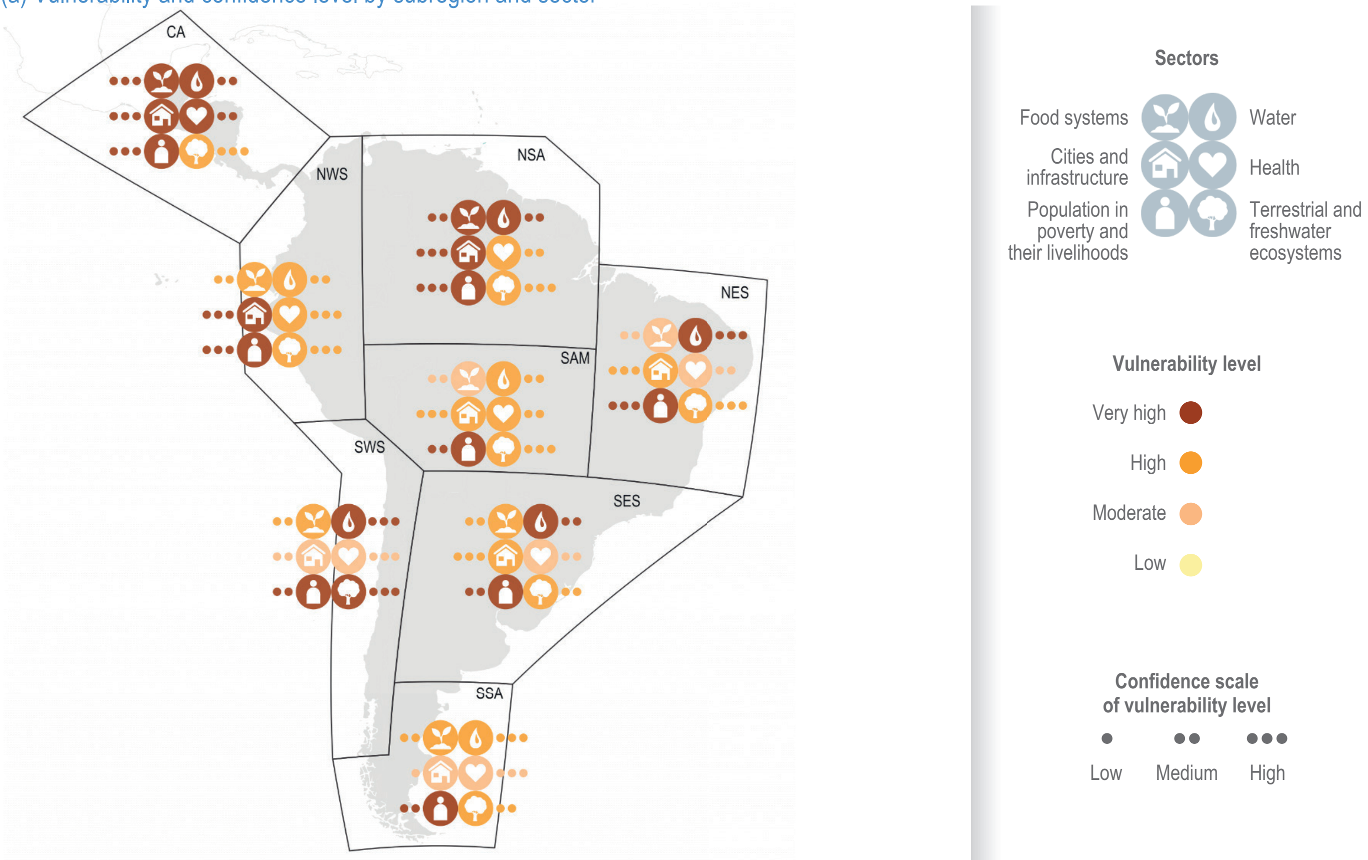
Sectoral distribution of vulnerability to climate change for Central and South America

(a) Vulnerability and confidence level by subregion and sector



(b) References used and vulnerability level attributed by subregion and sector

Sectors	CA	NES	NSA	NWS	SAM	SES	SSA	SWS
Food systems	4,6,9,11, 14,19,21, 27,35, 40,47	6,9,16, 21,22,27, 35,47	6,9,11,14, 19,21,27, 35,45,47	6,14,19,21 ,22,27,35, 40,45	6,21,27, 35,47	6,9,14,2 1,22,27, 35,47	6,14,21, 22,27,35, 39,47	6,14,21, 22,27,35, 39,40, 45
Cities and infrastructure	5,35	5,31,25	5,35	5,35	5,35	5,35	5,35	5,35
Population in poverty and their livelihoods	7,15,10, 12,13,23 ,25,40	10,12,13 ,15,17,2 5,28,49	10,12,13, 15,17,25, 28,33	10,12,13, 15,25,40	10,12,13, 15,17,25	10,12,13, 15,17,25, 28	10,12,13, 15,25	10,12,13, 15,25,40, 44
Water	26,35,41	26,35,48, 49,50	24,26,35	24,26,35	24,26,35	24,26,35, 41	24,26,35, 39	24,26,35, 39
Health	20,30,35	20,30,35 ,50	20,30,35	20,30,35	20,30,35	20,30,35	20,30,35	20,30,35
Terrestrial and freshwater ecosystems	29,35,38	2,29,32, 35,37,38 42	2,29,35, 37,38	2,8,24, 29,35,3 7,38	2,29,35, 37,38	29,35,38	24,29,35, 38	3,18,24, 29,35,38 ,46

Central America (CA) • Northwestern South America (NWS) • Northern South America (NSA) • South America Monsoon (SAM) • Northeastern South America (NES) • Southwestern South America (SWS) • Southeastern South America (SES) • Southern South America (SSA)

Figure 12.7 | Sectoral distribution of vulnerability levels to climate change for sub-regions. The vulnerability levels are based on studies that include: (a) databases with climate-change vulnerability indexes by country and sector, (b) studies that apply climate-change vulnerability indexes by sector at the local, national, regional or global scale, and (c) studies that define some vulnerability level based on the authors' expert judgment.

Panel (a) shows the vulnerability and confidence levels for each sub-region.

Panel (b) indicates the references used and the level of vulnerability by sub-region. The numbers within the table indicate the reference used for the assessment in the following order: (1) Aitken et al. (2016); (2) Anderson et al. (2018b); (3) Bañales-Seguel et al. (2018); (4) Bouroncle et al. (2017); (5) CAF (2014); (6) Carrão et al. (2016); (7) Donatti et al. (2019); (8) Eguiguren-Velepucha et al. (2016); (9) FAO (2020a); (10) FAO (2020b); (11) FAO (2021a); (12) FAO (2021b); (13) FAO (2021c); (14) FAO et al. (2021); (15) FAO and ECLAC (2020); (16) Ferreira Filho and Moraes (2015); (17) Filho et al. (2016); (18) Fuentes-Castillo et al. (2020); (19) FSIN and Global Network Against Food Crisis (2021); (20) Global Health Security Index (2019); (21) Godber and Wall (2014); (22) Handisyde et al. (2017); (23) Hannah et al. (2017); (24) Immerzeel et al. (2020); (25) Inform Risk Index (2021); (26) Koutroulis et al. (2019); (27) Krishnamurthy et al. (2014); (28) Lapola et al. (2019a); (29) Li et al. (2018); (30) Lin et al. (2020); (31) Mansur et al. (2016); (32) Martins et al. (2017); (33) Menezes et al. (2018); (34) Nagy et al. (2018);35) ND-Gain (2020); (36) Northey et al. (2017); (37) Olivares et al. (2015); (38) Pacifici et al. (2015); (39) Qin et al. (2020); (40) Romeo et al. (2020); (41) Liu and Chen (2021); (42) Silva et al. (2019b); (43) Soto Winckler and Del Castillo Pantoja (2019); (44) Soto et al. (2019); (45) Tomby and Zhang (2019); (46) Venegas-González et al. (2018b); (47) Yeni and Alpas (2017); (48) Marengo et al. (2017); (49) Bedran-Martins et al. (2018); (50) Confalonieri et al. (2014a). Detailed methodology can be found in SM12.2.

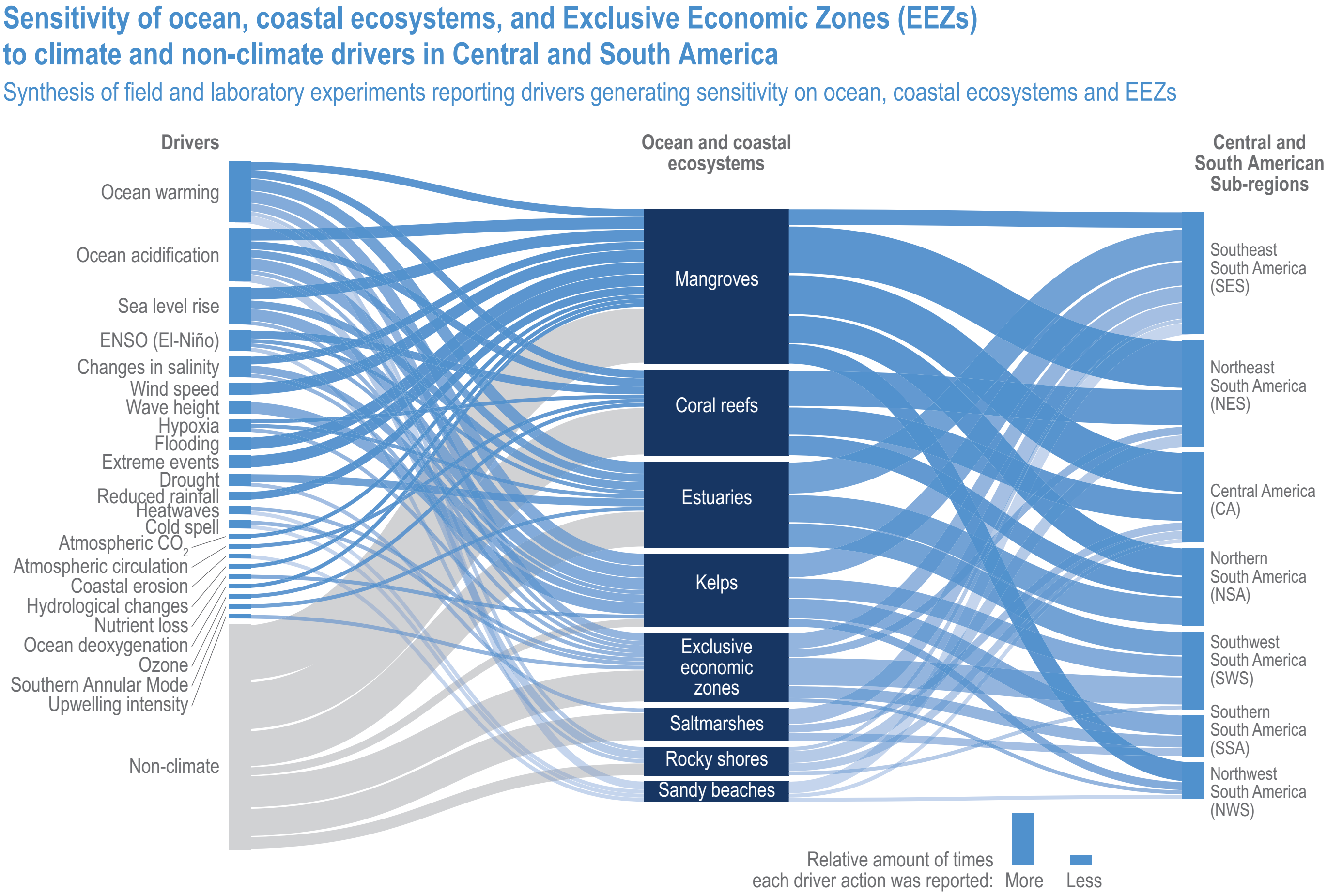


Figure 12.8 | Climate and non-climate sensitivity drivers of ocean, coastal ecosystems and EEZs of Central and South America.

12.4 Key Impacts and Risks

This section synthesises key risks across the CSA region. It follows the definition and concept of risk given in AR5, distinguishing the risk components, climatic hazards, exposure and vulnerabilities of people and assets (IPCC, 2014). This concept is further developed in AR6, defining key risks as potentially severe risks (Section 16.5). Key risks may refer to present or future conditions, with a focus on the 21st century. Both mitigation and adaptation can moderate the extent or severity of risks. The identification and evaluation of risks imply sociocultural values, which may vary across individuals, communities or cultures.

In line with Chapter 16 of this report, this chapter uses a risk outcome perspective, that is, the focus is on consequences related to risks, which could result from different combinations of hazards, exposure and vulnerabilities. Few studies in the literature focus on severe risks in the CSA region, and scant studies consider specifically and explicitly risk drivers such as level of warming, level of exposure, vulnerability and adaptation.

Criteria for identifying key risks for this chapter include the magnitude of the consequences, in particular the number of people potentially affected; the severity of the negative effects of the risk (e.g., lives threatened, major negative effects on livelihoods, well-being or the economy); the importance of the affected system (e.g., for vital ecosystem services, for large population groups); the irreversibility of either the process leading to the risk or the consequences; and the potential to reduce the risk.

Several of the key risks identified for the CSA region align well with the overarching key risks assessed in AR5 (Oppenheimer et al., 2014) and later in O'Neill et al. (2017), as well as with the representative key risks assessed in Section 16.5 of this report. The identified key risks include the following: KR1: risk of food insecurity due to frequent and/or extreme droughts; KR2: risk to life and infrastructure due to floods and landslides; KR3: risk of water insecurity; KR4: risk of severe health effects due to increasing epidemics (in particular vector-borne diseases); KR5: systemic risks of surpassing infrastructure and public service systems capacities; KR6: risk of large-scale changes and biome shifts in the Amazon; KR7: risk to coral reef ecosystems due to coral bleaching; KR8: risks to coastal socioecological systems due to SLR, storm surges and coastal erosion (Table 12.6; Figure 12.11; Table SM12.5).

Identification and assessment of key risks are informed by observed and projected impacts in the different sub-regions of CSA (Section 12.3). Figure 12.10 shows a summary of different levels of observed and future impacts per sub-region for different sectors, based on a detailed assessment of climate-change impacts on various

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Table 12.6 | Synthesis of key risks identified and assessed for Central and South America region

Consequence that would make the risk severe	Associated changes in hazards	Associated changes in exposure	Associated changes in vulnerability
1. Risk of food insecurity due to frequent/extreme droughts			
Substantial decrease in yield for key crops, disruption of food provision chains, reduced capacity or production of goods, reduced food security and increased malnutrition.	More frequent and/or longer drought periods; decrease in annual rainfall, severe decrease in rainfall at onset of rainy season; desertification of semiarid regions.	More people exposed to food insecurity due to spatially more extensive drought, high population growth rate (including rural areas) and greater population dependence on agricultural goods.	Reduced capacity of farmers (especially small-scale) to adapt to changing climatic conditions; soil degradation, insufficient government support of adaptation measures, financial contributions, infrastructure, insurance, and research efforts; inefficient water management.
2. Risk to life and infrastructure due to floods and landslides			
Death and severe health effects, disruption of critical infrastructure and service systems.	More frequent and severe storms and heavy precipitation events; changing snow conditions and thawing permafrost; retreating glaciers, formation of glacier lakes, increased GLOF hazard.	More people exposed to floods and landslides due to changing hazards, land use and increased population; occupation of more risk-prone areas such as flood plains and steep slopes.	Low-income and marginal populations and low resilience of infrastructure and critical service systems; limited government support through insurance, monitoring, EWSs and recovery.
3. Risk of water insecurity			
Seasonal water availability change and decline due to glacier shrinkage, snow cover change, more pronounced dry periods and poor or failed water management and governance.	Glacier shrinkage, snow cover change, more pronounced dry periods, precipitation and circulation changes.	Increase in population dependent on contribution of glacier/snow melt, especially during drought conditions; increased demand from intensification of agriculture, mining, hydropower and urbanisation.	Unequal water consumption systems, failed water management and government capacities, low water infrastructure efficiency, growing urban areas.
4. Risk of severe health effects due to increasing epidemics (in particular vector-borne diseases)			
Increased rate of epidemics of vector-borne diseases (malaria, dengue, Zika, leishmaniasis) together with diarrheal diseases. Severe health effects and damage to health systems in countries with low adaptive capacity and where original endemicity is high and control status poor.	Higher temperatures increase the geographical range of vectors, leading to expansion of climate suitable areas.	Increased population density and mobility through urbanisation results in high transmission rate. Increased population exposed to arboviruses due to expansion of vectors, including higher altitudes and latitudes.	Poor sanitation conditions, particularly in low-income communities and for Indigenous Peoples. Insufficient coverage of appropriate water provision and sewage systems. Low structural or economic capacity to cope; underfunding of health systems. Increase in infections can increase incidence of more severe forms of dengue.
5. Systemic risks of surpassing infrastructure and public service systems capacities			
Breakdown of public service systems, including infrastructure and health services due to cascading impacts of natural hazards and epidemics, affecting a large part of the population.	Higher frequency and magnitude of climate-related events (storms, floods, landslides), together with an increase in spatial and temporal distribution of pathogens/vectors for malaria, dengue, Zika and leishmaniasis.	More people and infrastructure exposed to climate/weather events; increase in population exposed to arboviruses due to spatial expansion of vectors.	Increasing vulnerability of public service and infrastructure systems; insufficient disaster management; little improvement, maintenance and expansion of public healthcare systems; low system resilience.

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Consequence that would make the risk severe	Associated changes in hazards	Associated changes in exposure	Associated changes in vulnerability
6. Risk of large-scale changes and biome shifts in Amazon			
Transition from tropical forest into other biomes such as seasonal forest or savannah through forest degradation and deforestation; risk of shifting from carbon sink to source.	More frequent, stronger and more persistent drought periods; temperature increase and reduction in annual rainfall.	Reduced availability of natural sources for local people; land use and land cover change (mining, deforestation); loss of biodiversity and ecosystem services; health impacts from increased forest fires particularly for Indigenous Peoples.	Strong dependence on non-climatic drivers, in particular land use change, deforestation, forest fire practices; low capacity to monitor and control deforestation.
7. Risk to coral reef ecosystems due to coral bleaching			
Degradation and possible death of Mesoamerican coral reef, the second largest reef in the world; severe damage to habitat for marine species, degrading coastal protection and other ecosystem services, decreased food security from fisheries, lack of income from tourism.	Ocean SST increase, lowered seawater pH and carbonate levels due to increased atmospheric CO_2 levels, leading to ocean acidification and coral bleaching.	Continued exposure to increased atmospheric CO_2 levels and SSTs together with destruction from coastal development, fishing practices and tourism.	Ecosystem highly sensitive to water temperature and pH fluctuations; high levels of negative human interference with reefs including runoff and pollution.
8. Risks to coastal socioecological systems due to SLR, storm surges and coastal erosion			
Coastal flooding and erosion causing severe damage to coastal population and infrastructure; loss of fisheries, reef degradation and decline in coastal protection due to increased storm surges and waves;saltwater intrusion and land subsidence.	High continuing trajectories of SLR; More intense and persistent coastal flooding, saltwater intrusion, coastal erosion.	Coastal population growth; increased number of people, infrastructure and services (coastal tourism) exposed; need for relocation of millions of people.	Poor planning in coastal development and infrastructure, disproportionate vulnerability and limited adaptation options for rural communities and Indigenous Peoples, increasing urbanisation in coastal cities; significant economic losses and unemployment from declining tourism.

systems and components for the corresponding sector (Figure 12.9). This assessment is consistent with and complementary to the assessment in Section 12.3. A synthesis of these impacts (Figure 12.10) indicates the following: Climate change has or will have a major impact on the observed and future decline of Andean glaciers and snow (*high confidence*) and lead to the degradation of permafrost and destabilisation of related landscapes (*medium evidence, high agreement*). Water quality is a major concern across the region, but there is *limited evidence* of impacts of climate change on water quality as well as on groundwater. Climate change has had a significant impact on terrestrial and freshwater ecosystems in the NWS, SES and SWS sub-regions and a medium impact in the other sub-regions, but the level of confidence varies across sub-regions. Projections indicate a strong impact of climate change on these ecosystems for the future (*medium confidence: medium evidence, high agreement*). Many aspects and assets of ocean and coastal ecosystems (e.g., mangroves, coral reefs, saltmarshes) were identified as being strongly impacted by climate change, both for observed and future periods (*high confidence*) (Section 12.5.2; Figure 12.9).

In most sub-regions, crop, livestock, fisheries and food systems in general show medium to high impacts of climate change over the observed period, as does the remaineder of the 21st century (*medium confidence: medium evidence, high agreement*). For some sub-regions, the available literature does not allow for an assessment of impacts on various human systems, including cities and infrastructure, health, poverty, livelihoods, migration, conflicts and IKLK, especially for future time periods. This points to important knowledge gaps about climate-change impacts on human systems. The indication of high impacts on several human systems and sub-regions points to the need to close these knowledge gaps.

Assessment of key observed and projected impacts and risks shows that in the CSA region several systems are already approaching critical thresholds under current warming levels, in particular glaciers in the Andes, coral reefs in CA (*high confidence*) and ocean and coastal ecosystems in virtually all sub-regions (*medium confidence: medium evidence, high agreement*). Some systems could cross these thresholds with different levels of reversibility depending on the degree of future warming, that is, glaciers in the Andes and coral reefs in CA, which will show partial but irreversible loss already under low levels of warming (RCP2.6) (*high confidence*). The risk of large-scale ecological changes and biome shifts of the Amazon rainforest, that is, a transition from tropical forest into other biomes such as seasonal forest or savannah, is now assessed with *medium confidence*, with the extent of the changes depending on the level of future warming and non-climatic drivers (land use change, deforestation, forest fire practices).

Systemic risks where critical infrastructure and public service system capacities are surpassed due to storms, floods and epidemics, with cascading impacts through vulnerable systems and populations and economic sectors, have the potential to affect large parts of populations and are therefore of major concern (*medium confidence: limited evidence, high agreement*). The COVID-19 crisis has exposed the existing vulnerabilities in important systems, in particular health systems and public services (Phillips et al., 2020). However, tipping

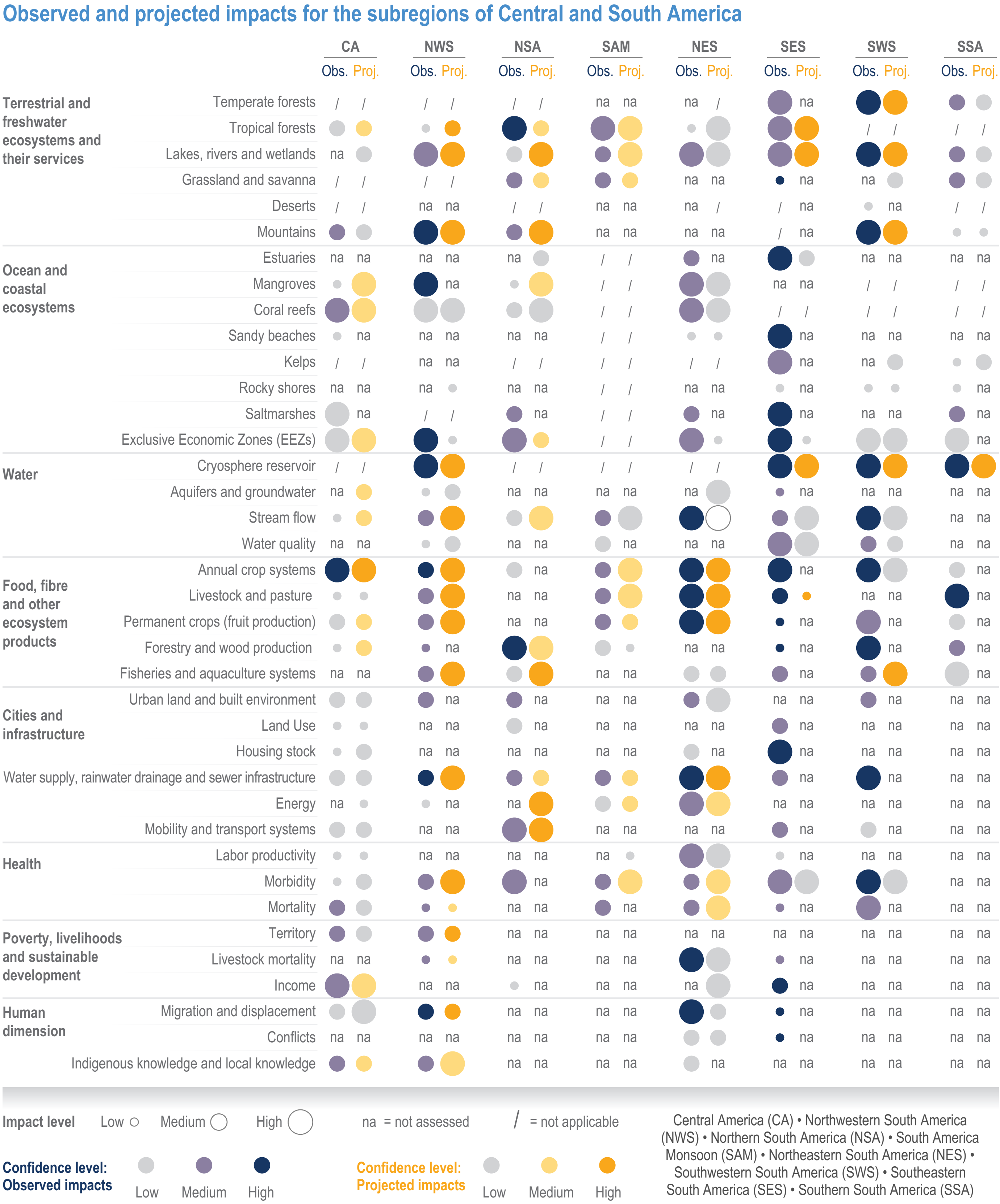

Figure 12.9 | Observed and projected impacts for sub-regions of CSA. Impacts are distinguished for main sectors and for their corresponding systems (or components). Observed impacts relate to the last several decades. Projected impacts represent a synthesis across several emission and warming scenarios, indicative of a time period from the middle to end of the 21st century. For each system (e.g., coral reefs) climate-change impacts are identified as being low, medium or high. The references underlying this assessment can be found in SM12.4.1.

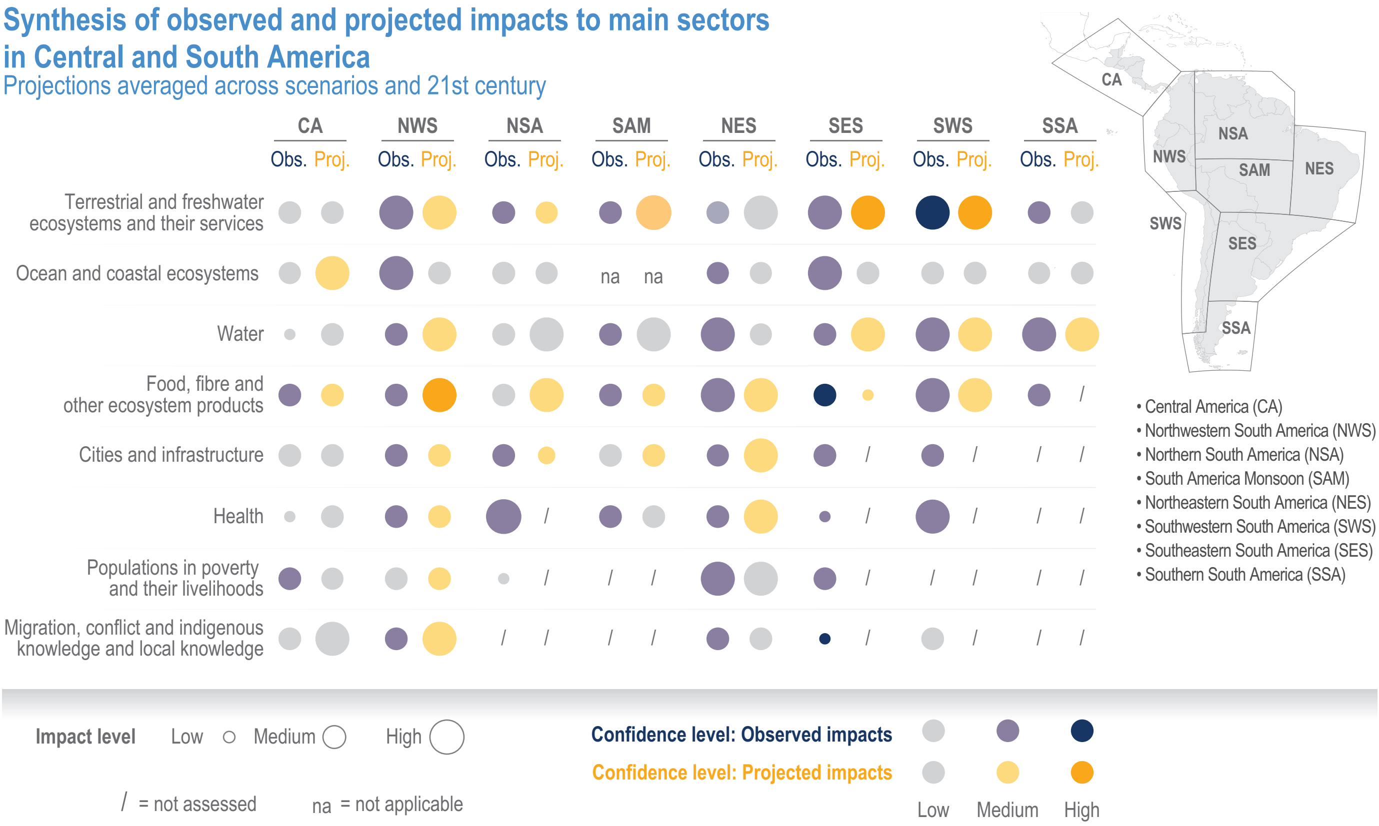

Figure 12.10 | Synthesis of observed and projected impacts, distinguished for different sectors and each sub-region of CSA. Observed impacts relate to the last several decades. Projected impacts represent a synthesis across several emission and warming scenarios, indicative of a time period from the middle to end of the 21st century. For each sector (e.g., health) climate-change impacts are identified as being low, medium or high. The references underlying this assessment can be found in SM12.4.1 and the methodology to complete the synthesis is found in SM12.4.2.

points in social systems are poorly understood (Bentley et al., 2014; Milkoreit et al., 2018), and there is *limited evidence* to inform understanding about which level of compound climatic, environmental and socioeconomic stressors social systems will withstand in CSA.

Overall, most key risks and their severity and extent are strongly driven and determined by system exposure, vulnerability and adaptive capacity. In particular, the high vulnerability of large populations, infrastructure and service systems, such as health, food and energy production and supply, are important factors, along with high levels of inequality and poor governance, for creating and increasing key risks (*high confidence*). Prevailing low levels of available information and understanding exacerbate the uncertainties surrounding key risks and so pose limitations to adaptation. An example is CA, with its high levels of vulnerability and exposure, but there is *limited evidence* and understanding on impacts and risks, making this region susceptible to inappropriate adaptation to expected future climate-change impacts.

12.5 Adaptation

Adaptation initiatives across the region have increased since AR5. National Communications (NCs), Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) (https://unfccc.int) recently published are providing guidance for adaptation in CSA. There is also a diversity of non-governmental adaptation initiatives, at both the national and sub-national levels. In this context, this section assesses, through a sectoral approach, the main challenges, opportunities, trends and initiatives to adapt to climate change in the region.

12.5.1 Terrestrial and Freshwater Ecosystems and Their Services

CSA is one of the most biodiverse regions in the world, hosting unique socioecosystems that will be strongly impacted by climate change (*high confidence*) (Section 12.3; Cross-Chapter Paper 1; CAF, 2014; Camacho Guerreiro et al., 2016; IPBES, 2018a; Li et al., 2018; Retsa et al., 2020). Warming has generated extreme heat events in many parts of CSA (IPCC, 2019a) that, together with droughts and floods, will seriously affect the integrity of terrestrial and freshwater ecosystems in the entire region (Section 12.3; CAF, 2014). A reduction in net primary productivity in tropical forests and glacier retreat in the Andes, for example, are expected to cause significant negative socioecological impacts (Feldpausch et al., 2016; Lyra et al., 2017; Cuesta et al., 2019) (Case Study, 12.7.1). Biodiversity hotspots in the region are well assessed in the literature compared to other regions of the world, especially the Atlantic Forest, Mesoamerica and Cerrado (Section CCP1.2.2; Manes et al., 2021). Up to 85% of evaluated natural systems (species, habitats and communities) in the literature for biodiversity hotspots since AR5 were projected to be negatively

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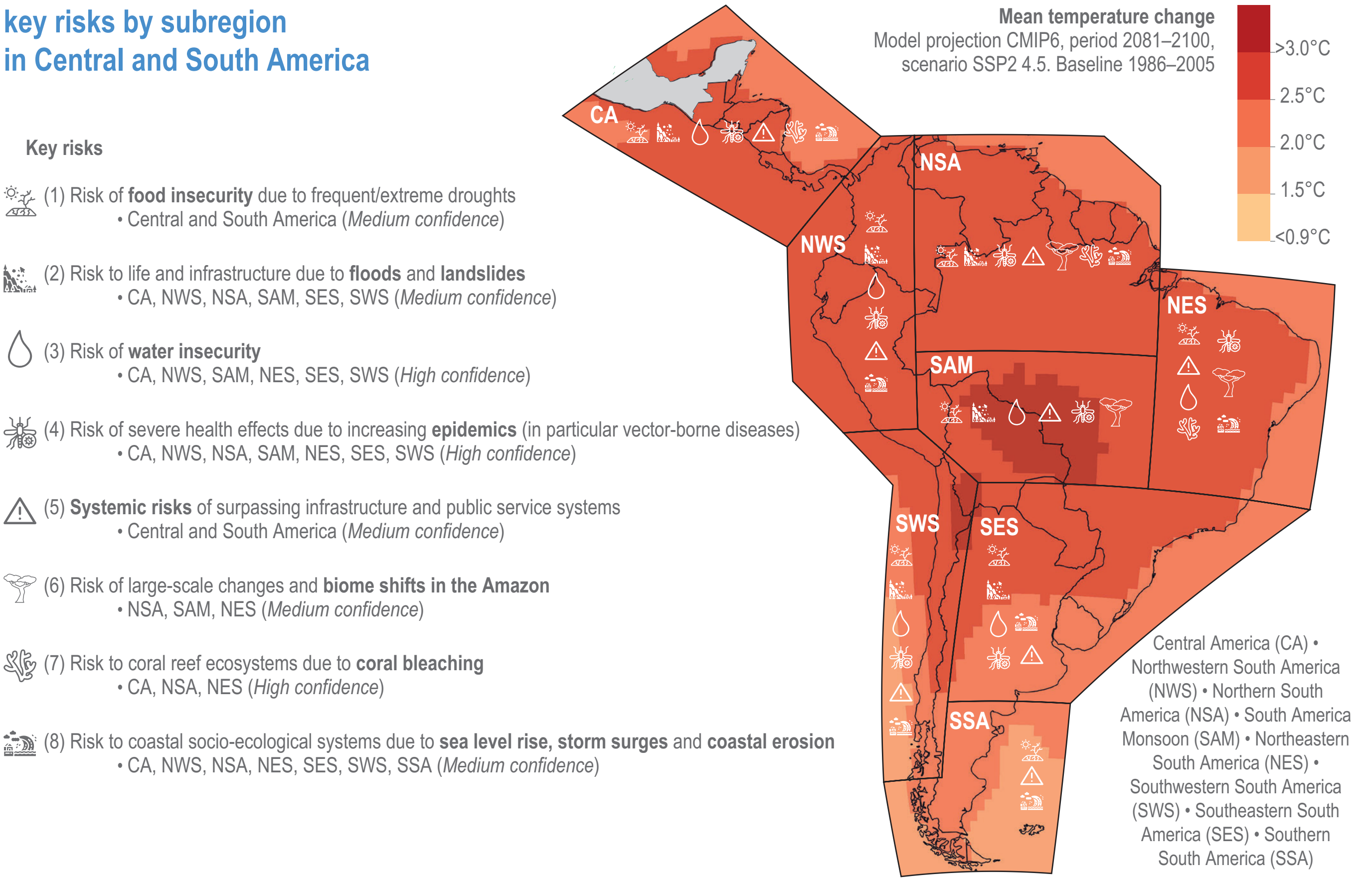

Figure 12.11 | Synthesis of key risks for the CSA region. The base map indicates the mean temperature change between the SSP2 4.5 scenario using CMIP6 model projections for 2081–2100 and a baseline period of 1986–2005 (WGI AR6 Atlas, Gutiérrez et al., 2021).

impacted by climate change (*high confidence*), with 26% of projections predicting species extinctions (Section CCP1.2.2; Manes et al., 2021). IKLK play an important role in adaptation and are vital components of many socioecological systems, while also being threatened by climate change (*high confidence*) (Box 7.1) (Valdivia et al., 2010; Tengö et al., 2014; Mistry et al., 2016; Harvey et al., 2017; Diamond and Ansharyani, 2018; Camico et al., 2021).

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12.5.1.1 Challenges and Opportunities

The conversion of natural ecosystems to agriculture, pasture and other land uses in CSA has been identified as a major challenge to climate-change adaptation in the region (*high confidence*) (Scarano et al., 2018; IPCC, 2019a). In the last three decades, SA has been a significant contributor to the growth of agricultural production worldwide (OECD/Food and Agriculture Organization of the United Nations, 2015), driven partly by increased international demand for commodities, especially soybeans and meat (IPCC, 2019a). Between 2001 and 2015 about 65% of all forest disturbance in the region was associated with commodity-driven deforestation (Curtis et al., 2018). High rates of native vegetation conversion in Argentina, Bolivia, Brazil, Colombia, Ecuador, Paraguay and Peru threaten important ecosystems (Amazon, Cerrado, Chacos and Llanos savannahs, Atlantic rainforest, Caatinga and Yungas) (Graesser et al., 2015; FAO, 2016c). Almost two-thirds of soy consumed in EU+ comes from Brazil, Argentina and Paraguay (IDH, 2020), increasing conversion risk in the Amazon, Cerrado and Gran Chaco. Despite growing commodity production traceability, in 2018 only 19% of the soybean meal consumed in EU+ was certified deforestation-free and 38% compliant with the FEFAC Soy Sourcing Guidelines (IDH, 2020), which poses a serious challenge at the international level (Negra et al., 2014; Curtis et al., 2018; Lambin et al., 2018; IDH, 2020).

Investing in actions aimed at protection, restoration and the sustainable use of biodiversity and ecosystems represents a good approach to maintaining critical ecosystem services and constitutes part of a common strategy for adaptation, mitigation and disaster risk reduction in the region (*high confidence*) (Kabisch et al., 2016; Scarano et al., 2018). These strategies also satisfy international forest and water conservation agendas in terms of optimising resources and solutions (Strassburg et al., 2019). Global conservation and sustainable development commitments, such as the Aichi Targets (Convention on Biological Diversity [CBD]), Sustainable Development Goals (UN), the NDCs under the Paris Agreement and the New York Declaration on Forests, strongly rely on nature-based solutions (NbS) to achieve their objectives (Brancalion et al., 2019) (Figure 12.12). The COVID-19 outbreak also brought attention to the need to preserve tropical forests as a means of preventing spillover of viruses from wildlife to humans, with concerns over that risk in the Amazon (Allen et al., 2017b; Dobson et al., 2020; IPBES, 2020; Ferreira et al., 2021). These represent an important opportunity for ecosystem-based adaptation (EbA) to be at the core of NbS for climate change, access finance and promote climate resilient development pathways in CSA.

The Declaration on Protected Areas and Climate Change, presented by 18 CSA countries during the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties 21 (COP21), highlights the fundamental role of protected areas in providing the so-called GI needed to implement climate-change mitigation and adaptation and safeguard the provision of essential ecosystem services and the livelihoods of Indigenous Peoples and local communities (Gross et al., 2016). Protected area in CSA are underfunded (*very high confidence*). Latin American (including Mexico) governments allocate just about 1% of their national environmental budgets on protected areas (about USD 1.18 ha^{-1} on average). This figure only covers 54% of their basic needs, resulting in insufficient management. The financing gap to achieve optimal needs for protected areas in CSA is approximately USD 700 million yr^{-1} (Bovarnick et al., 2010). This seriously compromises the management and delivery capacity of protected areas for climate-change adaptation and preparedness for ongoing ecological transformation (van Kerkhoff et al., 2019). Furthermore, to become a relevant mechanism for resilience, protected areas need to be managed for this purpose (Mansourian et al., 2009). About 40% of protected areas in Latin America and the Caribbean (including Mexico) have undertaken management effectiveness evaluations (UNEP-WCMC and IUCN, 2020a). This is hardly representative of Aichi's Target 11, although far better than the 11% global average. Collaborations with Indigenous Peoples and local communities are also an important issue to consolidate protected areas (Gross et al., 2016). In addition to protected areas as solutions for climate-change adaptation and mitigation, there is also a need to protect or restore ecosystems outside the protected areas, as illustrated by the Mesoamerican Biological Corridor (Imbach et al., 2013).

Despite some local and specific assessments (e.g., Warner (2016)), there is a significant gap when it comes to identifying barriers to adaptation or maladaptation in the region (Dow et al., 2013). In their NCs, NDCs and/or NAPs, most countries identified inadequate financing and access to technology as barriers to adaptation relevant to terrestrial and freshwater socioecosystems (*high confidence*). Insufficient institutional coordination is also frequently mentioned (Rangecroft et al., 2013; Cameron et al., 2015). These limitations could be partially addressed through multi-lateral cooperation, incorporation of synergies from local to national scales, local empowerment and poverty alleviation (Rangecroft et al., 2013; Harvey et al., 2017; Murcia et al., 2017; Calispa, 2018; Chain-Guadarrama et al., 2018).

12.5.1.2 Governance and Financing

All CSA countries have formulated policies that include measures relevant for socioecosystem adaptation in their NCs, NDCs and NAPs, with an emphasis on protecting and restoring water and forests (*high confidence*). Existing proposed measures, instruments and programmes, however, do not yet reflect the vision needed to integrate the ecosystem and human dimensions of vulnerability. Administration coordination and the progress in adaptive ecosystem management are still in their early stages, due in part to the lack of stable financial resources and scientific knowledge and IKLK about adapting ecosystems to climate change (Bustamante et al., 2020). Brazil was an exception, showing dramatic policy-driven reduction in deforestation in the Amazon between 2004–2012, with a concomitant 70% increase in soy production, the most profitable Amazon crop (Hansen et al., 2013; Nepstad et al., 2014). Policies included territorial planning (protected areas, Indigenous territories and land tenure), satellite monitoring and market and credit restrictions on high-deforesting municipalities, plus some incentives to small farmers (Boucher et al., 2013; Hansen et al., 2013; Nepstad et al., 2014; Castelo, 2015; Cunha et al., 2016a). It is important to highlight the important role of Indigenous territories, in addition to protected areas, in forest conservation in the Amazon (*high evidence*, *medium agreement*) (Schwartzman et al., 2013; Barber et al., 2014; Nepstad et al., 2014; Walker et al., 2014b). These policies were partially funded by results-based compensation through the Amazon Fund. Since 2012, however, policies and institutions have weakened, and Amazon deforestation rates have started to rise (Carvalho et al., 2019), becoming more acute in recent years (Silva Junior et al., 2021). Conservation incentives, a new complementary and allegedly cost-effective approach, is increasingly being implemented in the region (Magrin et al., 2014). They include PES, REDD+, environmental certification and conservation easements, but remain controversial, and more research is needed on their effectiveness, possible negative side effects, participatory management systems and collective decision-making processes (Larson and Petkova, 2011; Locatelli et al., 2011; Pinho et al., 2014; Strassburg et al., 2014; Mistry et al., 2016; Gebara and Agrawal, 2017; Scarano et al., 2018; Ruggiero et al., 2019; To and Dressler, 2019; Vallet et al., 2019).

12.5.1.3 Adaptation Options to Avert and Reduce Key Risks to Terrestrial and Freshwater Ecosystems

Research, monitoring systems and other initiatives for knowledge management are promoted in the region on terrestrial and freshwater socioecosystem adaptation (*high confidence*) (NCs, NDCs and NAPs, https://unfccc.int). In Chile, for example, the Eco-social Observatory of Climate Change Effects for High Altitude Wetlands of Tarapacá has been collecting information on physical, biological and social variables since 2013 (Uribe Rivera et al., 2017). Other examples in the Andes are the GLORIA-Andes network (Cuesta et al., 2017a), the Andean Forest Network (Malizia et al., 2020) and the Initiative of Hydrological Monitoring in the Andes (IMHEA), with measures to optimise watershed management and protection and reduce the risk of water insecurity (Correa et al., 2020).

Poverty is a driver of climate-change risk, while the sustainable use of ecosystems fosters adaptation (Kasecker et al., 2018) (*high confidence*). Most of the 398 ecosystem-based adaptation hotspots identified in Brazil on this premise are located in some of the ecosystems that are most vulnerable to climate change (Kasecker et al., 2018). Although conservation and restoration are reported as being effective at reducing risk (*medium confidence: medium evidence*, *high agreement*) (Anderson et al., 2010; Borsdorf et al., 2013; Keenan, 2015; Pires et al., 2017; Ramalho et al., 2021), their effectiveness depends on the integration of conservation actions with enhancements of local socioeconomic conditions (*medium confidence: medium evidence, high agreement*) (Scarano and Ceotto, 2015; Pires et al., 2017; Kasecker et al., 2018; de Siqueira et al., 2021; Vale et al., 2021).

Since AR5, there has been an increase in the number of adaptation measures through natural resource and ecosystem service management. The main approaches are EbA and community-based adaptation (CbA) (*high confidence*) (NCs, NDCs and NAPs, https://unfccc.int). IKLK can be very detailed and usually relates to people's priorities as identified by collective decision-making (Box 7.1) (Hurlbert et al., 2019, SRCCL Section 7.6.4; SRCCL Cross-Chapter Box 13 ILK; de Coninck et al., 2018, SR1.5 Section 4.3.5.5). In Manaus, central Amazon, fishermen perceive reductions in fish size, diversity and capture levels caused by droughts, while recognising that floods hinder access to fishing grounds (Keenan, 2015; Camacho Guerreiro et al., 2016). In the Amazon floodplains, small-scale fisher and farmer communities incorporate their knowledge on natural hydrologic and ecological processes into management systems that reduce climate-change risk and impacts (Oviedo et al., 2016). Smallholder grain farmers in Guatemala and Honduras implement EbA practices based on local knowledge (e.g., live fences, home gardens, shade trees in coffee plantations, dispersed trees in corn fields and other food insecurity risk reduction practices) (Harvey et al., 2017; Chain-Guadarrama et al., 2018). There is, therefore, great potential for terrestrial and freshwater ecosystem adaptation to climate change in CSA, provided the right incentives and sociocultural protective measures are in place (*high confidence*) (Section 12.5.10.4; Table SM12.7).

Disarticulation between policy and implementation is a common problem. Ecuadorian climate public policy points towards a CbA approach, but it is often downsized when implemented (Calispa, 2018). Important adaptation actions have been undertaken in Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, El Salvador, Paraguay, Peru and Uruguay, both in policymaking and institutional arrangements, but they tend to be poorly coordinated with policies on development, land planning and other sectoral policies (Ryan, 2012). Some type of community participation mechanisms is present in most country strategies, but their levels of implementation vary considerably (*medium confidence: medium evidence, high agreement*) (Ryan, 2012; Pires et al., 2017; Calispa, 2018).

There is an ecosystem bias in adaptation priorities for research and implementation, hindering the development of comprehensive adaptation programmes. Most scientific research on adaptation in Peru focuses on the highlands and coastal regions, while mitigation research focuses on forests (Chazarin et al., 2014). Combined adaptation and mitigation strategies can produce positive results, but they are often disconnected (Locatelli et al., 2015). Most reviewed cases in agriculture and forestry in Latin America (84% of 274 cases) reported positive synergies between adaptation and mitigation. Nevertheless, research on Latin American forests tend to focus on mitigation, while studies on agriculture are usually oriented towards adaptation (*high confidence*) (Locatelli et al., 2015, 2017).

Rural communities in the Cusco region, Peru, ground their ability to adapt to climate change on four cultural values, known in Quechua as *ayni* (reciprocity), *ayllu* (collectiveness), *yanantin* (equilibrium) and *chanincha* (solidarity), but policies oriented towards so-called modernisation undermine these traditional mechanisms. Adaptation strategies could benefit from integrating these and other insights from traditional cultures, fostering risk reduction and transformational adaptation towards intrinsically sustainable systems (*medium confidence: medium evidence, high agreement*) (Walshe and Argumedo, 2016).

Protected areas have become an important component as enablers of national climate-change adaptation strategies. They increase ecosystems' adaptive potential, reducing climate risk and delivering numerous ecosystem services and sustainable development benefits while playing an important role in climate-change mitigation (*high confidence*) (Mackey et al., 2008; Dudley et al., 2010; Gross et al., 2016; Bebber and Butt, 2017; Dinerstein et al., 2019; IPCC, 2019a). CSA already has a greater percentage of land (24.1%) under protected status than the world average (14.7%) (UNEP-WCMC and IUCN, 2020b). Some countries, including Belize, Bolivia, Brazil, Guatemala, Nicaragua and Venezuela, have already met or surpassed the 30% CDB and IUCN goal (Dinerstein et al., 2019), and others, like Costa Rica and Honduras, are very close to doing so. In some cases, the establishment of protected areas not accompanied by collective decision-making processes has displaced local people or denied them access to natural resources, increasing their vulnerability to climate change (Brockington and Wilkie, 2015).

In addition to better managing and expanding protected area networks, other effective area-based conservation measures (OECMs), recently defined by the Parties to the Convention on Biological Diversity (Dudley et al., 2018), could also enhance ecosystem resilience (*low confidence*). Private protected areas in the mountain regions of the Americas (e.g., Andes) play an important role in closing the gaps in fragmented biomes and expanding protection in underrepresented areas (Hora et al., 2018). In Brazil, there is also huge potential for conservation and sustainable management in private areas, as roughly 53% of the country's native vegetation is within private land (Lapola et al., 2014; Soares-Filho et al., 2014).

Large-scale restoration is also seen as pivotal to limiting both climate change (IPCC, 2019a) and species extinction (IPBES, 2018a) (*very high confidence*). A new multi-criteria approach to optimising multiple restoration outcomes (for biodiversity, climate-change mitigation and cost), for example, indicate that SA has the greatest extension of converted lands, evenly distributed in the top 50% of global priorities (Strassburg et al., 2020).

12.5.2 Ocean and Coastal Ecosystems and Their Services

Ocean and coastal ecosystems provide suitable habitats for a high number of species that support important local fisheries, the tourism sector and the regional economy (*high confidence*) (Section 3.5; Table 3.9; González and Holtmann-Ahumada, 2017; Venerus and Cedrola, 2017; CEPAL, 2018; Carvache-Franco et al., 2019; SROCC Section 5.4, Bindoff et al., 2019). There is *high confidence* that CSA ocean and coastal ecosystems are already being impacted by climate change (Figure 12.9, 12.10; Table SM12.3; Section 3.4; Section 5.4 in SROCC, Bindoff et al., 2019) and are highly sensitive to non-climatic stressors (Figure 12.8; Table SM12.3; Section 3.4). Projections for CSA ocean and coastal ecosystems warn about significant and negative impacts (*high confidence*), which include major loss of ecosystem structure and functionality, changes in the distributional range of several species and ecosystems, major mortality rates and increasing numbers of coral bleaching events (Figure 12.9; Figure 12.10; Table SM12.3; Section 3.4; SROCC Sections 5.3, 5.4, Bindoff et al., 2019).

CSA sub-regions are highly dependent on ocean and coastal ecosystems and, thus, vulnerable to climate change (FAO, 2018). Fisheries and aquaculture contribute significantly to food security and livelihoods by creating employment (more than two million people), income and economic growth for the region (Section 3.5; FAO, 2018). More than 45% of the total fisheries in CSA are based on marine products (CEPALSTAT, 2019). Peru, Chile, Argentina and Ecuador are among the 15 countries with the largest marine capture production worldwide (Gutiérrez et al., 2016a; FAO, 2018; Vannuccini et al., 2018), while more than 90% of the hydrological resources produced by aquaculture in CSA have a marine origin (CEPALSTAT, 2019). There is *high confidence* about important current and future impacts of climate-change hazards in marine resources used by fisheries; however, there is *low evidence* regarding impacts on regional economies (Figure 12.9, 12.10; Table SM12.3).

12.5.2.1 Adaptation Measures and Strategies Applied to Oceans and Coasts of Central and South America

Similar to those strategies pointed out by WGII AR5 Chapter 27 (Magrin et al., 2014) and Chapter 3 (Section 3.5; Section 3.6.2; Box SLR in Chapter 3), adaptation strategies in ocean and coastal ecosystems in CSA remain focused on ecosystem protection and restoration and the sustainable use of marine resources (*high confidence*). There is *low evidence* on how coastal urban areas and tourist settlements of CSA countries are adapting to SLR and extreme events (Calil et al., 2017; Villamizar et al., 2017). Some of these strategies include planned relocation (Dannenberg et al., 2019) and the use of grey infrastructures like seawalls and bulkheads (Silva et al., 2014; Isla et al., 2018).

There is *medium confidence* that EbA is the main strategy used in CSA coral reef ecosystems. The set of strategies applied include the protection, restoration (e.g., coral gardening, larval propagation) and conservation of coral reef areas through the application of spatial ocean zoning schemes such as marine protected areas (MPAs), marine managed areas (MMAs), national parks, wildlife refuges, special zones of marine protection, special management zones, responsible fishing areas and the establishment of management plans with some level of participatory processes. These strategies are complemented by actions that promote the development of research and education programmes, recreational and cultural activities, the use of community-based approaches and the creation of national specific laws (Graham, 2017) and the adherence to international treaties (e.g., Convention on International Trade in Endangered Species of Wild Fauna and Flora [CITIES], AGENDA 21, United Nations Convention on the Law of the Sea (UNCLOS), Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat) (Cruz-Garcia and Peters, 2015; Gopal et al., 2015; Graham, 2017; Bayraktarov et al., 2020).

Adaptation measures in mangrove ecosystems are mainly focused on the application of EbA strategies (*high confidence*). These measures include the application of restoration programmes, the creation of management plans, which also have significant co-benefits with mitigation (Section 3.6.2.1), and the establishment of coastal protected areas, followed by the development of research activities and the creation of specific mangrove policies through new laws and resolutions (e.g., Colombia) (Cvitanovic et al., 2014; Krause, 2014; Blanco-Libreros and Estrada-Urrea, 2015; Carter et al., 2015; Estrada et al., 2015; Ferreira and Lacerda, 2016; Oliveira-Filho et al., 2016; Rodríguez-Rodríguez et al., 2016; Alvarado et al., 2017; Álvarez-León and Álvarez Puerto, 2017; Baptiste et al., 2017; Borges et al., 2017; Jaramillo et al., 2018; Salazar et al., 2018; Armenteras et al., 2019; Blanco-Libreros and Álvarez-León, 2019; Maretti et al., 2019; Ellison et al., 2020).

The use of territorial planning tools, the promotion of sustainable resource exploitation, the adherence to certification schemes and the implementation of management instruments, such as ecosystem-based management (EbM), followed by the use of an integrated coastal zone management, coastal marine spatial planning and capacity building, ecological risk assessments, have been the main strategies used to ensure the sustainability of marine resources in fisheries across EEZs of CSA (*high confidence*) (Hellebrandt et al., 2014; Gelcich et al., 2015; Singh-Renton and McIvor, 2015; Gutiérrez et al., 2016a; Karlsson and Bryceson, 2016; Oyanedel et al., 2016; Debels et al., 2017; Isaac and Ferrari, 2017; Mariano Gutiérrez et al., 2017; Barragán and Lazo, 2018; Bertrand et al., 2018; Lluch-Cota et al., 2018; Guerrero-Gatica et al., 2020). Other strategies include the application of local regulations (e.g., closed seasons) (Fontoura et al., 2016) and the use of participative programmes (Hellebrandt et al., 2014; Arroyo Mina et al., 2016; Matera, 2016).

12.5.2.2 Adaptation Success in Ocean and Coastal Ecosystems of Central and South America

There is *low evidence* about how the strategies and actions taken and implemented in ocean and coastal systems of CSA have contributed to advance in the protection and conservation of ocean and coastal ecosystems. However, some important advances are visible in Colombian Pacific areas with coral reefs (new conservation plans, research monitoring and conservation practices) (*low confidence*) (Cruz-Garcia and Peters, 2015; Alvarado et al., 2017; Bayraktarov et al., 2020). In Panama, actions taken have allowed the protection of a high number of marine areas with coral reefs, as well as the incorporation of management approaches that include several sectors such as fisheries, tourism, coral protection and coral conservation (*low confidence*) (Alvarado et al., 2017). In the case of Costa Rica, 80% of coral habitats are located inside of MPAs, multiple research coral-related activities have been performed, and several training activities have favoured the engagement of the local community in their protection against climate and non-climate hazards (*low confidence*) (Alvarado et al., 2017).

There is *low evidence* of how the incorporation of mangroves as Ramsar sites, the reforms of legislations (e.g., fines and stronger regulations), and the creation of reserves and private protection initiatives (e.g., Belize Association of Private Protected Areas BAPPA), and capacity-building projects or new educational programmes have promoted the protection of mangroves in CSA countries such as Honduras, Guatemala and Belize (Cvitanovic et al., 2014; Carter et al., 2015; Ellison et al., 2020). In Brazil, between 75–84% of mangroves are under some level of protection which has improved the forest structures, and multiple research programmes (e.g., Mangrove Dynamics and Management, MADAM, and 'GEF-Mangle') have been developed (*medium confidence*) (Krause, 2014; Medeiros et al., 2014; Estrada et al., 2015; Ferreira and Lacerda, 2016; Oliveira-Filho et al., 2016; Borges et al., 2017; Maretti et al., 2019; Strassburg et al., 2019). In Colombia, research projects (e.g., Mangroves of Colombia Projects, MCP), the installation of a geographic information system for mangroves (e.g., SIGMA Sistema de Información para la Gestión de los Manglares en Colombia), surveillance monitoring plans (e.g., EGRETTA Herramientas para el Control y Vigilancia de los Manglares), and the establishment of protected areas have contributed to decrease loss of the mangrove forest (*high confidence*) (Blanco-Libreros and Estrada-Urrea, 2015; Rodríguez-Rodríguez et al., 2016; Álvarez-León and Álvarez Puerto, 2017; Baptiste et al., 2017; Jaramillo et al., 2018; Salazar et al., 2018; Armenteras et al., 2019; Blanco-Libreros and Álvarez-León, 2019).

There is *low evidence* whether the establishment of MPAs and the creation of legal instruments have allowed the development of new research activities have increased the environmental awareness, decreased the illegal extraction, and improved the local coordination which have promoted the sustainable use of marine resources, and improved the community-government cooperation in marine ecosystems (Alvarado et al., 2017). The experience in countries like Chile demonstrates the importance of implementing robust management plans that guarantee the protection objectives and the sustainability through the implementation of EbA measures such as MPAs (Petit et al., 2018).

There is *low confidence* about how measures adopted are ensuring the sustainability of marine resources used by fisheries. In Peru, industrial fisheries follow an adaptive management approach (i.e., stock assessments, catch limits), while in Chile, small-scale fisheries of benthic-demersal resources is managed through the granting of exclusive territorial use rights (called TURFS) with established quotas defined by the central authority (Bertrand et al., 2018). In addition, MPAs in Chile play a key role in climate-change adaptation for fisheries (*medium confidence*) (Gelcich et al., 2015; Petit et al., 2018), and an increasing amount of funds have been invested in initiatives to reduce the vulnerability of fishery and aquaculture sectors to climate change (OECD, 2017). Since 2016, Argentina has been developing a strategy to implement EbM on fisheries with support from the Global Environment Facility (GEF) programme. Also, Argentina and Chile are promoting the local consumption of seafood and the certification of its fishery products (OECD, 2017), while Brazil and Chile have advanced in their response to climate change through the development of new research studies and methodologies incorporating research institutions (Nagy et al., 2015). Uruguay is incorporating stakeholders in its climate-change adaptation strategies (*low confidence*) (Nagy et al., 2015), while Colombia is supporting the capacity building of fishers, promoting livelihood diversification to increase the resilience of the sector (*medium confidence: medium evidence, high agreement*) (Hellebrandt et al., 2014; Arroyo Mina et al., 2016; Matera, 2016). Chile and Peru have made certain advances in the development of guidelines for the management of the coast line and the implementation of the EbM, which has favoured the collaboration of diverse and multiple stakeholders (fishers, academics, municipal institutions), the development of outreach and educational activities, the creation of networks and the interests of other fishery communities to implement EbM (*medium confidence: medium evidence, high agreement*) (Hellebrandt et al., 2014; Gelcich et al., 2015; Gutiérrez et al., 2016a; Oyanedel et al., 2016; Guerrero-Gatica et al., 2020). In countries like Peru and Chile, there is an increasing presence of intergovernmental and international cooperation agencies, in addition to new funding (e.g., GEF) and projects (Inter-American Development, SPINCAM) related to change adaptation for the fishery sector (*medium confidence: medium evidence, high agreement*) (Galarza and Kámiche, 2015; Barragán and Lazo, 2018).

Table 12.7 | National plans with adaptation goals for ocean and coasts in CSA.

CSA country	Adaptation initiative	Year
Argentina	Plan Nacional de Adaptación y Mitigación al Cambio Climático[1]	2019
Brazil	National Climate Change Adaptation Plan (Volume 1); General Strategies[2]	2016
	National Climate Change Adaptation Plan (Volume 2); Sectoral and thematic strategies[3]	2016
Chile	Plan Nacional de Adaptación al Cambio Climático[4]	2014
	Plan Sectorial de Adaptación al Cambio Climático en Biodiversidad[5]	2014
	Plan Sectorial de Adaptación al Cambio Climático en Pesca y Acuicultura[6]	2015
	Plan de Adaptación y Mitigación de los Servicios de Infraestructura al Cambio Climático[7]	2017
	Plan de Adaptación al Cambio Climático Sector Salud[8]	2017
Colombia	Plan Nacional de Adaptación al Cambio Climático[9]	2016
Costa Rica	Política Nacional de Adaptación al Cambio Climático[10]	2018
Ecuador	Plan Nacional de Cambio Climático[11]	2015
El Salvador	Plan Nacional de Cambio Climático[12]	2015
Guatemala	Plan de Acción Nacional de Cambio Climático[13]	2018
Guyana	Política de Adaptación y Plan de Implementación[14]	2001
Honduras	Plan Nacional de Adaptación al Cambio[15]	2018
Nicaragua	Plan de Adaptación a la Variabilidad y el Cambio Climático en el Sector Agropecuario, Forestal y Pesca[16]	2013
Peru	Plan Nacional de Adaptación al Cambio Climático del Peru[17]	2021
Suriname	Suriname National Adaptation Plan[18]	2019
Uruguay	Plan Nacional de Respuesta al Cambio Climático[19]	2010
Belize	Not Available	2019
Panamá	Not Available	
Venezuela	Not Available	

References: [1](Ministerio de Ambiente y Desarrollo Sostenible de la República de Argentina, 2019) [2](Ministry of Environment of Brazil, 2016a) [3](Ministry of Environment of Brazil, 2016b) [4](Ministerio de Medio Ambiente de Chile, 2014b) [5](Ministerio de Medio Ambiente de Chile, 2014a) [6](Ministerio de Economía Fomento y Turismo de Chile, 2015) [7](Ministerio de Medio Ambiente de Chile, 2017) [8](Ministerio de Salud de Chile, 2017) [9](Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2016) [10](Ministerio de Ambiente y Energía de la República de Costa Rica, 2018) [11](Gobierno Nacional de la República del Ecuador, 2015) [12](Ministerio de Medio Ambiente y Recursos Naturales de El Salvador, 2015) [13](Consejo Nacional de Cambio Climático y la Secretaría de Planificación y Programación de la Presidencia de Guatemala, 2018) [14](National Ozone Action Unit of Guyana, 2016) [15](Secretaría de Recursos Naturales y Ambiente del Gobierno de la República de Honduras, 2018) [16](Ministerio Agropecuario y Forestal de Nicaragua, 2013) [17](Ministerio del Ambiente Gobierno del Perú, 2021) [18](Government of Suriname, 2019) [19](Ministerio de Vivienda Ordenamiento Territorial y Medio Ambiente de la República de Uruguay, 2010)

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Adaptation Goals identified for ocean and coastal systems
in National Adaptation Plans of Central and South American countries

	Research and monitoring	Legislation and policies	Biodiversity and conservation	Risk management	Productive management	Infrastructure and tech	Capacity building and awareness	Financial management	Water and residues management	Social inclusion	Traditional practices
Chile	30	10	7	1	4	2	4	1	1		
Guatemala	9	8	16	3	4	3	3	1	4	1	2
Brazil	24	8	2	6	1		1	1	1		
Peru	4	3	3	8	7	2	5			2	1
Suriname	6	9	3		2	4	1	2	4		
Guyana	3	4	2	7	4	1	1	4	2	2	
Honduras	2	5	8	2	5	2					
Argentina	3	3	4	2	1	2					
Uruguay	3	1		5			1	4		1	1
Colombia		1	4	1		1		1	1		
Nicaragua		1			6						
Ecuador			2								
Costa Rica											
El Salvador											
Total	84	53	51	35	34	17	16	14	13	6	4

Number of adaptation goals: 1 – >30

Figure 12.12 | Type and amount of adaptation goals identified in NAPs for ocean and coastal systems of CSA countries.

12.5.2.3 National Climate Change Commitments for Ocean and Coasts

Beyond the protection, conservation and climate-change adaptation strategies implemented on CSA ocean and coastal areas and their ecosystems, a high number of adaptation goals to address climate-change impacts on ocean and coastal ecosystems and their services are incorporated into most of the national climate-change adaptation commitments of CSA countries (Table 12.7).

Current goals in national and sectoral adaptation plans attempt to promote research and monitoring (e.g., new research actions, modelling, knowledge management), the development of new legislative tools and policies (e.g., inter-institutional and territorial coordination, improvement of public policies), the conservation of ocean and coastal ecosystems and their biodiversity (e.g., creation of new MPAs, protection tools), the management of climate risks (e.g., warning systems), the management of productive activities (e.g., diversification of resources), the promotion of the construction of new infrastructure and technology (e.g., grey-green infrastructure [GGI]), the creation of new financial tools (e.g., types of insurance), improved the capacity building (e.g., education, awareness), water and residue management (e.g., sewage and freshwater availability), social inclusion (e.g., strategies to support vulnerable sectors, gender inclusion) and the incorporation of traditional practices (e.g., restoring traditional practices including Indigenous knowledge [IK]). However, the amount and type of adaptation goals differ enormously from country to country (Figure 12.12).

12.5.2.4 Limits and Barriers to Adaptation in Ocean and Coastal Ecosystems

Although current NAPs and many other actions and strategies focus on improving the conservation and restoration of ocean and coastal ecosystems, as well as the suitability of marine resources throughout CSA, these measures are still not able to reduce the vulnerability and sensitivity of these ecosystems to climate-change hazards (*high confidence*) (Figure 12.6; Table SM12.3; Leal Filho, 2018; Nagy et al., 2019). There is *high confidence* that sandy beach ecosystems of CSA countries have suffered significant losses of dunes as a consequence of the construction of infrastructures that have caused interruptions in the natural dynamic of beaches, reducing protection against tides, waves, extreme events or tsunamis (*high confidence*) (Amaral et al., 2016; Bernardino et al., 2016; González and Holtmann-Ahumada, 2017; Obraczka et al., 2017). Also, adaptation measures to cope with SLR and coastal extreme events sometimes fail because they exacerbate coastal erosion and damage (*medium confidence: medium evidence, high agreement*) (Spalding et al., 2014; Lins-de-Barros and Parente-Ribeiro, 2018). There is *medium evidence* but *high agreement* that the most serious barriers limiting the success of adaptation strategies in ocean and coastal systems in CSA stem from a lack of coordination (e.g., absence of participatory processes, overlapping among fishing and protection activities), lack of knowledge (e.g., poor monitoring, poor control and surveillance, no long-term studies) and lack of adequate metrics for evaluating adaptation actions informing decision makers hinder the continuity and adjustment of measures and lead to weak governance (e.g., perverse incentives, resource overexploitation,

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conflicts), a lack of financial resources and long-term commitments (e.g., crisis, lack of budgets, market fluctuations), weak policies, cultural constraints, poverty, low flexibility, lack of awareness of climate risks and lack of engagement by stakeholders (Leal Filho, 2018; Nagy et al., 2019; Moreno et al., 2020b; Aburto et al., 2021).

Some important limits and barriers have been detected for productive systems such as fisheries and tourism in CSA (*medium confidence: medium evidence, high agreement*). Major Brazilian fisheries do not follow an ecosystem approach to management, although some small-scale fisheries apply a precautionary approach (Singh-Renton and McIvor, 2015). The management of Peruvian artisanal (medium and small-scale) fisheries is minimal and is governed by a lack of regulations, control and management actions (Bertrand et al., 2018). In Argentina, recreational marine fisheries have been largely unregulated, and there exists a lack of monitoring programmes, which has contributed to the overexploitation of some key coastal stocks (Venerus and Cedrola, 2017). Moreover, womenfisher in CSA are excluded of the decision-making processes (FAO, 2016b; Bruguere and Williams, 2017). Due to the lack of monitoring programmes, it is unknown how this tourist industry will respond to long-term changes driven by climate change (Weatherdon et al., 2016).

12.5.2.5 Challenges and Opportunities

There is *low evidence and high agreement* that empowering local stakeholders (e.g., multi-lateral fisheries agreements) improves public awareness and simplifies regulations and increases the flexibility and sustainability of marine resources managed in fisheries under future scenarios (Weatherdon et al., 2016; Kalikoski et al., 2019). Ecosystem-based fisheries management (EBFM) has emerged as a suitable tool to minimise the risk to climate change, avoid ecosystem degradation and related services (Gullestad et al., 2017). Further, when EBFM includes climate complexity and the relationships among species within the ecological systems it contributes to maintain long-term socioeconomic benefits (Long et al., 2015). There is *high confidence* that EbA is more successful and feasible than hard coastal defences for the protection, management and restoration of ocean and coastal ecosystems and their resources (Spalding et al., 2014; González and Holtmann-Ahumada, 2017; Scarano, 2017).

There is *high confidence* that ecological and social resilience is improved by the presence of adequate metrics to evaluate adaptation measures to allow dynamic changes; and by increasing basic research and climate data (Moreno et al., 2020b). Resilience also increases with the existence of EWSs, improved local institutions, the construction of adequate infrastructure, major funding for capacity building and the enhanced engagement and empowerment of women (FAO, 2016b; Harper et al., 2017; Frangoudes and Gerrard, 2018; Gallardo-Fernández and Saunders, 2018; Leal Filho, 2018).

12.5.3 Water

CSA is one of the regions most affected by current and future hydrological risks to water security with an increasing number of vulnerable people depending on water from mountains (*high confidence*) (Sections 4.3, 4.4, 4.5; Immerzeel et al., 2020; Viviroli et al., 2020; WWAP, 2020). Adaptation to changing water availability is therefore a priority, but most efforts are documented only in the grey literature (e.g., governmental documents, project reports) with highly variable standards of quality and evidence. Most of the documented adaptation initiatives are in an early planning or implementation stage and evidence on successful outcomes is quite limited (Berrang-Ford et al., 2021). However, the growing number of adaptation initiatives across the CSA region has contributed to improved understanding of complex interlinkages of climate change, human vulnerabilities, local policies and feasible adaptation approaches (McDowell et al., 2019).

12.5.3.1 Challenges and Opportunities

In several regions of CSA, water scarcity is a serious challenge to local livelihoods and economic activities. Regions that are (seasonally) dry, partly with large populations and increasing water demand, exhibit particularly significant water stress. These include the Dry Corridor in CA, coastal areas of Peru (SWS) and northern Chile (SWS), the Bolivian-Peruvian Altiplano (NWS, SAM), the Dry Andes of Central Chile (SWS), Western Argentina and Chaco in northwestern Paraguay (SES) and Sertão in northeastern Brazil (NES) (*high confidence*) (Kummu et al., 2016; Mekonnen and Hoekstra, 2016; Schoolmeester et al., 2018). In NWS and SWS, downstream areas are increasingly affected by decreasing and unreliable river runoff due to rapid glacier shrinkage (*high confidence*) (Table SM12.6; Carey et al., 2014; Drenkhan et al., 2015; Buytaert et al., 2017). Many regions in CSA rely heavily on hydroelectric energy, and as a result of rising energy demand, hydropower capacity is constantly being extended (Schoolmeester et al., 2018). Worldwide, SA features the second-fastest growth rate, with about 5.2 GW additional annual capacity installed in 2019 (IHA, 2020). This development requires additional water storage options, which entail the construction of large dams and reservoirs with important social-ecological implications. River fragmentation and corresponding loss of habitat connectivity due to dam constructions have been described for, for example, the NSA, SAM, NES and SES (*high confidence*) (Grill et al., 2015; Anderson et al., 2018a), with important implications for freshwater biota, such as fish migration (*medium confidence*) (Pelicice et al., 2015; Herrera-R et al., 2020). Furthermore, examples in, for instance, NWS (Carey et al., 2012; Duarte-Abadía et al., 2015; Hommes and Boelens, 2018) and SWS (Muñoz et al., 2019b) showcase unresolved water-related conflicts between local villagers, peasant communities, hydropower operators and governmental institutions in a context of distrust and lack of water governance (*high confidence*).

Increasing water scarcity is also shaped by poor water quality, which has barely been assessed in CSA. Declining water quality can be observed, for example, due to intense agricultural and industrial activities in SWS, SES and SSA (*medium confidence*) (Mekonnen et al., 2015; Gomez et al., 2021), mining in Andean headwaters (NWS, SWS and Western SAM) and tropical lowlands (eastern SAM and NSA) (*medium confidence*) (Bebbington et al., 2015 risk and climate resilience; Vuille et al., 2018), urban domestic use (Desbureaux and Rodella, 2019), decreasing meltwater contribution (Milner et al., 2017) and acid rock drainages from recently exposed glacial sediments (Santofimia et al., 2017; Vuille et al., 2018). The level of water pollution is often exacerbated by missing water treatment infrastructure and low governance levels (*medium confidence*) (Mekonnen et al., 2015), with considerable negative implications for human health (Lizarralde Oliver and Ribeiro, 2016).

Water scarcity risks are projected to affect a growing number of people in the near and mid-term future in view of growing water demand in most regions (*medium confidence: medium evidence, high agreement*) (Veldkamp et al., 2017; Schoolmeester et al., 2018; Viviroli et al., 2020), expected precipitation reductions in western and northern SAM and SWS (*medium confidence: medium evidence, medium agreement*) (Neukom et al., 2015; Schoolmeester et al., 2018), substantial vanishing of glacier extent in NWS, SAM and SWS (Table SM12.6; Rabatel et al., 2018; Vuille et al., 2018; Cuesta et al., 2019; Drenkhan et al., 2019) and increasing evaporation rates in CA (*medium confidence*) (CEPAL, 2017). Furthermore, flood risk is a serious concern (Arnell et al., 2016) and expected to increase, especially in NWS, SAM, SES and SWS in the mid- and long-term future (*high confidence*) (Arnell and Gosling, 2016; Alfieri et al., 2017).

Risks of water scarcity and flood threaten people unevenly across the region. In CSA, about 26% (130 million people) of the population have no access to safe drinking water, and strong disparities prevail regarding its spatial distribution; for example, in Chile, 99% of the population have access, compared to 50% in Peru, 73% in Colombia, 52% in Nicaragua or 56% in Guatemala (*high confidence*) (UNICEF and WHO, 2019). Inequalities can be further exacerbated by unregulated or privately owned water rights and allocation systems (e.g., in Chile) (Muñoz et al., 2020a). The most vulnerable people belong to low-income groups in rural areas and informal settlements of large urban areas (*high confidence*) (WWAP, 2020).

Considerable uncertainties remain concerning future hydrological risks that strongly depend on the respective pathways of human intervention, management, adaptation and socioeconomic development. The combination of (seasonally) reduced water supply, growing water demand, declining water quality, ecosystem deterioration and habitat loss and low water governance could lead to increasing competition and conflict associated with high economic losses (*high confidence*) (Vergara et al., 2007; Vuille et al., 2018; Desbureaux and Rodella, 2019). This situation threatens human water security in the long term and poses an increasing risk to adaptation success in CSA (*high confidence*) (Drenkhan et al., 2015; Huggel et al., 2015b; Urquiza and Billi, 2020a).

Important progress has been made on climate change and water management policies in combination with more inclusive stakeholder processes. For instance, the implementation of NDCs in most countries of the region provides an important baseline for improving water efficiency, quality and governance at a multi-sectoral level and, thus, long-term adaptation planning (UNEP, 2015).

12.5.3.2 Main Concepts and Approaches

Adaptation in the water sector includes a broad set of responses to improve and transform, for example, water infrastructure, ecosystem functions, institutions, capacity building and knowledge production, habits and culture and local-national policies (Section 4.6).

Most adaptive water management approaches in CSA centre around extending the water supply side, including large infrastructure projects. However, 'hard path' interventions are now strongly contested because negative effects exacerbate local water conflicts (Carey et al., 2012; Boelens et al., 2019; Drenkhan et al., 2019), potentially leading to increasing water demand, vulnerabilities and water shortage risks (Di Baldassarre et al., 2018), thereby limiting adaptive capacity (*high confidence*) (Ochoa-Tocachi et al., 2019). More integrated approaches focus on multiple uses of water storage with shared stakeholder vision, responsibilities, rights and costs, as well as risks and benefits, and often integrating water and risk management (Branche, 2017; Haeberli et al., 2017; Drenkhan et al., 2019). In this chapter, a feasibility assessment was carried out for six major dimensions of multi-use water storage for the entire CSA (Table 12.11). While geophysical and economic aspects allow for the implementation of water storage projects under a multi-use approach, the institutional, social and environmental dimensions pose a major barrier (Section 12.5.3). Further demand-oriented approaches focus on incentives for the reduction of water use through changes in people's habits, efficiency increase and smart water management (Gleick, 2002). These are promoted in some regions, such as in CA and NWS (e.g., Colombia, Ecuador and Peru), to foster a sustainable water culture (Bremer et al., 2016; Paerregaard et al., 2016).

Major emphasis has been placed on NbS, that is, catchment interventions that are inspired and supported by nature and leverage natural processes and ecosystem services to contribute to the improved management of water. NbS potentially enhance water infiltration, groundwater recharge and surface storage, contribute to disaster risk reduction and can replace or complement grey (i.e., conventionally built) infrastructure that is often socioenvironmentally contested (WWAP, 2018). Some examples include the reactivation of ancestral infiltration enhancement systems in the Peruvian Andes (NWS) (Ochoa-Tocachi et al., 2019), the use of erosion control structures in the Bolivian Altiplano (SAM) (Hartman et al., 2016) and the potential improvement of drinking water quality and flood risk reduction in urban areas of CSA (Tellman et al., 2018) (Section 12.5.5.3.2). Additionally, NbS in combination with ecosystem and community-based adaptation potentially generate important co-benefits, including increasing water security and the attenuation of social conflicts in Chile (SWS) (Reid et al., 2018), water conservation in coastal Peru (NWS) and flood protection in Guyana (NSA) (*medium confidence: medium evidence, medium agreement*) (Spencer et al., 2017). However, the evaluation of implementation success of NbS is often hampered by limited evidence on actual benefits (WWAP, 2018).

In recent years, the inclusion of IKLK in current adaptation baselines has attracted increasing attention, particularly in regions with a high share of Indigenous Peoples (NWS, SAN, SWS, NSA) (*high confidence*) (Reyes-García et al., 2016; Schoolmeester et al., 2018; McDowell et al., 2019). One example is the adapted use of agrobiodiversity when dealing with more frequent and intense tidal floods in the Amazon delta (NSA) (Vogt et al., 2016). In another context, IKLK has been considered for the evaluation of water scarcity and GLOF risks in Peru (NWS) (Motschmann et al., 2020b). Additionally, local citizen science-based initiatives (Buytaert et al., 2014; Tellman et al., 2016; Njue et al., 2019) can support the production of multiple forms of knowledge

Overview map of observed glacier changes, associated impacts, adaptation and policy efforts across the Andes

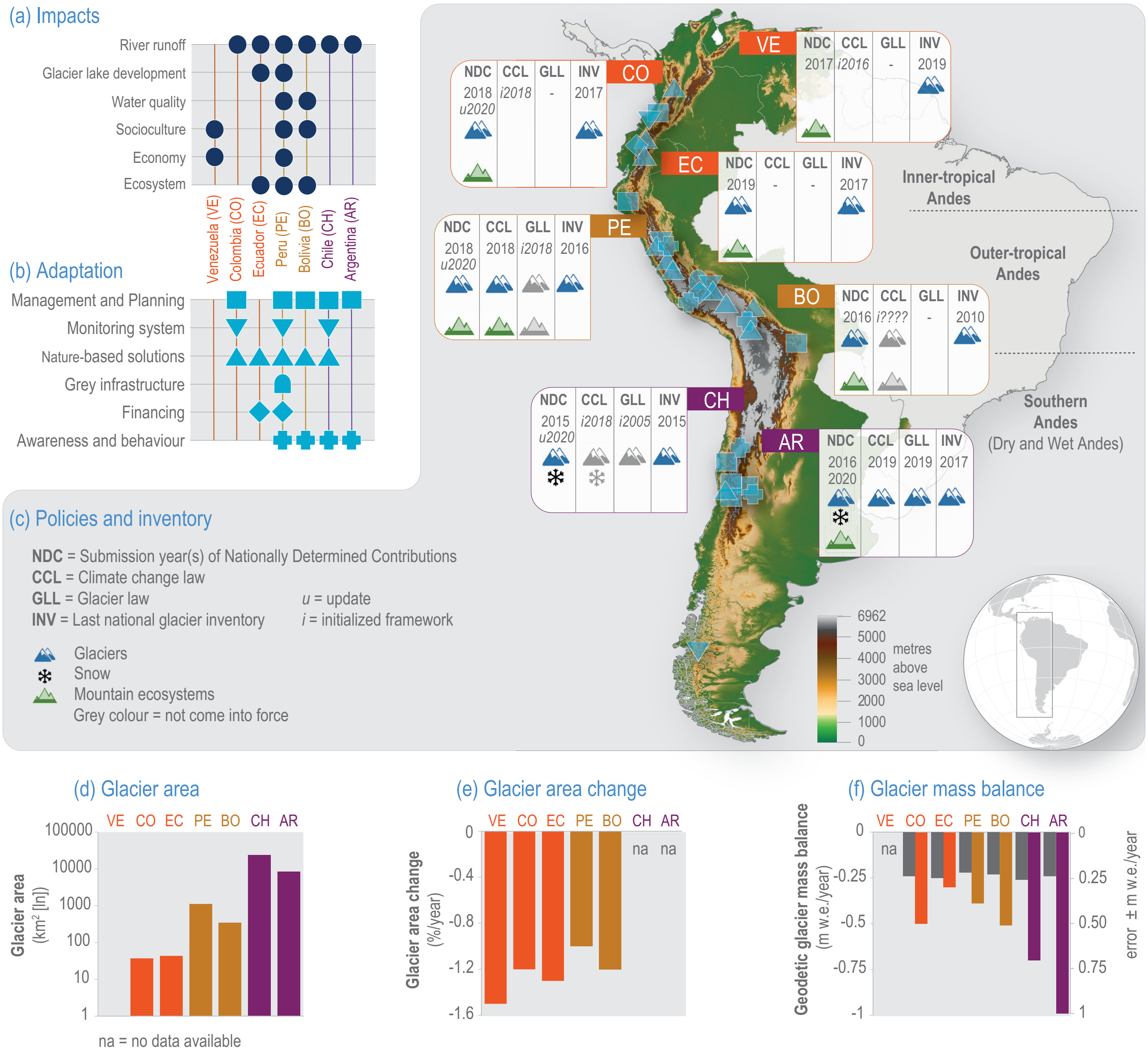

Figure 12.13 | Overview map of observed glacier changes, associated impacts, adaptation and policy efforts across the Andes.

(a) Selected impacts from glacier shrinkage.

(b) Selected adaptation efforts (see upper-right map for the location of each adaptation measure).

(c) Policies and glacier inventory: NDC = submission year(s) of Nationally Determined Contributions (u = update), CCL = climate change law, GLL = glacier law (i = initialised framework), INV = last national glacier inventory. The explicit mention of glaciers, snow and mountain ecosystems within each law/inventory is highlighted with the corresponding symbols (grey = has not come into force).

(d) Glacier area (km²) according to last national inventory.

(e) Glacier area change (%/year) according to baseline of last national inventory.

(f) Geodetic glacier mass balance in metres water equivalent per year (m w.e./year) and error estimate (±m w.e./year) retrieved from Dussaillant et al. (2019). nd = no data available. Further details can be found in the appendix in Table SM12.6.

with flexible and extensive data collection. Important questions centre around how to integrate IKLK and other types of knowledge from the early planning stages on, to achieve enhanced or transformational adaptation building on co-produced knowledge (Kates et al., 2012; Klenk et al., 2017). NbS combined with community engagement and integration of diverse knowledge can foster transformational adaptation of social-ecological systems (Palomo et al., 2021).

12.5.3.3 Policies, Governance and Financing

National policies on climate change, water protection, regulation and management laws are important focal areas of adaptation in the water sector (Section 4.7). Notable in the jurisdiction field is the Glacier Protection Law in place in Argentina (2010–2019) and under construction in Chile (since 2005). This first glacier law in the world represents a milestone for high-mountain conservation but is also criticised for hindering effective disaster risk adaptation measures and excluding local socioeconomic needs (Anacona et al., 2018). Furthermore, the first Framework Law on Climate Change was implemented in Peru (2018) and is under way in Colombia, Chile and Venezuela (Figure 12.13; Table SM12.6). Overarching regional institutions (e.g., OAS [2016]) and most countries in CSA promote a move towards more integrative and sustainable management of water resources through new legislation and financing mechanisms. For instance, new water laws that include principles of integrated water resource management (IWRM) have entered into force, for example, in Nicaragua (2007), Peru (2009), Ecuador (2014) and Costa Rica (2014), or are under way, such as in Colombia (since 2009). However, current realities in all regions show major challenges in implementing IWRM mechanisms and policies, related but not limited to political and institutional instabilities, governance structures, fragmented service provision, lack of economies of scale and scope, corruption and social conflicts (*high confidence*) (WWAP, 2020).

Many water-related conflicts in CSA are rooted in inequitable water governance that excludes water users from decisions on water allocation (*high confidence*) (Drenkhan et al., 2015; Vuille et al., 2018). In turn, inclusive water regimes leverage long-term adaptation planning. These have been addressed in some national strategies, such as in Brazil (Ministry of Environment of Brazil, 2016a). At the local level, a decentralised and participatory bottom-up water governance model was induced by civil society and research institutions to foster rainwater harvesting technologies reducing drought risk in semiarid Brazil (NES) (Lindoso et al., 2018).

Water fund programmes can generate important co-benefits for sustainable development, contributing to improved governance and conservation of watershed systems in CSA. Nevertheless, only a few experiences have been evaluated as successful due to insufficient implementation, low decision-making ability of some stakeholder groups and poor evidence-based approaches (*medium confidence*) (Bremer et al., 2016; Leisher et al., 2019). Furthermore, financing mechanisms that produce incentives for sustainable water management have been promoted, tested or implemented. PES for water provision represents such an example and such mechanisms have been implemented across CSA since the 1990s (Grima et al., 2016).

Only about 50–70% of required financial resources are currently allocated per year to meet the national targets in the water, sanitation and hygiene (WASH) sector for the Sustainable Development Goal (SDG) 6 agenda in several regions of CSA. This share drops down to less than 50% in NSA (Venezuela) and SES (Argentina, Uruguay, Paraguay), except for Panama in CA, which allocates more than 75% of the required financial resources. For the implementation of NbS, evidence suggests that the overall expenditure remains well below 1% of total investment in water resource management infrastructure (WWAP, 2018). These funding deficits set important limitations on future water provision, adaptation to changing water resources and the achievement of the SDGs by 2030 (*high confidence*) (WHO, 2017).

12.5.3.4 Successful Adaptation and Limitations

Although a growing body of adaptation initiatives exists for CSA, evidence on their effectiveness is scarce. In many parts of CSA the level of success of adaptation measures depends largely on the governance of projects and stakeholder-based processes and is closely related to their effectiveness, efficiency, social equity and sociopolitical legitimacy (*high confidence*) (Adger et al., 2005; Rasmussen, 2016b; Moulton et al., 2021). Several PES experiences across CSA have been described as successful measures for watershed conservation and adaptation (*high confidence*). An example of success is the Quito water fund in Ecuador, which aims to improve the city's water quality by integrating public and private stakeholder interests with ecosystem conservation and local community development since the 2000s (Bremer et al., 2016; Grima et al., 2016) (Case Study 12.6.1). At the same time, in Moyobamba in Peru, the development of a watershed protection programme was leveraged by a multi-stakeholder platform process that enabled deep social learning (Lindsay, 2018). In turn, initiatives that do not consider the entire set of social-ecological dimensions and dynamics of adaptation or unintentionally increase vulnerabilities of human or natural systems are at risk of leading to reduced outcomes (McDowell et al., 2021) or maladaptation (Reid et al., 2018; McDowell et al., 2019; Eriksen et al., 2021). However, systematic assessments of maladaptation in the water sector have barely been provided for CSA.

In CSA, only limited information on the limits of adaptation in relation to water is available, for instance on the possible path dependency of institutions and associated resistance to change (Barnett et al., 2015). Examples of soft adaptation limits (i.e., options to avoid intolerable risks currently not available) include lack of trust and stakeholder flexibility, associated with unequal power relations that lead to reduced social learning and poor outcomes for improved water management, as reported in, for example, NWS (Lindsay, 2018). An example of hard adaptation limits (i.e., intolerable risks cannot be avoided) in the region is the loss of livelihoods and cultural values associated with glacier shrinkage in NWS (Jurt et al., 2015).

Most barriers to advance adaptation in CSA correspond to soft limits associated with missing links of science–society–policy processes, institutional fragilities, pronounced hierarchies, unequal power relations and top-down water governance regimes (*high confidence*). One example is the abandonment of long-term hydrological monitoring sites within tropical Andean ecosystems (paramo) in Venezuela (Rodríguez-Morales et al., 2019) due to the lack of governmental support during the political crisis. In that regard, the collection and availability of consistent hydroclimatic and socioeconomic data at adequate scales represent an important challenge in CSA. Major adaptation barriers are furthermore reported from central Chile in the context of a mega-drought since 2010, related to socioeconomic factors and a deficient bottom-up approach to informing and developing public policy (Aldunce et al., 2017). These gaps could be bridged by strengthening transdisciplinary approaches at the science–

policy interface (Lillo-Ortega et al., 2019) with blended bottom-up and top-down adaptation to include scientific knowledge with impact and scenario assessments in local adaptation agendas (Huggel et al., 2015b). For instance, a new allocation rule for the Laja reservoir in southern Chile (SWS), based on consistent water balance modelling results, could inform policy and water management and potentially improve local water management and reduce water conflicts over the long term (Muñoz et al., 2019b).

12.5.4 Food, Fibre and Other Ecosystem Products

The CSA region globally has the greatest agricultural land and water availability per capita. With 15% of the world's land area, it receives 29% of global precipitation and has 33% of globally available renewable resources (Flachsbarth et al., 2015). Agricultural commodities (coffee, bananas, sugar, soybean, corn, sugarcane, beef livestock) are some of the highest users of ecosystem resources such as land, water, nutrients and technology. These exports have gained importance in the past two decades as international trade and globalisation of markets have shaped the global agri-food system. However continuous overuse of the environment might account for resource depletion (deforestation, land degradation, nutrient depletion, pollution), affecting the natural capital base. The effects of climate change on humans, via ecological systems, exacerbate the impact related to the depletion of ecosystem services (Scholes, 2016; IPBES, 2018b; Castaneda Sanchez et al., 2019; Clerici et al., 2019; Tellman et al., 2020; Pacheco et al., 2021).

12.5.4.1 Challenges and Opportunities

Even though several regions have seen significant improvements in food availability, many countries are also experiencing a declining trend in food self-sufficiency (Porkka et al., 2013; Rolando et al., 2017). Drought conditions in CA and the Caribbean increased in line with climate model predictions (Herrera et al., 2018a). The direct social and economic consequences for the sector are evident in CA's so-called Dry Corridor, with a growing dependence on food imports (Porkka et al., 2013), and these degrees of dependency make the region more vulnerable to price variability, climatic conditions (Bren d'Amour et al., 2016; ECLAC, 2018) and, therefore, to food insecurity in the absence of adaptation actions (*high confidence*) (Porkka et al., 2013; Bren d'Amour et al., 2016; López Feldman and Hernández Cortés, 2016; Eitzinger et al., 2017; Imbach et al., 2017; Lachaud et al., 2017; Harvey et al., 2018; Niles and Salerno, 2018; del Pozo et al., 2019; Alpízar et al., 2020; Anaya et al., 2020).

Given these circumstances, some regions in CSA (Andes region and CA) will just meet, or fall below, the critical food supply/demand ratio for their populations (Bacon et al., 2014; Barbier and Hochard, 2018b). Meanwhile, the more temperate part of SA in the south is projected to have agricultural production surpluses (*low confidence*) (Webb et al., 2016; Prager et al., 2020). The challenge for this region will be to retain the ability to feed and adequately nourish its internal population as well as making food supplies available to the rest of the world.

The access of other markets to the region's agricultural products might be conditioned on the adoption of low-carbon-agriculture measures. Achieving net-zero emissions while improving standards of living will be possible but will also require developing transition policy frameworks to reach the target (Frank et al., 2019; Mahlknecht et al., 2020; Cárdenas et al., 2021).

12.5.4.2 Governance and Barriers for Adaptation

The governance of adaptation for CSA implies modifying agricultural, socioeconomic and institutional systems in response to and in preparation for actual or expected impacts of climate variability and change, to reduce harmful effects and exploit beneficial opportunities (*high confidence*). CSA agriculture has a diversity of systems and segments of producers. While small-scale farmers contribute significantly to food production and food security, especially in developing economies, they face global policies oriented towards global commodity markets (Knapp, 2017; Fernández et al., 2019). Climate action initiatives that consider CSA's high levels of poverty and inequality to reduce these pervasive problems are central for adaptation in the region (Crumpler et al., 2020; Locatelli et al., 2020).

Since AR5, important advances at the institutional level have occurred based on the development and implementation of NAPs for the agriculture and forestry sector among countries. Adapting to climate change entails the interaction of decision makers, stakeholders and institutions at different scales of government, from local to national. The Climate-Adapted Sustainable Agriculture Strategy for the region of the Central American Integration System (EASAC) of the Central American Agricultural Council of Ministers of Agriculture constitutes a valuable example of how to undertake climate action in the agricultural sector, as a block of countries and in an intersectoral manner, to enhance results and make better use of resources (IICA, 2019).

In Brazil, the Low-Carbon Agriculture (LCA) programme (Programa ABC) funds practices for reducing GHG emissions in the sector (Government of Brazil, 2012), accounting for about 15% of the total agriculture official finance portfolio, although it faces challenges to advance (Souza Piao et al., 2021). Costa Rica offers an example on how reforestation can help achieve Paris Agreement objectives. Reforestation through natural regeneration on abandoned pastures boosted forest cover from 48% in 2005 to 53.4% in 2010 (Reid et al., 2019; Cárdenas et al., 2021). Some key success factors included a strong institutional context, fiscal and financial incentives for reforestation, conservation measures such as payment for environmental services, cattle ranch subsidy reform and a historically strong enforcement and focus on land titles that favoured the restoration of lands. Uruguay offers another example, with the farm sector contribution of 32.8% of all exports and 73.8% of the country's emissions, so decarbonisation is not just an environmental issue but an economic competitiveness one as well. In the Intended Nationally Determined Contributions (INDCs) submitted to the UNFCCC in 2015, Uruguay set a specific target for the agriculture sector to reduce enteric methane emissions intensity per kilogram of beef (live weight) by 33% to 46% in 2030 by improving efficiency of beef production by controlling the grazing intensity to increase animal intake, reproductive efficiency and daily weight gain (Picasso et al., 2014).

It is relevant to create conditions for the development of sustainable agricultural practices in a framework where factors associated with climate have become important for producers, given recent experiences of drought and lack of water (*high confidence*) (Clarvis and Allan, 2014; Roco et al., 2016; Hurlbert and Gupta, 2017; Pérez-Escamilla et al., 2017; Cruz et al., 2018; Zúñiga et al., 2021). Solutions that consider relevant drivers that have demonstrated a positive effect in diffusion of adaptation strategies are more efficient (Table 12.8). Some conditions, such as the promotion of education programmes, participation in cooperatives, credit access and land tenure security, can help. In the same line, in CSA some elements, such as technology and information access and local knowledge, reinforce climate-change adaptation (Khatri-Chhetri et al., 2019; Piggott-McKellar et al., 2019). As stated in Table 12.8, barriers of various origins persist in connection with climate-change adaptation in the region increasing the vulnerability of farming systems and rural livelihoods.

Limited information regarding cost-benefit analyses of adaptation is available in the region and regarding avoiding maladaptation effects and promoting site-specific and dynamic adaptation options considering available technologies (*medium confidence*) (Roco et al., 2017; Zavaleta et al., 2018; Ponce, 2020; Shapiro-Garza et al., 2020).

Climate information services has an important role in climate-change adaptation and there is a recognised gap between climate science and farmers (*high confidence*) (Vaughan et al., 2017; Loboguerrero et al., 2018; Tall et al., 2018; Thornton et al., 2018; Ewbank et al., 2019). Such services should address the challenges of ensuring that climate information and advisory services are relevant to the decisions of smallholder and family farmers, providing timely climate service access to remote rural communities with marginal infrastructure and ensuring that farmers own climate services and shape their design and delivery. An interesting case facing this gap is the implementation of local technical agro-climatic committees in Colombia, which make it possible to share and validate climatic and weather forecasts, as well as crop model results for seasonal drought events (Loboguerrero et al., 2018). Another example is the web service AdaptaBrasil-MCTI, which forecasts the risk of climate-change impacts on strategic sectors (e.g., food, energy, water) in Brazil (Government of Brazil and Ministry of Science Technology and Innovation Secretariat of Policies and Programs, 2021).

Barriers to financial access are present in the region, restricting effective adaptation to extreme weather events (*high confidence*) (Chen et al., 2018; Fisher et al., 2019; Piggott-McKellar et al., 2019; Vidal Merino et al., 2019; de Souza Filho et al., 2021). In 2014, the penetration rate of this type of insurance in the region averaged 0.03% of GDP, and a few countries dominate the market (Brazil, Argentina). Beyond these countries, some initiatives also exist in Uruguay, Paraguay, Chile and Ecuador. In most Latin American and Caribbean countries, the public sector plays an important role in providing insurance or reinsurance and coexists with private-sector companies (Cárdenas et al., 2021). Insurance protections represent a strategy to transfer climate risk to protect the well-being of vulnerable small farmers and accelerate uptake (recovery) after a climate-related extreme weather event. Lack of finance and proper infrastructure is compounded by limited knowledge of sustainable farming practices and high rates of financial illiteracy (*high confidence*) (Hurlbert and Gupta, 2017; Piggott-McKellar et al., 2019).

Insufficient access to digital services and technologies further widens the gap between the rural poor and more urban populations of Latin America and the Caribbean (*medium confidence: insufficient evidence, high agreement*). In turn, these factors compromise productivity and competitiveness. Support for the rural poor can be focused on both economic competitiveness and social development. Finally, to align the identified adaptation options as a priority for achieving future food security in the NDCs of CSA countries to mitigation commitments, it will be essential to highlight synergies by generating evidence (national research) in relation to progress towards increasing productivity and resilience and reducing GHG, in addition to demonstrating its added value as a development initiative (Rudel et al., 2015 sustainable; Loboguerrero et al., 2019).

12.5.4.3 Adaptation Options

To contextualise the adaptation options at the regional level, the majority of the NDCs of the CSA countries reported observed and/or projected climate-related hazards: occurrence of droughts and floods (80% of countries each), followed by storms (45%) and landslides (30%), as well as extreme heat, wildfire and invasion by pests and non-native species in agriculture (25% each) (Crumpler et al., 2020).

The main adaptation options for climate change in the region include preventive measures against soil erosion; climate-smart agriculture, which provides a framework for synergies between adaptation, mitigation and improved food security; climate information systems; land use planning; shifting plantations at high altitudes to avoid temperature increases and plagues; and improved varieties of pastures and cattle (Lee et al., 2014; Jat et al., 2016; Crumpler et al., 2020; Moreno et al., 2020a; Aragón et al., 2021). Agricultural technologies are not necessarily changing, but the economic activity is shifting to accommodate increasing climate variation and adapt to changes in water availability and ideal growing conditions (*high confidence*), as is observed in Argentina, Colombia and Brazil (McMartin et al., 2018; Rolla et al., 2018; Sloat et al., 2020; Gori Maia et al., 2021). Coffee plantations are moving further up mountain regions, with the land at lower elevations converted for other uses. In Brazil, crop modelling suggests the need for the development of new cultivars, with a longer crop cycle and with higher tolerance to high temperatures, a necessary technological advance for maize, an essential staple crop, to be produced in the future. Additionally, irrigation becomes essential for sustaining productivity in adverse climate-change scenarios in several regions of CSA (McMartin et al., 2018; Lyons, 2019; Reay, 2019).

Livestock production is for small farmers one of the main sources of protein and contributes to food security (Rodríguez et al., 2016). The importance of this sub-sector in CSA will continue to increase as the demand for meat products does as well in the coming years, driven by growing incomes in the region (OECD and FAO, 2019). However, the increase in animal production has been associated with land degradation, triggered by the conversion of native vegetation to pastureland and aggravated by overgrazing and abandoning of the degraded pastures (Baumann et al., 2017; ECLAC, 2018; Müller-Hansen et al., 2019). Sá et al. (2017) simulated the adoption of agricultural systems based on LCA strategies towards 2050. According to the simulation, the adoption of LCA strategies in the SA region can

Table 12.8 | Recent studies related to climate-change adaptation of agricultural systems and its determinants in Central and South America region.

Reference	Countries	Sample size (n)	Study approach	Crop systems	Adaptation strategies	Main drivers promoting climate-change adaptation	Main barriers limiting climate-change adaptation	Main barriers detected
de Souza Filho et al. (2021)	Brazil	175	Quant.	Cattle farmers	Integrated crop-livestock and livestock-forestry systems	Credit access, extension services	Lack of resources	Lack of agricultural market access strategies
Magalhães et al. (2021)	Brazil	94	Qual.	Several crops	Farm management	Previous experience with risks	Inadequate infrastructure, low purchasing power	Opportunities limited by infrastructure
Carrer et al. (2020)	Brazil	175	Quant.	Several crops	Agricultural insurance	Schooling, technical assistance	Higher risk propensity	Limited financial market access
Quiroga et al. (2020)	Nicaragua	212	Quant.	Coffee	Several adaptation measures	Farm size, awareness of climate change, schooling	Limited access to rain water	Absence of climate-change education
Bro et al. (2019)	Nicaragua	236	Quant.	Coffee	Crop, soil and water	Schooling, participation in cooperatives, radio	Household size	Institutional framework to promote cooperatives
Leroy (2019)	Venezuela and Colombia	73	Qual.	Several crops at high altitudes	Irrigation management	Perception of water scarcity, local knowledge	Degradation of fragile areas	Ineffectiveness of local institutions
Cherubin et al. (2019)	Colombia	6	Quant.	Several crops and pasture	Agroforestry systems	Improving soil quality and biota	Degradation of conventional pasture	Lack of crop diversification
Harvey et al. (2018)	Costa Rica, Honduras and Guatemala	860	Quant.	Coffee, beans and maize	Several adaptation practices	Awareness of climate change	Affordability of adaptation practices	Lack of adaptation involving agroecological and socioeconomic contexts
Chen et al. (2018)	Costa Rica and Nicaragua	559	Quant.	Several crops	Intensification and diversification	Access to weather information, participation in organisations, credit access, farming experience	Land renting	Lack of crop and practices diversification
Vidal Merino et al. (2019)	Peru	137	Quant.	Several crops	Water management	Farm size, capital, irrigated proportion	Limited access to off-farm activities, small cultivated area	Lack of site-specific design of interventions
Meldrum et al. (2018)	Bolivia	193	Quant.	Potato, quinoa and others	Diversification of crop portfolio	Weather information	Loss to traditional knowledge	Lack of resilience and actions to expand and maintain variety portfolio
Lan et al. (2018)	Nicaragua	180	Quant.	Cocoa	Crop management	Schooling, household size, farm size	Lack of income	Income inequality, gaps of profitability of practices, benefits of practices depends on costs
Kongsager (2017)	Belize	125	Qual.	Maize	Alley cropping	Schooling	Land tenure, market distance, degradation of fragile areas	Lack of land tenure, lack of market access, lack of trust
Schembergue et al. (2017)	Brazil	5485[a]	Quant.	Several crops	Agroforestry systems	Financing, presence of associations, credit access	High potential for agriculture, lack of climate information	Adaptation conditioned by agricultural, socioeconomic and climatic conditions

Reference	Countries	Sample size (n)	Study approach	Crop systems	Adaptation strategies	Main drivers promoting climate-change adaptation	Main barriers limiting climate-change adaptation	Main barriers detected
Harvey et al. (2017)	Guatemala, Honduras and Costa Rica	300	Quant.	Coffee and maize	Ecosystem-based adaptation	Schooling, age, farming experience, access to technological support	Lack of land tenure	Lack of access to training and finance
Roco et al. (2016)	Chile	665	Quant.	Several crops	Water management	Farm size, access to weather information	Locations, age	Lack of availability and access to climate-change information
Mussetta and Barrientos (2015)	Argentina	41	Qual.	Vine and others	Crop and water management	Organisation of producers, labour availability, knowledge and information access, technology access	Water allocation system	Lack of water management and distribution strategies

Notes:
(a) municipalities; Quant.: mainly quantitative; Qual.: mainly qualitative.

alter the growing trend of land use and land use change emissions, and at the same time, it can increase meat production by 55 Mt for the entire period (2016–2050). The restoration of degraded pasture and livestock intensification account for 71.2% and integrated crop–livestock–forestry system contributes 28.8% of total meat production for the entire period. These results indicate that combined actions in agricultural management systems in SA can result in synergistic responses that can be used to make agriculture and livestock production an important part of the solution of global climate change and advance food security (*medium confidence: insufficient evidence and high agreement*) (Zu Ermgassen et al., 2018; Pompeu et al., 2021). Crop–livestock–forestry systems are also important for climate-change adaptation as they provide multiple benefits, including the coproduction of food, animal feed, organic fertilizers and soil organic carbon sequestration (Sharma et al., 2016; Rodríguez et al., 2021), achieving mitigation and adaptation goals (*high confidence*) (Picasso et al., 2014; Modernel et al., 2016, 2019; Rolla et al., 2019; Locatelli et al., 2020). A recent analysis of agroforestry in Brazil showed positive and relevant impacts on the heads/pasture area rate in livestock production and that the system may have also stimulated a shift towards other production activities with higher gross added value (Gori Maia et al., 2021). Agroforestry has also proven to have protective benefits to obtain more stable, less fluctuating yields due to climate-related damage in coffee production (*high confidence*) (Bacon et al., 2017; Durand-Bessart et al., 2020; Ovalle-Rivera et al., 2020). In the same way, the production of plant-based fibre can be less vulnerable to economic and climatic variability through farming system diversification. Textile fibre crops for the case of cotton include crop rotation, agroecological intercropping and agroforestry (Oliveira Duarte et al., 2019).

Adaptation strategies also concern Indigenous agriculture, that is, the vast majority of the 44 million Amerindians (CEPAL, 2014). IKLK can play an important role in adaptation (Zavaleta et al., 2018). On one hand, they ensure the conservation of a very rich agrobiodiversity that is likely to meet the challenges of climate change (*high confidence*) (Carneiro da Cunha and Morim de Lima, 2017; Magni, 2017; Emperaire, 2018; Donatti et al., 2019), while on the other hand, the sustainability of large territories that assure their livelihood (Singh and Singh, 2017; Mustonen et al., 2021). In the Andes, ancient technologies increased the quantity of crops produced and made it possible to cope with climatic changes and water scarcity, while nutrition conditions were improved (*high confidence*) (López Feldman and Hernández Cortés, 2016; Parraguez-Vergara et al., 2018; Carrasco-Torrontegui et al., 2020 food). Also, fire prevention management and protection against forest and biodiversity loss are recognised as important elements in IK (Mistry et al., 2016; Bowman et al., 2021).

12.5.5 Cities, Settlements and Infrastructure

CSA is the second most urbanised region of the world, with 5 megacities and half of the urban population in 129 secondary cities (UNDESA, 2019), huge metropolitan areas concentrated on the coast and an increasing number of small cities by the sea (Barragán and de Andrés, 2016). Besides the many climatic events threatening urban areas in the region (extreme heat, droughts, heavy storms, floods, landslides), cities by the coast are also exposed to SLR (Section 12.3; Figure 12.6; Dawson et al., 2018; Leal Filho et al., 2018; Le, 2020). The main determinants of urban vulnerability assessed in the region are poor and unevenly distributed infrastructure, housing deficits and informality, poverty and the occupation of risk areas, including LECZs (Section 12.3). Those features of urban systems increase the risks to health, ecosystems and its services, water, food and energy supplies (Section 12.4). Impacts of climate events on urban water supply, drainage and sewer infrastructures are the most frequently reported in the region (Section 12.3; Figure 12.9).

12.5.5.1 Challenges and Opportunities

The inequality, poverty and informality shaping cities in the region increase vulnerability to climate change (*high confidence*) (Romero-Lankao et al., 2014; Rasch, 2017; Filho et al., 2019) and can hinder adaptation (Section 12.5.7.1), while interventions addressing these social challenges and the existing development deficits (e.g., build or improve infrastructure and housing applying climate-adapted patterns) can go hand in hand with adaptation and mitigation (*medium confidence: high agreement, medium evidence*) (Section 12.5.7.3; Creutzig et al., 2016; Le, 2020; Satterthwaite et al., 2020). Over 20% of the urban population in Latin America and the Caribbean live in slums and many other forms of precarious and segregated neighbourhoods, settled in risk areas and lacking infrastructure (Rasch, 2017; UN-Habitat, 2018; Rojas, 2019). This vulnerable condition is boosted by unstable political and governmental institutions, which suffer from ongoing corruption, weak governance and reduced capacity to finance adaptation (Rasch, 2016). Facing governance challenges by including diverse stakeholders and encouraging and learning from community-based experiences has also presented the opportunity to improve adaptation strategies (Archer et al., 2014). An example of this is the Regional Climate Change Adaptation Plan of Santiago (Krellenberg and Katrin, 2014).

12.5.5.2 Governance and Financing

The lack of a high multi-level and intersectoral governance capacity with strong multi-player horizontal and vertical coordination and long-term support limit adaptation in the region (*high confidence*) (Anguelovski et al., 2014; Bai et al., 2016; Chu et al., 2016; Schaller et al., 2016; Miranda Sara et al., 2017). The ability to enrol stakeholders and include community-based initiatives can determine adaptation success, particularly considering their impact in the decision-making arena (*high confidence*) (Section 12.5.8.1; Section 6.4; Anguelovski et al., 2014; Archer et al., 2014; Chu et al., 2017; Rosenzweig et al., 2018).

Lima's Climate Action Strategy is an example (Metropolitan Municipality of Lima, 2014). It was approved following a participatory and consultative process with the technical group on climate change from the Metropolitan Environmental Commission, focusing on the reduction of water vulnerabilities to drought and heavy rain, on the basis of which 10 (out of 51 with Callao) Lima district municipalities are developing and starting to implement adaptation measures (Foro Ciudades Para la Vida, 2021). In 2021 the municipality of Lima also approved its Local Climate Change Plan (Metropolitan Municipality of Lima, 2021) under a similar process. The engagement of local players was central to spreading and mobilising different types of knowledge and creating networks able to support adaptation (Section 12.6.3; Miranda Sara and Baud, 2014; Miranda Sara et al., 2017). The inclusive process is also a goal based on the example of Chile Municipalities Network Facing Climate Change (RedMuniCC) engaged in developing participatory strategic plans for climate adaptation and mitigation (RedMuniCC, 2021).

New forms of financing and leadership focused on community-based approaches have been developed to overcome the funding challenge and enable adaptation in the region (*medium confidence: medium evidence, medium agreement*) (Castán Broto and Bulkeley, 2013; Archer et al., 2014; Paterson and Charles, 2019). Systems for measuring, reporting and verifying adaptation financing, as in Colombia (Guzmán et al., 2018), or a national legislation geared towards adaptation, can also help access funds. The Peruvian Law on the Retribution Mechanism of Eco-Systemic Services and Code (Miranda Sara and Baud, 2014; MINAM Peru, 2016) in addition to the Ley Marco de la Gestión y Prestación de los Servicios de Saneamiento and Its Code (Ministerio de Vivienda, Construcción y Saneamiento de Perú, 2017), allowed potable water companies to add 1% to the bill to guarantee ecosystem services, water treatment and reuse with GI. Another 4% of bill go to developing and implementing adaptation plans and measures (Government of Peru, 2016).

12.5.5.3 Adaptation Options in Urban Design and Planning

Both the shape and activities of a city have an impact on carbon emissions, adaptation and mitigation opportunities (*high confidence*) (Raven et al., 2018; Satterthwaite et al., 2018). Combining urgent measures, strategic action (Chu et al., 2017) on long-term planning is central for transformative adaptation and avoiding maladaptation (Filho et al., 2019). Urban planning, considering climate risk assessments, and regulation (e.g., land use and building codes), including climate-adapted parameters, are central to coordinating and fostering private and public investments in adaptation, reducing risks related to features of the built environment (infrastructure and buildings) and the occupation of risk areas (e.g., threatened by floods and landslides) (Rosenzweig et al., 2018). A lack of information at the local scale, human resources and clear liability for climate-change response planning can limit adaptation (Aylett, 2015).

Strategic adaptation approaches have been adopted by many cities in dealing with the multi-level and intersectoral complexity of urban systems, with gains in fostering leadership and facing the predominant pattern of uneven urban development in the region (*medium confidence: limited evidence, high agreement*) (Chu et al., 2017). Medellin's metropolitan green belt, for example, focuses on problems such as irregular settlements, inequality and poor governance, formulating programmes and projects of the municipality of Medellin and the municipalities of the Vale do Aburra in a strategic long-term plan. Places with informal and precarious settlements were slated to be transformed with the belt's integration areas: eco-parks and eco-gardens (Alcaldía de Medellín, 2012; Chu et al., 2017).

12.5.5.3.1 Housing, Informality and Risk Areas

Informality and precariousness in housing is one of the most sensitive issues for adaptation in CSA cities (*medium confidence: medium evidence, high agreement*) (Satterthwaite et al., 2018; UN-Habitat, 2018). Housing deficit in 2009, as a regional baseline, estimated that 37% of households suffered from quantitative or qualitative deficiencies due to the high cost of housing and the incidence of poverty (Blanco Blanco et al., 2014; McTarnaghan et al., 2016; NU CEPAL et al., 2016; Vargas et al., 2018a; Rojas, 2019).

Policies and programmes have been implemented accumulating good practices and reducing the percentage of population in informal and precarious settlements (33.7% in 1990 to 21% in 2014) (NU CEPAL et al., 2016; Satterthwaite et al., 2018; Teferi and Newman, 2018; UN-Habitat, 2018). Slum upgrading and built-environment interventions (housing and infrastructure improvement and provision) in informal settlements can enhance adaptation (*high confidence*) (Teferi and Newman, 2018; Núñez Collado and Wang, 2020; Satterthwaite et al.,

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2020) while reducing floods, landslides and cascading impacts of storms, floods and epidemics, as observed with the 'incremental housing approach' in Quinta Monroy (Rojas, 2019) and the 'social urbanism' in Medellin (Garcia Ferrari et al., 2018).

The climate adaptation plans of several large CSA cities include efficient land use and occupation planning and urban control systems (comprising regulation, monitoring), fostering the articulation with housing and environmental policy (by means of intersectoral and multi-level governance), inhibiting and reducing the occupation of risk areas (mainly flooding and landslides risks); increasing population density in areas already served by infrastructure; expanding slum urbanisation and technical assistance programmes to improve and expand social housing (*high confidence*) (Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021).

Housing programmes and initiatives that consider resilient construction and site selection strategies are still in their nascent stages (Martin et al., 2013). Initiatives in slum upgrading, social housing improvement and regularising land tenure, associated with infrastructure provision, do not usually focus on adaptation, although they often focus on risk reduction. Those initiatives, associated with a housing policy that guarantees access to land and decent housing, represent a comprehensive intervention in vulnerable neighbourhoods for their adaptation to climate change, and CbA (community-based adaptation) strategies, including housing self-management and the participation of cooperatives, demonstrate the need and opportunity to transition to a transformative urban agenda that encompasses sustainable development, poverty reduction, disaster-risk reduction, climate-change adaptation and climate-change mitigation (*high confidence*) (Muntó, 2018; UN-Habitat, 2018; Valadares and Cunha, 2018; Bárcena et al., 2020b; Núñez Collado and Wang, 2020; Satterthwaite et al., 2020).

Several large cities are implementing municipal risk management plans and management and restoration plans for hydrologically relevant areas, considering threats of drought and heat waves, integrated watershed management and flood control programmes (*high confidence*) (Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021). Quito and Rio de Janeiro are two examples of comprehensive and effective city-level climate action that includes creating environmental protected areas, managing appropriate land use, household relocation and EWSs in areas vulnerable to high levels of precipitation associated with EbA, such as reforestation projects, to address natural hazards (ELLA, 2013; Anguelovski et al., 2014; Calvello et al., 2015; Alcaldía de Quito, 2017; Sandholz et al., 2018; Prefeitura da Cidade do Rio de Janeiro, 2021) (Section 12.6.1). EWS and the use of mapping tools as undertaken in La Paz proved to be an effective adaptation measure in the face of increasing hydro-climatic extreme events (Aparicio-Effen et al., 2018).

12.5.5.3.2 Green and Grey Infrastructure

Hybrid solutions, combining green and grey infrastructure (GGI), have been adopted for better efficiency in flood control (Ahmed et al., 2019; Drosou et al., 2019; Romero-Duque et al., 2020), sanitation, water scarcity, landslide prevention and coastal protection (*high confidence*) (Section 12.5.6.4; Mangone, 2016; Depietri and McPhearson, 2017; Leal Filho et al., 2018; McPhearson et al., 2018). The adoption of NbS, which embraces well-known approaches such as GI and EbA (Pauleit et al., 2017; Le, 2020), has increased (Box 1.3). The Fund for the Protection of Water (FONAG) and the Participative Urban Agriculture (AGRUPAR) are initiatives using NbS in Quito (Section 12.6.1). An example of GGI is a stormwater detention pond as a water storage solution to flood prevention, allowing multiple uses of an urban space, and adapting and revitalising a degraded area in Mesquita, Rio's metropolitan region (Jacob et al., 2019). These systemic and holistic solutions still need to overcome governance and sectorial barriers to be more widely adopted (Herzog and Rozado, 2019; Wamsler et al., 2020; Valente de Macedo et al., 2021).

Managing water in cities in an adaptive way has been central to reducing impacts such as floods and contributes to water security (*high confidence*) (Van Leeuwen et al., 2016; Okumura et al., 2021). Many cities facing frequent heavy storms that impact mostly underprivileged communities, slums and vulnerable areas could benefit from integrated NbS for disaster risk reduction and adaptation (*high confidence*) (Sandholz et al., 2018; Ronchi and Arcidiacono, 2019). A study covering 70 Latin American cities estimated that 96 million people would benefit from improving main watersheds with GI (Tellman et al., 2018). In several municipal climate plans, NbSs were introduced mainly to enhance rainwater management, reduce energy consumption and urban heat areas, improve water quality, prevent landslides and set aside green areas (*high confidence*) (Gobierno de la Ciudad de Buenos Aires, 2015; Municipio del Distrito Metropolitano de Quito, 2020; Prefeitura Municipal de Curitiba, 2020; Alcaldía de Medellín, 2021; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021; Prefeitura do Município de São Paulo, 2021). São Paulo's project for Jaguaré River proposes a large-scale landscape transformation applying innovative multi-functional NbSs instead of exclusively large, expensive and monofunctional hard-engineered solutions to manage stormwater (Marques et al., 2018; Herzog and Rozado, 2019). In Bogota, the Humedales Foundation has restored wetlands to enhance areas near the Van Der Hammen reserve to improve water quality and quantity, restore habitat for biodiversity and provide flood protection (Portugal Del Pino et al., 2020). In Petrópolis, a medium-sized city in the hills of Rio de Janeiro state, the water service company has implemented 10 NbS multi-functional micro wastewater treatment plants in low-income areas, helping to reduce cascading impacts of storms, floods and epidemics (Herzog and Rozado, 2019). In Costanera Sur, Buenos Aires, a public initiative to protect an auto-regenerated River Plate bank, which had received demolition material to create land, currently offers numerous ecosystem services for residents and attract visitors, activating the tourist industry and helping reducing riverine floods (Bertonatti, 2021; OICS, 2021).

A hybrid solution to water management that merges traditional interventions in urban areas with sustainable urban drainage systems

(SUDSs) (Davis and Naumann, 2017), considering small-scale low-impact development (LID) measures scattered over the watershed instead of concentrate huge hydraulic grey structures, can help reduce the risk and damage of flooding (*high confidence*) (Miguez et al., 2014, 2015a; Depietri and McPhearson, 2017; Da Silva et al., 2018a; de Macedo et al., 2018). Quito's climate plan explicitly cites the strategy for implementing blue and grey infrastructure to reduce risk due to extreme precipitation and its associated impacts such as flooding and landslides and the possible impact of water scarcity (Municipio del Distrito Metropolitano de Quito, 2020). The Integrated Iguaçu-Sarapuí River Basin Flood Control Master Plan, in Rio's metropolitan area, combines different solutions to flood protection, focusing on river restoration by retrofitting levee systems combined with adapting land use to provide a multi-functional landscape as an alternative to bring together green and grey solutions, creating urban parks to prevent further paving and avoid irregular occupation of riverbanks and provide storage capacity for damping flood peaks (Miguez et al., 2015b).

Many cities are implementing adaptation measures on integrated water and flood management systems (Sarkodie and Strezov, 2019), improving basic sanitation services (*medium confidence: medium evidence, high agreement*). The main strategies are established by NAPs periodically focusing on improving water distribution network and reservoir systems, as in Honduras (Government of Honduras, 2018) and Ecuador (Mills-Novoa et al., 2020), sewage and effluent treatment, as in Guatemala, Brazil and Paraguay (Government of Brazil, 2007; Government of Guatemala, 2016; Government of Paraguay, 2017), facing water scarcity and environmental degradation. Local authorities follow this guideline in an effort to maintain and upgrade existing drainage systems in Georgetown (Mycoo, 2014) or in Medellin, focusing on improving drainage systems to prevent landslides or flooding (Núñez Collado and Wang, 2020; Alcaldía de Medellín, 2021). Rio de Janeiro has constructed three large stormwater detention reservoirs to deal with frequent flood, (Prefeitura da Cidade do Rio de Janeiro, 2015), adopting a set of exclusively grey solutions, not combined into a NbS that could improve urban flood resilience (Rezende et al., 2019). The main proposed actions still consider the traditional approach in improving the hydraulic capacity of urban drainage systems as an adaptive measure (*high confidence*) (Gobierno de la Ciudad de Buenos Aires, 2020; Prefeitura Municipal do Salvador, 2020; Municipalidad de Lima, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021). In addition to this strategy, several local plans propose actions for the retention and storage of rainwater, both in urban drainage networks on a smaller intervention scale (Prefeitura Municipal de Curitiba, 2020) and along rivers and canals with large-scale works (*medium confidence: medium evidence, high agreement*) (Gobierno de la Ciudad de Buenos Aires, 2020; Prefeitura Municipal de Curitiba, 2020; Alcaldía de Medellín, 2021; Prefeitura da Cidade do Rio de Janeiro, 2021).

12.5.5.3.3 Mobility and Transport System

Mobility and transport systems play a key role in urban resilience (*high confidence*) (Walker et al., 2014a; Caprì et al., 2016; Espinet et al., 2016; Lee and Lee, 2016; Ford et al., 2018; Mehrotra et al., 2018; Quinn et al., 2018). Examples reported in the scientific literature assessed focus on mitigation strategies, even when they are labelled as adaptation measures (da Silva and Buendía, 2016; Di Giulio et al., 2018; Valderrama et al., 2019; Goes et al., 2020).

The integration of transport and land use planning and the improvement of public transport, also as important mitigation actions, has emerged as a consensus in countries' adaptation plans; nevertheless, emphasis on mobility and transport systems in the many published NAPs is low (*medium confidence: medium evidence, high agreement*). The NAPs of Honduras, Costa Rica and El Salvador do not approach adaptation or mitigation in the sector, while those of Peru, Ecuador, Guatemala and Paraguay focus on mitigation only. The NAPs of Chile, Colombia and Brazil focus on both mitigation and adaptation of mobility and transport systems. Chile's and Colombia's plans dedicate specific action lines to adapting mobility and transport systems to climate change, while Brazil published a complementary volume to accompany its NAP that is dedicated exclusively to sectoral strategies, although it presents only general guidelines (Government of Peru, 2010; Government of Chile, 2014; Government of Ecuador, 2015; Government of Brazil, 2016; Government of Colombia, 2016; Government of Guatemala, 2016; Government of Paraguay, 2017; Government of Costa Rica, 2018; Government of Honduras, 2018; Government of El Salvador, 2019).

On the municipal scale, among the biggest cities, São Paulo, Rio de Janeiro, Lima and Santiago stand out for including mobility and transport as a strategic axis of its climatic plans, though they prioritise mitigation, while Buenos Aires and Bogota do not delve into the issue in their plans (Gobierno de la Ciudad de Buenos Aires, 2015; Prefeitura da Cidade do Rio de Janeiro, 2016; Alcaldía Mayor de Bogotá D.C., 2018; Municipalidad de Lima, 2021; Municipalidad de Santiago, 2021; Prefeitura do Município de São Paulo, 2021). Most of those same cities have sectoral mobility plans, which are key tools in urban resilience. Those plans, however, do not focus on adaptation actions, instead emphasising mitigation (Government of Peru, 2005; Gobierno de la Ciudad de Buenos Aires, 2011; Prefeitura do Município de São Paulo, 2015; Alcaldía Mayor de Bogotá D.C., 2017; Ilustre Municipalidad de Santiago, 2019; Município de Rio de Janeiro, 2019).

12.5.6 Health and Well-being

The most common adaptation strategies include the development of climate services such as epidemic forecast tools, integrated climate-health surveillance and observatories and forecasting climate-related disasters (floods, heat waves). Geographic information system (GIS) technologies are being used to identify locations where vulnerable populations are exposed to climate hazards and associated health risks.

12.5.6.1 Climate Services for Health

The measures most directly linked to diminishing risk are those related to climate services for health (*high confidence*). Climate services provide tailored, sector-specific information from climate forecasts to support decision-making (WHO and WMO, 2016); they allow decision makers and practitioners to plan interventions in anticipation of a weather/climate event (Mahon et al., 2019). More recently, climate services, such as EWSs and forecast models, have been promoted for the health sector (WHO and WMO, 2012, 2016; WMO, 2014; Thomson and Mason, 2018) and are an important adaptation measure to reduce the impacts of climate on health (*high confidence*). To guide this process, the Global Framework for Climate Services (GFCS) issued a Health Exemplar (Lowe et al., 2014; WMO, 2014), which aims to foster stakeholder engagement between health and climate actors at all levels to promote the effective use of climate information within health research, policy and practice.

There exist at least 24 EWS in SA to avoid deaths and injuries from floods in the countries such as Argentina, Colombia, Ecuador, Bolivia, Brazil, Peru, Uruguay and Venezuela (Bravo et al., 2010; Bidegain, 2014; Moreno et al., 2014; Dávila, 2016; del Granado et al., 2016; López-García et al., 2017; Carrizo Sineiro et al., 2018). A total of 149 emergency prevention and response systems are reported in CA (UNESCO, 2012). In addition, some countries implement programmes for the relocation of families who are in risk condition, like in Bogota and Medellin, Colombia (World Bank, 2014; Watanabe, 2015).

Epidemic forecast tools are an example of an adaptation measure being developed and/or implemented in this region (*high confidence*). Climate-driven forecast models have been developed for dengue in Ecuador, Puerto Rico, Peru, Brazil, Mexico, Dominican Republic, and Colombia (Lowe et al., 2013; Eastin et al., 2014; Johansson et al., 2016; Lowe et al., 2017; Johansson et al., 2019); for Zika virus infections across the Americas (Muñoz et al., 2017); for cutaneous leishmaniasis in Costa Rica and Brazil (Chaves and Pascual, 2006; Lewnard et al., 2014); for Aedes-borne diseases across the Americas (Muñoz et al., 2020b); and a nowcast model for chikungunya virus infections across the Americas (Johansson et al., 2014). In Ecuador, a prototype system utilised forecasts of seasonal climate and ENSO forecasts of to predict dengue transmission, providing the health sector with warnings of increased transmission several months ahead of time (Stewart-Ibarra and Lowe, 2013; Lowe et al., 2017). Despite these advances, few tools have become operational and mainstreamed in decision making processes. However, Brazil and Panama have been able to operationalise an EWS for the surveillance of dengue fever transmission (Codeço et al., 2016; McDonald et al., 2016).

One of the most promising climate services for the health sector are heat and cold early-warning and alert systems (*medium confidence*). These have been developed by the national meteorological institutes in Peru, Argentina, and Uruguay (Bidegain, 2014). A heat alert system was implemented in Argentina in 2017 and daily alerts are issued for 57 localities across the country. A stoplight colour scheme is used to issue alerts, identifying specific groups at risk and actions to be taken to reduce the risk (Herrera et al., 2018b).

The public dissemination of climate–health warnings via bulletins, websites and other outlets can be an adaptation measure to address climate change and weather variability to reduce health risks (*high confidence*). The information produced is systematised to be communicated to authorities and the general public. The Caribbean Health-Climatic Bulletin has been issued quarterly since 2018 to health ministries across the region, including CA and NSA. Regional climate and health authorities meet to review 3-month climate forecasts and issue statements about the probable impacts on health (Trotman et al., 2018). In Panama, information on dengue is distributed in a monthly bulletin that is used by health authorities to inform vector control activities (McDonald et al., 2016). Another example is the climate-driven forecast of dengue risk that was produced prior to Brazil's 2014 FIFA World Cup to inform disease prevention interventions (Lowe et al., 2014, 2016). In Colombia, the Intersectoral National Technical Commission for Environmental Health publishes a monthly bulletin with regional weather forecasts and potential effects on health (CONASA, 2019). Paraguay improves epidemiological surveillance and trains first-level health staff via information campaigns on the prevention of climate-sensitive diseases and promotes health networks with the participation of civil society (Environmental Secretariat of Paraguay, 2011).

12.5.6.2 Integrated Climate–Health Surveillance and Observatories

Integrated climate–health surveillance systems are another key adaptation strategy (*medium confidence*). This information can be used by the health sector to inform decision-making about when and where to deploy a public health intervention. It can also feed into an EWS, particularly if the data are compatible in format and spatiotemporal scales. An integrated climate–health surveillance system for vector-borne disease control was developed in southern coastal Ecuador through a partnership among the climate and health sectors and academia (Borbor-Cordova et al., 2016; Lowe et al., 2017). Additionally, an interdisciplinary multi-national team working at the border of Ecuador and Peru created a cooperation network for climate-informed dengue surveillance (Quichi et al., 2016), and their successful binational collaboration resulted in the local elimination of malaria (Krisher et al., 2016). A similar tool is innovative community-based data collection to understand and find solutions to rainfall-related diarrheal diseases in Ecuador (Palacios et al., 2016).

Climate and health observatories represent a promising strategy that is being developed at sub-national, national (e.g., Brazil, Argentina) and regional levels (*high confidence*) (Muñoz et al., 2016; Rusticucci et al., 2020). The Brazilian Observatory of Climate and Health brings together climate and health information for the Amazon region of Manaus (Barcellos et al., 2016). At the national level, Brazil has created a climate and health observatory, where information and data visualisations are available for various climate-sensitive health indicators (Ministério da Saúde and FIOCRUZ, 2021).

12.5.6.3 Vulnerability and Risk Maps

Vulnerability and risk maps have been widely used as an adaptation strategy to understand the potential impacts of climate on health outcomes both directly (e.g., maps of disease risk) and indirectly (e.g., maps of populations vulnerable to climate disasters) (*high confidence*). There are many examples of where climate services have been used to construct vulnerability maps for health outcomes, including maps in the aforementioned climate–health observatories. Dengue, malaria and Zika vulnerability maps using climate, social and environmental information have been developed in Brazil and Colombia (Cunha et al.,

https://doi.org/10.1017/9781009325844.014

2016b; López-Álvarez, 2016; Pereda, 2016; IDEAM, 2017). Argentina focuses on improving its health system using a climate change risk map system as a tool that identifies the risks and allows assessing their management (OPS and WHO, 2018).

Vulnerability and risk maps for climate disasters have been developed at the city level, for example in Bogota, Cartagena de Indias and Mocoa in Colombia (Yamin et al., 2013; Guzman Torres and Barrera Arciniegas, 2014; Tehelen and Pacha, 2017; Zamora, 2018), and for the metropolitan district of Quito in Ecuador (Tehelen and Pacha, 2017). In addition, vulnerability maps were created for the primary road network of Colombia (Tehelen and Pacha, 2017). At the regional level, vulnerability maps using climate-change probability, disaster risk and food insecurity variables have been produced for the Andean region (WFP, 2014). In Brazil, vulnerability maps that consider exposure, sensitivity and adaptive capacity, coupled with climate scenarios, were designed to support the NAP on a municipal scale (Chang and Garcia, 2018; Duval et al., 2018; Marinho and Silva, 2018; Menezes, 2018; Santos and Marinho, 2018; Silva et al., 2018). A Climate Change Vulnerability Index was used to generate vulnerability maps for countries of the Latin American and Caribbean region (Vörösmarty et al., 2013; CAF, 2014).

12.5.6.4 Other Adaptation Actions

Diverse adaptation measures are being implemented through public policies, private household responses and communal management that directly or indirectly reduce the impacts of climate change on human health (*high confidence*) (Table 12.9). Private and communal management measures could be considered indirect measures because they might be adopted even in the absence of climate change.

Participatory management can be relevant in the case of mosquito-borne disease prevention (e.g., dengue fever or malaria), where the reduction in mosquito habitat in one area or 'hotspot' can reduce the risk for all surrounding households. This approach is also relevant when considering new places where vector-borne diseases can emerge because of changes in climate (Andersson et al., 2015).

Adaptation strategies implemented by the public sector include a diverse suite of strategies ranging from the creation of green spaces in urban areas, relocation of families located in disaster-prone areas, ecosystem restoration and improved access to clean water, among many others (*high confidence*) (Table 12.9). Building GGI has been a popular public adaptation measure to reduce deaths and injuries because of floods (Section 12.5.5.3.2). Infrastructure has been improved at schools, public buildings and drainage systems in cities such as

Table 12.9 | Hazards from climate change that impact human health and examples of adaptation strategies proposed or implemented in CSA. Based on McMichael et al. (2006), Miller et al. (2013a, b, c, d), Hardoy et al. (2014), IPCC (2014), Janches et al. (2014), Lee et al. (2014), Mejia (2014), Sosa-Rodriguez (2014), Vergara et al. (2014), Lemos et al. (2016), Villamizar et al. (2017), Magoni and Munoz (2018) and Zhao et al. (2019).

Hazard and impacts on human health	Examples of adaptation strategies		
	Public	Private	Communal
Extreme heat and cold: deaths/illness by thermal stress	– Creation of urban green spaces – Health promotion campaigns – Shelters during heatwaves – Technology transfer for home heating	– Cooling by swamp coolers, air conditioning, open windows, wet floors, shade trees – Bioclimatic building design	– Training of community health volunteers to recognise and treat heat strain
Extreme rainfall, wildfire, wind speed: injuries/deaths from floods, storms, cyclones, bushfires and landslides (Key risk 2, Table 12.6)	– EWSs for extreme climate events – Safe housing programmes and relocation – GGI (e.g., channels, drainage systems)	– GGI to prevent landslides – Insurance mechanisms and financing for long-term recovery	– Communal efforts to clear debris from canals to reduce flood risk – Cooperative efforts to rebuild following flood events
Drought and dryness: poor nutrition due to reduced food yields and dehydration due to limited or inadequate management of freshwater (Key risk 1, Table 12.6)	– Formalising land ownership for small farmers and Indigenous people – Address emerging water conflicts	– Water infrastructure and irrigation – Soil moisture retention techniques – Insurance mechanisms – Selection of drought-resistant crops	– Incorporation of local stakeholders in formulating adaptation responses – Recognition of Indigenous and local wisdom and knowledge
Changes in climate that promote microbial proliferation: food poisoning and unsafe drinking water (Key risk 3, Table 12.6).	– Restoration of watersheds – Integrated health-climate surveillance – Improve access to drinking water, drainage, sanitation and waste removal	– Water disinfection: boiling, chlorination – Purchasing water or water filters	– Participatory water management strategies, including protection of drinking water sources
Changes in climate that affect vector–pathogen host relations and infectious disease geography/seasonality (Key risk 4, Table 12.6)	– Vector control – EWS for epidemics – NbS (e.g., forest conservation)	– Use of bed nets and screens – Use of repellent and insecticides – Elimination of standing water	– Community volunteers to collect blood smears for malaria diagnosis – Community-led elimination of vector habitat
SLR and storm surges: impaired crop, livestock and fisheries yields; unsafe drinking water, leading to impaired nutrition (Key risk 8, Table 12.6)	– Improve governance of water utilities – Address emerging water conflicts – Protection, restoration and soil conservation to recharge aquifers	– Improve water efficiency in agriculture	– Incorporation of local stakeholders in formulating adaptation responses – Recognition of Indigenous and local wisdom and knowledge
Environmental degradation: loss of livelihoods and displacement leading to poverty and adverse health outcomes (related to Key risk 6, Table 12.6)	– Long-term risk management planning for cities – Sustainable forestry programmes – Protection and restoration of lacustrine areas	– Identification of alternative livelihoods	– Community-led efforts to reforest and restore/protect watersheds

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Bogota, Colombia (World Bank, 2014) and La Paz, Bolivia (Fernández and Buss, 2016). In Brazil, channel works were implemented to reduce the flooding of the Tiete River, which crosses the metropolitan area of São Paulo; these projects were designed based on simulated flood scenarios (Hori et al., 2017).

Another example of a public adaptation measure is the protection and restoration of natural areas, which have the potential to decrease the transmission of water- and vector-borne infectious diseases (*medium confidence: robust evidence, low agreement*). Studies have shown that these measures can diminish the cases of malaria and diarrhoea in Brazil and cases of diarrhoea in children in Colombia (Bauch et al., 2015; Herrera et al., 2017; Chaves et al., 2018). However, deforestation and malaria have a complex relationship that relies on local context interactions, where land use and land cover changes play an important role due to vector ecology alterations and social conditions of human settlements (Rubio-Palis et al., 2013). Forest conservation can improve hydrological cycle control and soil erosion that can help to improve water quality and reduce the burden of water-borne diseases. In addition, forest cover can help to diminish the habitat for larval mosquitoes that transmit malaria. These measures can help to design policies at sites where these problems do not currently exist but can emerge as a consequence of climate change and the increase in the frequency of weather extreme events.

12.5.6.5 Challenges and Opportunities

Despite the proliferation of disaster EWSs in the region, only 37 can be considered operational, because many of these systems do not operate or function properly or do not meet the requirements that would allow them to be considered EWSs (UNESCO, 2012). Sustainable financing and political support are needed to ensure the functioning of disaster EWSs (*high confidence*) (Table 12.11). Several studies identified difficulties in implementing disaster EWSs due to a lack of community engagement and response to the alerts that are issued (del Granado et al., 2016; López-García et al., 2017). To address these challenges, the document 'Developing Early Warning Systems: A Checklist' provides guidance for the implementation of a *people-centred approach to early warning systems*, as proposed in the Hyogo Framework for Action 2005–2015 (Wiltshire, 2006).

With respect to the development of climate-driven epidemic forecasts, efforts are needed to improve the utility of such forecasts for the health sector. Few such forecasts have been operationalised to inform health-sector decision-making. A review of 73 studies that predicted and forecasted Zika virus infections (42% from the Americas) identified a high degree of variation in access, reproducibility, timeliness and incorporation of uncertainty (Kobres et al., 2019). A recent systematic review of epidemic forecasting and prediction studies found that no reporting guidelines exist; the development of guidance to improve the transparency, quality and implementation of forecast models in the public health sector was recommended (Pollett et al., 2020). An earlier review of dengue early-warning models found that few models incorporated both spatial and temporal aspects of disease risk (Racloz et al., 2012), limiting their potential application as an adaptation strategy by the health sector. Advances have been made in the last decade with respect to modelling and computing tools, increasing access to digital climate information and health records and the use of Earth observations to forecast climate-sensitive diseases (Fletcher et al., 2021; Wimberly et al., 2021).

The growing field of implementation science—defined as 'a discipline focused on systematically examining the gap between knowledge and action'—represents another opportunity to address the challenges and barriers to using climate information for health-sector decision-making (Boyer et al., 2020). Implementation science in the health sector in CSA is nascent; research in this area could help to address barriers to mainstreaming climate information in the health sector as an adaptation strategy (Table 12.11; Table SM12.7).

12.5.6.6 Governance and Financing

A description of the governance and financing dimensions of the feasibility of implementing EWSs is presented in Table 12.11 and Table SM12.7.

12.5.6.6.1 National Health Plans

Some countries have developed national plans on health including the role of climate. Chile has a Climate Change Adaptation Plan of the Health Sector that proposes several actions to enhance monitoring, institutions and citizen information and education (Ministry of Health of Chile and Ministry of Environment of Chile, 2016). Based on the identification of vulnerability to climate change, Colombia has developed 11 regional adaptation plans to strengthen institutional capacities, climate-change education for behavioural changes and cost estimation to promote health resilience (WHO and UNFCCC, 2015). In addition, El Salvador implemented actions to strengthen health infrastructure using high latrines for housing in flood communities, as well as other measures focused on water supply and quality based on an education and awareness programme (Ministry of Environment and Natural Resources of El Salvador, 2013). Only Brazil and Peru have implemented actions so far in the region derived from national health adaptation plans, and only Brazil completed a national assessment of impacts, vulnerability and adaptation for health (Watts et al., 2018). Some countries include health as a priority sector in their NAPs, as in the case of Ecuador and Costa Rica, which has a national plan addressing the prevention and care of climate-sensitive diseases coupled with a National Health Plan (2016–2020) (Ministry of Health Costa Rica, 2016; Jiménez, n. d.).

12.5.6.6.2 National Disaster Management Plans

National Risk Management Plans or National Disaster Response Plans are tools for adapting to climate change that can help to diminish death and injuries from disasters (*high confidence*). These plans are generally promoted by governments as national instruments that guide the processes of estimating, preventing and reducing disaster risk. Updated National Risk Management Plans have been found for Guatemala (CONRED, 2014), Honduras (COPECO, 2014), El Salvador (Ministry of Health of El Salvador, 2017), Costa Rica (CNE, 2016), Ecuador (SGR, 2018), Peru (SGRD et al., 2014), Argentina (Ministerio de Seguridad de Argentina, 2018), Bolivia (VIDECI, 2017), Chile (ONEMI, 2015) and Colombia (UNGRD, 2015). It has been shown in Brazil that information on drought conditions can be used to reduced health impacts of drought using a national disaster risk reduction framework (Sena et al., 2016).

12.5.7 Poverty, Livelihood and Sustainable Development

Climate-change impacts are increasing and exacerbating poverty and social inequalities, affecting those already vulnerable and disfavoured, generating new and interlinked risk and challenging climate resilient development pathways (*high confidence*) (Section 8.2.1.4; Shi et al., 2016; Otto et al., 2017; Johnson et al., 2021). Poverty, high levels of inequality and pre-existing vulnerabilities can also be worsened by climate-change policies (Antwi-Agyei et al., 2018; IPCC, 2018; Roy et al., 2018; Eriksen et al., 2021). Those already suffering are losing their livelihoods and reducing their development options; poor populations and countries are more vulnerable and have lower adaptive capacity to climate change compared to rich ones (*very high confidence*) (Section 8.5.2.1; Rao et al., 2017).

Inequality is growing, a CSA structural characteristic; the Gini index average for Latin American countries (including Mexico) decreased to 0.466 in 2017, where 1% of the richest got 22 times more income than 10% of the poorest (ECLAC, 2019b; Busso and Messina, 2020), but in 2018, 29.6% of Latin American populations were poor (which increased to 182 million) and 10.2% were living in extreme poverty; in 2018 (increased to 63 million) (ECLAC, 2019b) and in 2020, due to the COVID crisis, the Gini coefficient projection of increases range from 1.1% to 7.8% (ECLAC and PAHO, 2020), with poverty increasing to 33.7% (209 millions) and extreme poverty to 12.5% (78 millions) (ECLAC and PAHO, 2020; ECLAC, 2021). Those poverty and extreme poverty rates are higher among children, young people, women, Indigenous Peoples (Reckien et al., 2017; Busso and Messina, 2020), migrants (Dodman et al., 2019) and rural populations. Climate change has differential impacts, and even within a household there may be important differences in relation to age, gender, health and disability; these factors may intersect with one another (*high confidence*) (Reckien et al., 2017; Busso and Messina, 2020).

In IPCC's Third Assessment Report (TAR), AR4 and AR5, WGII recognised higher risks associated with poor living conditions, substandard housing, inadequate services, location of hazardous sites stemming from a lack of alternatives and the need to work more seriously on strengthening governance structures involving residents and community organisations, among others (Wilbanks et al., 2007; Revi et al., 2014). The AR5 CSA chapter stated that poverty levels remained high (45% for CA and 30% for SA in 2010) despite years of sustained economic growth. Poor and vulnerable groups are disproportionately affected in negative ways by climate change (Section 8.2.1.4; Section 8.2.2.3; SR15 Section 5.2 and Section 5.2.1, Roy et al., 2018) due to physical exposure derived from their place of residence or work, illiteracy, low income and skills, political and institutional marginalisation tied to a lack of recognition of informal settlements and employment, poor access to good-quality services and infrastructure, resources and information and other factors (*very high confidence*) (UN-Habitat, 2018; SR15 Sections 5.2.1, 5.6.2, 5.6.3, 5.6.4, Roy et al., 2018).

International agreements aim for climate resilient development pathways where efforts to eradicate poverty, reduce inequality and promote fair and cross-scalar adaptation and mitigation are strengthened. The first and second objectives of the SDGs aim to reduce poverty, allowing no one to fall through the cracks (UN General Assembly, 2015). Researchers argue that poverty is mischaracterised and has multiple dimensions (Castán Broto and Bulkeley, 2013) (Section 8.1.1), that biodiversity loss, climate change and pollution will undermine efforts on 80% of assessed SDG targets, that biodiversity and climate change must be tackled together (Pörtner et al., 2021; United Nations Environment Programme, 2021) and due to the COVID crisis LAC countries have made uneven progress in terms of meeting SDGs (*high confidence*) (ECLAC, 2020).

12.5.7.1 Challenges and Opportunities

Climate change exacerbates pre-existing vulnerability conditions and can drive societies further away from achieving resilience, equity and sustainable development (Tanner et al., 2015b; Bartlett and Satterthwaite, 2016; Kalikoski et al., 2018; Bárcena et al., 2020a). Existing inequalities in the provision and consumption of services are bound to be exacerbated by future risks and uncertainties associated with climate-change scenarios (Miranda Sara et al., 2017). Climate change will be a major obstacle in reducing poverty (*high confidence*) (Bartlett and Satterthwaite, 2016; Allen et al., 2017a; Hallegatte et al., 2018; UN-Habitat, 2018; United Nations Environment Programme, 2021), affecting even wealthier populations that become vulnerable facing climate-change scenarios (WGI AR6 Chapter 12, Ranasinghe et al., 2021), dragging them into poverty and erasing decades of work and asset accumulation.

CSA is highly urbanised, and the vast majority of the region's poor live in urban areas (except in CA), while urban extreme poverty is becoming more pronounced (Rosenzweig et al., 2018; Dodman et al., 2019; Almansi et al., 2020; Sette Whitaker Ferreira et al., 2020), with those living in informal settlements and working within informal economy being critical factors in each city's economy (Satterthwaite et al., 2018, 2020). Many households in the region's cities live in precarious neighbourhoods with insufficient infrastructure and substandard housing (Adler et al., 2018; Rojas, 2019). On average, between 21% and 25% of urban populations live in informal settlements (Jaitman, 2015; UN-Habitat, 2015; Rojas, 2019; Sandoval and Sarmiento, 2019). This hides important disparities: Habitat III reports, by individual countries, the percentage of urban population living in informal settlements, which ranged from 5% to 60% and in absolute terms means 105 million people living in precarious conditions (106 million estimated in 1990) (Section 12.5.5; Sandoval and Sarmiento, 2019).

High levels of inequality and informality remain the biggest challenges in terms of adaptation measures being effective (Rosenzweig et al., 2018; Dodman et al., 2019). The interaction of projected impacts with existing vulnerabilities in the region (such as hunger, malnutrition and health inequalities, arising from the region's social, economic and demographic profile) affects CSA development and well-being in different ways (Reyer et al., 2017) increasing poverty and inequality and threatening paths to sustainable development (Section 18.1.1; Reckien et al., 2017).

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The uneven enforcement of land use regulations, relocations and evictions in connection with environmental risk management and climate adaptation is a contested issue (Brockington and Wilkie, 2015; Lavell, 2016; Quimbayo Ruiz and Vásquez Rodríguez, 2016a; Quimbayo Ruiz and Vásquez Rodríguez, 2016b; Anguelovski et al., 2018; Anguelovski et al., 2019; Shokry et al., 2020; Chávez Eslava, 2021; Oliver-Smith, 2021). This suggests that caution in framing climate adaptation and resilience related interventions equally benefits everyone (*high confidence*) (Brown, 2014; Chu et al., 2016; Connolly, 2019; Romero-Lankao and Gnatz, 2019; Johnson et al., 2021) and that equality and justice dimensions should be incorporated into decision-making (*very high confidence*) (Section 18.1.2.2; Agyeman et al., 2016; Meerow and Newell, 2016; Romero-Lankao et al., 2016; Shi et al., 2016; Reckien et al., 2017; Leal Filho et al., 2021).

Poor rural households in marginal territories that have a low productive potential and/or that are far from markets and infrastructure are highly vulnerable to climate-change impacts and could easily fall into poverty-environment traps (*high confidence*) (Barbier and Hochard, 2019; Heikkinen, 2021). Climate change is one of the main threats to rural livelihoods in CA, since agriculture is a pillar of rural economies and food security, especially in the poorest sectors, which rely on subsistence crops in areas with low soil fertility and rainfall seasonality (Bouroncle et al., 2017).

Impacts are likely to occur simultaneously, exacerbating the challenges faced by the poorer segments of society, but also creating new groups at risk (Miranda Sara et al., 2016; Rosenzweig et al., 2018; Dodman et al., 2019). The material basis for poor and vulnerable urban and rural populations' adaptations is in a critical state across the CSA region, magnifying extreme events' impacts, making CSA less resilient. Consequences in terms of social vulnerability and livelihood will be widely felt, inasmuch as the security and protection of critical assets (housing, infrastructure and water, land and ecosystem services) continue to lag behind. Small businesses are usually located within homes, and if the home is affected, so is the business (Stein and Moser, 2015), adding another layer of vulnerability for this population.

As productivity declines, outside sources of income are sought, and people rely on resource extraction for subsistence and for income, further increasing their vulnerability to climate change (Barbier and Hochard, 2018a). Cycles of declining productivity, environmental degradation, wildlife poaching and trafficking, the search for outside employment, reduced incomes, livelihood opportunities and poverty have been observed in rural El Salvador, Honduras, Amazonia (López-Feldman, 2014; Graham, 2017; Barbier and Hochard, 2018a). The protection of communities that defend and are dependent on wildlife and natural environments requires immediate attention. Latin America is home to eight million forest-dependent people, which represents about 82% of the region's rural extreme poor (FAO and UNEP, 2020).

Poverty and disaster risk reduction interlinked with climate-change adaptation share a focus on identifying and acting on local risks and their root causes, even though they view risk through different lenses (*very high confidence*) (IPCC, 2014; Allen et al., 2017a; Satterthwaite et al., 2018, 2020; UN-Habitat, 2018). Construction of climate knowledge and risk perceptions affect decision-making to define implementation priorities, but the poor are less able to cope with and adapt so as to avoid so-called adaptation injustices (*high confidence*) (Mansur et al., 2016; Miranda Sara et al., 2017; Reckien et al., 2017; Hardoy et al., 2019).

Adaptation, social policies, poverty reduction and inequality are weakly articulated to daily or chronic risk reduction. Poor residents are often caught in 'risk traps', accumulated cycles of everyday risks and small-scale disasters (*medium confidence: medium evidence, high agreement*) (Bartlett and Satterthwaite, 2016; Mansur et al., 2016; Allen et al., 2017a; Leal Filho et al., 2021), which are exacerbated by climate risks and COVID pandemic with the most vulnerable populations suffering. Chronic and everyday risks (poor access to infrastructure, services, incomes, housing, land tenure, education, security, location and poor-quality environment and networks and lack of a voice) are often exacerbated and generate new unknown risks by climate change (*medium confidence: medium evidence, high agreement*) (Bartlett and Satterthwaite, 2016; Mansur et al., 2016; Satterthwaite et al., 2018; Leal Filho et al., 2021), extreme events and risks related to ENSO oscillation. All these risks need to be considered simultaneously (UN-Habitat, 2018). Risks are seldom distributed equally, highlighting socioeconomic inequalities and governance failures (*high confidence*) (IPCC, 2014; Bartlett and Satterthwaite, 2016; Rasch, 2016; Romero-Lankao et al., 2018).

Adaptation, disaster risk reduction and social and poverty reduction policies contribute to sustainable development (Hallegatte et al., 2018; Satterthwaite et al., 2020) and improve prospects for climate-resilient pathways (Section 18.1.1). Without pro-poor interventions, adaptation options could reinforce poverty cycles (Kalikoski et al., 2018). Secure locations, good-quality infrastructure, services and housing are critical to reducing risks from extreme climate events (Satterthwaite et al., 2018; Dodman et al., 2019).

12.5.7.2 Governance and Finance

Poor and most vulnerable groups have limited political influence, fewer capacities and opportunities to participate in decision and policymaking and are less able to leverage government support to invest in adaptation measures linked with poverty, inequality and vulnerability reduction (*very high confidence)* (Chapter 8; Miranda Sara et al., 2017; Reyer et al., 2017; Kalikoski et al., 2018; Dodman et al., 2019; Satterthwaite et al., 2020).

Existing imbalances in power relations, corruption, historic structural problems and high levels of risk tolerance (Miranda Sara et al., 2016) constitute climate governance barriers to implementing more effective adaptation and preventive measures. Corruption, particularly in the construction and infrastructure sectors, has proven to be a barrier to CSA development, even reproducing and reconstructing the same risks (French and Mechler, 2017; Vergara, 2018; Durand, 2019). Critical infrastructure and valuable assets continue to be placed in vulnerable areas (Calil et al., 2017; Escalante Estrada and Miranda, 2020), demonstrating the persistence of maladaptation and adaptation deficit (Villamizar et al., 2017).

Social organisation, participation and governance reconfiguration are essential for building climate resilience (*very high confidence*) (Stein and Moser, 2015; Kalikoski et al., 2018; Satterthwaite et al., 2018, 2020; Stein et al., 2018; Hardoy et al., 2019; Stein, 2019; Miranda Sara, 2021). Adaptation measures have trade-offs that need to be acknowledged and acted upon, most importantly by developing the capacity to convene discussions that draw in all key actors and commit them to do things differently (Almeida et al., 2018; Hardoy et al., 2019). Collaborative approaches integrate groups and organisations (e.g., saving, women's groups, clubs, vendor associations, cooperatives) contributing to the exchange of information to visibilise people's needs, generate safety networks and negotiate for improvements and enhance adaptive capacity.

12.5.7.3 Adaptation Options

Effective adaptation can be achieved by addressing pre-existing development deficits, particularly the needs and priorities of informal settlements and economies (Revi et al., 2014; UN-Habitat, 2018). There is urgency in making sure that social systems are better able to respond to climate-related risks and increase their adaptive capacity (Lemos et al., 2016), focusing on path dependency, lock-ins and poor specific needs (Leal Filho et al., 2021).

The linkages between climate adaptation and poverty are not clearly addressed at the national level (Kalikoski et al., 2018). A revision of some NDCs presented by CSA countries (https://unfccc.int) shows that NDCs are developed with almost no connection to poverty and livelihoods. Exceptions include Bolivia, whose NDC developed the 'good life' concept as an alternative development pathway, supporting sustainable livelihoods as a means to eradicate poverty. Honduras asserts that climate action should improve living conditions. Peru defined a poverty and vulnerability reduction approach. Finally, El Salvador conditioned its NDCs to macroeconomic stability, economic growth and poverty reduction. A sustainable development approach permeates the proposed actions for sectors such as energy, agriculture, transport, water and forestry.

Adaptive capacity is linked to addressing climate-related risks (specific capacity) and structural deficits (generic capacity) and synergies, and a strategic balance between both is necessary (Eakin et al., 2014; Lemos et al., 2016). Adaptation institutional context can undermine one form of capacity with repercussions for the other compromising overall adaptation and sustainable development (Eakin et al., 2014).

The literature assessing the effectiveness of pro-poor or community-based adaptation practices and livelihood options continues to be weak, though such practices and options are being increasingly documented, as in AR5 (Magrin et al., 2014). A great variety of measures and financial instruments are being applied to strengthen and protect livelihoods and assets: collective insurance schemes, micro-credit, financial instruments for transferring risks, agricultural insurance and PES (Dávila, 2016; Hardoy and Velásquez, 2016; Lemos et al., 2016; Porras et al., 2016; Kalikoski et al., 2018). Small-scale household businesses in poor neighbourhoods develop adaptation strategies to keep operations going, showing how household-level adaptation strategies are multi-purpose (Stein et al., 2018; Stein, 2019). There are emerging interinstitutional communities of practice whose aim is to share practices and lessons learned (ECLAC, 2013, 2015, 2019a).

There is also increasing evidence of human mobility associated with climate change and disaster risk (IOM, 2021) and the adoption of sustainable tourism, diversification of livelihood strategies, climate forecasts, appropriate construction techniques, neighbourhood layout, integral urban upgrading initiatives, territorial and urban planning, regulatory frameworks, water harvesting and NbS (Stein and Moser, 2014; Hardoy and Mastrangelo, 2016; Almeida et al., 2018; Barbier and Hochard, 2018a; Desmaison et al., 2018; Satterthwaite et al., 2018, 2020; Villafuerte et al., 2018; Hidalgo, 2020). Mostly, socioeconomical and sociopolitical factors show that safety and continuity measures are critical enablers of adaptation.

At the municipal level, a study in CA highlighted that adaptive capacity in rural areas is associated with the satisfaction of basic needs (safe drinking water, school, quality dwelling, gender parity index), access to resources for innovation and action (road density, economically active population with non-agricultural employment and rural demographic dependency ratio) and access to credit and technical support (Bouroncle et al., 2017).

CSA adaptation initiatives to reduce poverty, improve livelihoods and achieve sustainable development in scale and scope, from planned and collective interventions to autonomous and individual actions. Many of them are bottom-up, community-led initiatives together with civil society organisations; others are government-led, including local governments, or a combination of them (McNamara and Buggy, 2017; Berrang-Ford et al., 2021). Vulnerable groups are a focus to achieve equity at planning and as a target including mainly rural low-income, Indigenous Peoples and women and migrants in most references. Responses detected were focused on behavioural and cultural followed by ecosystem-based responses, institutional, and technological/infrastructural responses. Out of 55 articles analysed from CSA (Berrang-Ford et al., 2021) about poverty, equity and adaptation options, half covered adaptation planning and early implementation, but only 2% could show evidence of risk reduction associated with adaptation efforts.

Tensions and conflicts may result from differing perceptions and knowledge of vulnerabilities and risk, which can hinder the acceptance of adaptation measures or the implementation of stronger adaptive or preventive actions (Miranda Sara et al., 2016). There is a need to better understand complex interactions and community responses to climate change in the Amazonian and Andean regions. Climate-change hotspot impacts have shown that poverty reduction measures alone were not enough to improve adaptive capacity because people will not necessarily invest in their enhancement (Pinho et al., 2014; Filho et al., 2016; Nelson et al., 2016; Lapola et al., 2018; Zavaleta et al., 2018). Current adaptation strategies and methods may be neglecting cultural values, even eroding them, in the Peruvian Andes, indicating that success of adaptation practices is tied to deep cultural values (Walshe and Argumedo, 2016).

Limits to adaptation include access to land, territory and resources (Mesclier et al., 2015), poor labour opportunities coupled with knowledge gaps, weak multi-actor coordination, and lack of effective policies and supportive frameworks (Berrang-Ford et al., 2021).

Low participation of women in income-earning opportunities contrasts with their role in unpaid activities (ECLAC, 2019b). Despite the progress that has been made, gender differences in labour markets remain an unjustifiable form of inequality (OIT, 2019), and women easily fall back on the informal labour market during crisis situations, such as those generated by climate events (Collodi et al., 2020).

Participatory processes are leveraging adaptation measures throughout CSA; they contribute to the prioritisation of specific adaptation measures as well as the strengthening of local capacities. Results of participatory processes show how climate adaptation needs to be part of larger transformation processes to that have vulnerable communities at the center and reduce vulnerability drivers (Stein and Moser, 2015; Stein et al., 2018; Stein, 2019). Stronger national policies interlinking poverty and inequality reduction to adaptation considering the coupled human-environmental systems to comprehend poor and vulnerable groups' capacity to adapt are urgently needed.

12.5.8 Cross-cutting Issues in the Human Dimension

12.5.8.1 Public Policies, Social Movements and Participation

Public policies related to adaptation must be seen in the wider context of environmental policies and governance, as they usually address climatic processes in synergy with other environmental and socioeconomic drivers (*very high confidence*) (Ding et al., 2017; Aldunce Ide et al., 2020; Comisión Europea, 2020; Lampis et al., 2020; Scoville-Simonds et al., 2020). However, some people point to education, sanitation or social assistance, among other sectors (Bonatti et al., 2019). In Brazil, for example, it would be difficult to clearly separate climate-change adaptation and urban policies (*high confidence*) (PBMC, 2016; Barbi and da Costa Ferreira, 2017; Marques Di Giulio et al., 2017; Empresa de Pesquisa Energética, 2018; Checco and Caldas, 2019; Canil et al., 2020).

Many public policies related to climate change have become symbolic, in conflict with prevailing economic policies and practices (*medium confidence: low evidence, high agreement*). Urban adaptation plans can be in conflict with other policies, and there may exist insufficient support in multiple areas such as social attitudes and behaviour, knowledge, education and human capital, finance, governance, institutions and policy (Villamizar et al., 2017; Koch, 2018). Some policies around climate-related displacements and migrants have been considered in NDCs (Priotto and Salvador Aruj, 2017; Yamamoto et al., 2018; de Salles Cavedon-Capdeville et al., 2020).

Because there are asymmetries among populations regarding the vulnerability and benefits of adaptation, along the lines of gender, age, socioeconomic conditions and ethnicity, it has been noticed that adaptation policies and programmes must be adequate to diverse conditions and actors (*very high confidence*) (Kaijser and Kronsell, 2014; Walshe and Argumedo, 2016; Baucom and Omelsky, 2017; Harvey et al., 2018).

Effective adaptation and mitigation depend on policies and measures at multiple scales, especially when it comes to the involvement of more exposed and vulnerable people. The participation of experts, communities and citizens has shown to be effective (FAO and Fundación Futuro Latinoamericano, 2019), particularly through partnerships between grassroots organisations and impoverished communities, providing valued expertise and capacities to support the implementation of government climate resilience strategies (World Bank Group, 2015). More inclusive planning processes correspond to higher climate equity and justice outcomes in the short term, but an emphasis on building dedicated multi-sector governance institutions may also enhance long-term programmes' stability while ensuring civil society has a voice in adaptation planning and implementation (Chu et al., 2016). Some local organisations and people have succeeded when they were in charge of their own resiliency efforts, where international projects and protocols proved less effective (Doughty, 2016). Some decentralised governmental programmes have tried to increase public responsiveness to the adaptation needs of the people, but such programmes have proven to be only mildly successful and provoke the mobilisation of communities against existing governance structures (Thompson, 2016).

IKLK participation is thought to be more considered in adaptation policies because it yields good results (*high confidence*) (Nagy et al., 2014b; Jurt et al., 2015; Arias et al., 2016; Stensrud, 2016). IK has been adaptive for long periods in the Andes (Cuvi, 2018), but there might be limits to adaptation in the face of present climatic and other environmental and socioeconomic drivers (Postigo, 2019). Approaches integrating IK with more formal sciences, to address research and policies, have improved adaptation processes, but they carry their own complications (*high confidence*) (Doswald et al., 2014; Metternicht et al., 2014; Tengö et al., 2014; Drenkhan et al., 2015; Keenan, 2015; Lasage et al., 2015; Camacho Guerreiro et al., 2016; Hurlbert and Gupta, 2016; Roco et al., 2016; Santos et al., 2016; Walshe and Argumedo, 2016; Uribe Rivera et al., 2017; Kasecker et al., 2018; Cuesta et al., 2019; Ulloa, 2019; Ariza-Montobbio and Cuvi, 2020). More interdisciplinary and transdisciplinary research will help to better understand and manage the relationships among governance, implementation, management priorities, wealth distribution and trade-offs between adaptation, mitigation and the SDGs.

Representations of climate change can also emerge as critiques and resistances that reveal that climate-change-labelled politics or interventions have posed even greater risks or do not address poverty issues (*medium confidence: medium evidence, high agreement*) (Lampis, 2013; Pokorny et al., 2013; Ojeda, 2014). Indigenous and social movements have joined with climate justice activists, calling for action to address climate change (Hicks and Fabricant, 2016; Ruiz-Mallén et al., 2017; Charles, 2021). The Bolivian Platform against Climate Change, a coalition of civil society and social movement organisations working to address the effects of global warming in Bolivia and to influence the broader global community, reflects an innovative dimension that, though at times conflictual, has shown how increasing climate variability hinders the right of Indigenous Peoples to the conservation of their culture and practices and illustrates how grassroots movements are increasingly taking over climate-change policy in the region (Hicks and Fabricant, 2016). Social movements have engaged with international networks, such as Blokadia, which surged after COP 23, whose claims try to go beyond the protection of the environment and delve into issues of democracy and resource control (Martínez-Alier et al., 2018).

Many social movements address adaptation to climate change. Some engage and participate in policy and planning, often producing good results at the local level. In contrast, top-down approaches without citizen or community participation have shown to be less effective (*high confidence*) (Krellenberg and Katrin, 2014; Nagy et al., 2014b; Stein and Moser, 2014; Ruiz-Mallén et al., 2015; Sherman et al., 2015; Waylen et al., 2015; Bizikova et al., 2016; Chelleri et al., 2016; Merlinsky, 2016; Villamizar et al., 2017).

Some conflicts in which the direct biophysical impacts of climate change play a major role can unleash social protests and strengthen social movements (Section 12.6.4). In Cartagena, since 2010, the increase in precipitation has increasingly impacted the *barrio* Policarpa, promoprting residents to call for solutions to the problems caused by the coupled effect of flooding and industrial pollution. Also, in El Cambray II, in Guatemala City, in 2015 a nearby hill collapsed, causing the deaths of 280 people, 70 missing and the destruction of hundreds of homes. The affected community entered into a conflict with the municipality demanding resettlement and a reform of land-use planning (Stein Heinemann, 2018).

12.5.8.2 Perceptions

Perception and understanding of climate change can be seen as an adaptive feature. In CSA, the awareness of climate change as a threat is increasing, a situation related to growth in climate justice activism and to the occurrence of extreme weather events of all kinds (*high confidence*) (Forero et al., 2014; Magrin et al., 2014; Capstick et al., 2015). Perception of climate change is positively associated across countries with the HDI and ND-Gain Readiness Index and negatively associated with the Vulnerability Index and, within countries, with education level, while perception is negatively associated with the degree of political affinity for the market economy (Azócar et al., 2021). However, some communities do not associate their problems with the scientific concept of climate change, so discussions on whether it is human induced and its causes or relationship with other problems can become irrelevant (Sapiains Arrué and Ugarte Caviedes, 2017). Even communities affected by the same changes do not necessarily perceive them in the same way (Bonatti et al., 2016). The interpretations of change, as well as its causes and effects, can vary widely (Paerregaard, 2018; Scoville-Simonds, 2018). Rather than adapting to climate change, some people adapt climate change to their social worlds (Rasmussen, 2016a).

Perceptions tend to be different in rural and urban areas (Sherman et al., 2015). In rural areas, it largely relates to temperature rise and changes in rainfall patterns, changes in agriculture (pests, calendars), biodiversity loss, solar radiation or changes in the oceans, and their impacts are sometimes related or even more attributed to socioeconomic and environmental drivers, as well as to negative financial outcomes (*high confidence*) (Infante and Infante, 2013; Postigo, 2014; Jacobi et al., 2015; Barrucand et al., 2017; Harvey et al., 2018; Martins and Gasalla, 2018; Meldrum et al., 2018; Córdoba Vargas et al., 2019; Leroy, 2019; Viguera et al., 2019; Gutierrez et al., 2020; Iniguez-Gallardo et al., 2020; Lambert and Eise, 2020). In such places as Amazonia, perception increases with age (Funatsu et al., 2019). In Mediterranean Chile, younger, more educated producers and those who own their land tend to have clearer perceptions than older, less educated or tenant farmers, but they do not have a clear perception or how it may affect their yields and farming operation (Roco et al., 2015). In some dry and humid Ecuadorian montane forests, peasantss perceptions are in line with the scientific data, but they have a lot of difficulties to predict the changes and believe that they may not be prepared and can only be reactive (Herrador-Valencia and Paredes, 2016). In an Andean community, perceptions of climate change are homogeneous and do not vary according to gender, age or ethnicity (Cáceres-Arteaga et al., 2020). Among representatives of five municipalities of Lima, it was found that climate change is not well understood and residents have trouble distinguishing it from other environmental issues (Siña et al., 2016). In an Amazonian region, farmers provided a more accurate description than regional institutions of how it affects the local livelihood system (Altea, 2020). In Cuenca Auqui peasants attribute recently experienced challenges in agricultural production mainly to perceived changes in precipitation patterns, but statistical analyses of daily precipitation records at nearby stations do not corroborate those perceived changes (Gurgiser et al., 2016).

12.5.8.3 Gender and Intersectionality

There is ample empirical evidence that the impacts of climate change are not of equal scope for men and women. Women, particularly the poorest, are more vulnerable and are impacted in greater proportion. Often, for several economic and social reasons, women have less capacity to adapt, further widening structural gender gaps (*high confidence*) (Box 7.4; Arana Zegarra, 2017; Casas Varez, 2017; Segnestam, 2017; Acosta et al., 2019; Aldunce Ide et al., 2020; Olivera et al., 2021; Silva Rodríguez de San Miguel et al., 2021). Gender equity is deemed to be central to discussions on climate-change adaptation policies. In issues such as drinking water, energy, disasters, impacts on health and agriculture and capacity to migrate, women (poor women in particular) are affected in greater proportion, further widening structural gender gaps. In a rural community vulnerable to drought, short-term coping was more common among the women, especially among female heads of household, while adaptive actions were more common among the men; there are gendered inequalities in access to and control over different forms of capital that lead to a gender-differentiated capacity to adapt, where men are better able to adapt and women experience a downward spiral in their capacity to adapt and increasing vulnerability to drought (Segnestam, 2017).

However, women are not always the more vulnerable group. While in a broad sense climate-change impacts women more severely, there are situations where they have reacted, adapted better to or been more resilient. Grassroots women self-help groups can be active agents of change for their communities, designing and delivering gender-responsive adaptation solutions (Huairou Commission, 2019). Some studies suggest that women establish friendlier relationships with the environment and towards natural resources; studies on masculinity and environment confirm this tendency (Brough et al., 2016). In a multi-country study, some female-headed households tend to be slightly less vulnerable and more resilient than male-headed households, though some exceptions were found among sub-groups (Andersen et al., 2017). In Chile, women are more likely to modernise irrigation

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and infrastructure, and gender appears to be an important element in drought adaptation (Roco et al., 2016). A change to agroecological practices has improved gender equality and adaptive capacity to climate change (Cáceres-Arteaga et al., 2020).

Recent studies emphasise that a gender approach to social inequalities ought to move beyond just looking at men and women as experiencing impacts in a differentiated manner; rather, an intersectional analysis illuminates how different individuals and groups relate differently to climate change due to their situatedness in power structures based on context-specific and dynamic social categorisations (*high confidence*) (Kaijser and Kronsell, 2014; Djoudi et al., 2016; Thompson-Hall et al., 2016; Olivera et al., 2021). Thus, the relationship between gender and adaptation demands an analytical framework that connects environmental problems with social inequalities in a complex way (Godfrey, 2012). An intersectional approach helps to better capture the diversity of adaptive strategies that men and women adopt vis-à-vis climate change. Particular constellations of race, gender, class, age or nationality reveal more complex realities (*high confidence*).

12.5.8.4 Migrations and Displacements

Migration and displacements are multi-causal phenomena, and climate may exacerbate political, social, economic or other environmental drivers (*high confidence*) (Kaenzig and Piguet, 2014; Brandt et al., 2016; Priotto and Salvador Aruj, 2017; Sudmeier-Rieux et al., 2017; Radel et al., 2018; Heslin et al., 2019; Hoffmann et al., 2020; Silva Rodríguez de San Miguel et al., 2021). Many case studies have been conducted on the region, but data to assess and monitor precisely the effects of climate- and weather-related disasters in migration and displacements from a broad perspective remain inaccurate (Priotto and Salvador Aruj, 2017; Abeldaño Zuñiga and Fanta Garrido, 2020). The most common climatic drivers include tropical storms and hurricanes, heavy rains, floods and droughts (Kaenzig and Piguet, 2014). Positive climatic conditions also can facilitate migration (Gray and Bilsborrow, 2013). Peru, Colombia and Guatemala are among the countries with the largest average displacements caused by hydro-meteorological causes; Brazil had 295,000 people displaced because of disasters in 2019 (Global Internal Displacement Database, https://www.internal-displacement.org/database/displacement-data).

These processes can be interpreted as impacts on vulnerable peoples, but also as adaptation strategies to manage risks and reduce exposure when people continue with their lives, temporarily or permanently, in a different but stable situationor when family members send remittances to those that remain in the affected areas (Section 7.4.3.2; Cross-Chapter Box MIGRATE in Chapter 7). The remittances create opportunities for adaptive capacity building because they reduce some vulnerabilities in the form of infrastructures, agricultural supplies, food, education or health, as in northern CA (NU CEPAL, 2018). Anyhow, migration as adaptation is not available to everyone (Kaenzig and Piguet, 2014), and the idea has also been contested because it may not help to overcome structural problems or point to in situ options (Radel et al., 2018; Ruiz-de-Oña et al., 2019). The causal processes are complex. Surveys of migrants usually find that the main reported reason for migration is to find a job or to increase household income (Wrathall and Suckall, 2016; OIM, 2017; Radel et al., 2018), but the underlying reason for the lack of a job or income is rarely examined and at times may be related to climatic hazards.

Migration most often originates in rural areas, with people moving to other rural or urban areas within their home countries (Table Cross-Chapter Box MIGRATE 1 in Chapter 7). In the Amazon, approximately 80% of the population are concentrated in cities due to rural–urban migrations in search of better income, livelihoods and services, in cases associated with extreme floods and droughts (Pinho et al., 2015). In Ecuador, environmental variables are most likely to enhance international than internal migration (Gray and Bilsborrow, 2013). Hurricanes have been seen as positive triggers for international migration in CA (Spencer and Urquhart, 2018). The highlands of Peru see different patterns, including daily circular migration to combine the scarce income from agricultural production with urban income, rather than abandoning farm land (Milan and Ho, 2014; Zimmerer, 2014; Bergmann et al., 2021).

Migration to cities can mean opportunities for migrants and for urban areas, but it can also worsen existing problems, as urban poor people can become even more exposed and vulnerable, and the pressure on urban capacities may not be well absorbed (*high confidence*) (Chisari and Miller, 2016; Gemenne et al., 2020). Internal migration to cities is likely to exacerbate pre-existing vulnerabilities related to inequality, poverty, indigence and informal activities and housing (Warn and Adamo, 2014). Immigration can make cities/residents more vulnerable to climate-change risks (Sections 12.5.5 and 12.5.7). Groups such as children, Indigenous Peoples and the poor are usually among the most vulnerable in migrations and displacements, which poses challenges to national policies and international aid (Sedeh, 2014; Gamez, 2016; Ulla, 2016; Priotto and Salvador Aruj, 2017; Ramos and de Salles Cavedon-Capdeville, 2017; Amar-Amar et al., 2019; Gemenne et al., 2020). In migration or displacement driven by climate effects, women are prone to lose their leadership, autonomy and voice, especially in new organisational structures imposed by authorities. This is especially the case in temporary accommodation camps created after disasters, exacerbating existing differentiated vulnerabilities (Aldunce Ide et al., 2020). International migration has become more dangerous and difficult as border controls have become stricter, but programmes such as one to help temporary agricultural workers from Guatemala to Canada have proven successful (Gabriel and Macdonald, 2018). At the same time, emigration may lead to the loss of IKLK for adaptation (Moreno et al., 2020b).

Some areas are more likely to generate climatic migration: the Andes, the dry areas of Amazonia, northern Brazil and northern countries in CA (*high confidence*). Northeastern Brazil will lose population that will move to the south, deepening existing inequalities (Oliveira and Pereda, 2020). In a study of eight countries around the world, including Guatemala and Peru, a link was found between rainfall variability and food insecurity, which could lead to migration in areas of high prevalence of rainfed agriculture and low diversification (Warner and Afifi, 2014). In CA, younger individuals are more likely to migrate in response to hurricanes and especially to droughts (Baez et al., 2017).

The perception of gradual changes lowers the likelihood of internal migration, while sudden-onset events increase movement (Koubi et al., 2016). On the other hand, it has been seen that extreme events like

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floods or droughts can hinder population mobility, immobilising them in their localities (Thiede et al., 2016). These immobilised populations are supposed to face a double set of risks: they are unable to move away from environmental threats, and their lack of capital makes them especially vulnerable to environmental changes (Black et al., 2011). In CSA, migrating to the US is becoming dangerous and expensive because that country is restricting entry; these trends expose local populations to the risk of becoming immobile in the near future in a place where they are extremely vulnerable (Ruano and Milan, 2014; McLeman, 2019). A survey in Guatemala found no correlation between migration to the US and severe food insecurity in households, but the correlation became significant if the level of food insecurity was moderate, suggesting that families in extreme hardship did not have the resources to migrate (Aguilar et al., 2019). At the same time, some populations just have chosen not to move, as in Peru, where immobility among dissatisfied people is more likely to be caused by attachment to place than resource constraints (Adams, 2016; Correia and Ojima, 2017). Some populations have chosen to adapt relying on their IKLK (Boillat and Berkes, 2013).

Migration is often the last resort for rural communities facing water stress problems (Magrin et al., 2014; Ruano and Milan, 2014). In Bolivia, glacial retreat has not triggered new migration flows and had a limited impact on the existing migratory patterns (Kaenzig, 2015). In SA, climatic variability increases the likelihood of interprovince migration, rather than trapping populations. In a study of interprovincial migration motivated by temperature, an exception arose in Bolivia, and even if that could suggest an immobilised population (Thiede et al., 2016), it is not clear whether they want to stay and adapt. In some cases, people want to move but wait for relocation until after the climate-related disasters have subsided (Priotto and Salvador Aruj, 2017).

12.5.8.5 Financing

Climate-change financing is unequally distributed among CSA countries (*high confidence*). Financing of climate-change adaptation remains very much delegated to multilateral and bilateral cooperation, and the governments in the region have heavily relied on it. Still, there are some concerns regarding justice in the distribution of these funds (Khan et al., 2020). The UNFCCC has created financing mechanisms throughout its functioning years, but a wide range of issues that present challenges for access by recipients (Hickmann et al., 2019). These include a lack of technical capacity, difficulties in following the procedures established by the various financial entities and low levels of awareness about the need for action, as well as the different sources of funds available. The fiscal policies of various countries have contributed to government financing in the fight against climate change (World Bank, 2021). Since the Paris Agreement, countries have pledged NDCs that introduce the need to design and implement carbon budgets with a corresponding consideration of the efficiency and costs and benefits involved in each mitigation or adaptation to climate-change projects (Fragkos, 2020).

According to UNFCCC, Latin America and the Caribbean, for the period 2015–2016, obtained 22% of climate financing from multilateral climate funds. In this section we use data from https://climatefundsupdate.org/data-dashboard, and most of the reported information for Latin American and the Caribbean includes Mexico, since the scope of this chapter does not include Mexico, so we must rely on the raw data included in the data dashboard mentioned in the link (see also Guzmán et al. [2016]). According to the data, 76% of climate-related financing went to mitigation projects, with the remaining 24% going to adaptation. Of the total financing provided by the multilateral climate funds to the region, 51% took the form of concessional loans, while 47% was provided as grants. For the region, approvals in the 2015–2016 period were concentrated in Argentina, Chile, Brazil and Colombia, where large-scale mitigation projects were launched supported by the Green Climate Fund (GCF) and the Clean Technology Fund (CTF). For the period 2003–2019, the total contribution of climate financing to SA and the Caribbean is about USD 3558 million. The largest contributors to climate financing in the region come from the GCF, which approved USD 824.2 million for 23 projects. Brazil is the top recipient with USD 195 million, followed by Argentina with about USD 162 million. The second provider is the Amazon Fund with USD 717 million allocated to 102 projects in Brazil. In 2018, the CTF became the third largest source of financing, with USD 483 million dollars approved for 24 projects; the main recipient is Chile with USD 16,207 million, followed by Colombia with USD 170 million. The five largest projects approved in the region in 2018 were through the GCF. Brazil (USD 195 million) received support for reducing energy consumption across Brazilian cities, while Argentina (USD 103 million) received support to scale up investments by small and medium-sized enterprises (SMEs) in renewable energy and energy efficiency. In both cases, financing is predominantly provided as concessional loans.

Climate financing in CSA is mainly focused on mitigation actions (*high confidence*). In SA and the Caribbean, 73% (USD 2579 million) of funding to date has supported mitigation. Only 21% (USD 761 million) of the funding supports adaptation projects, and the remaining 4% (USD 217 million) supports multi-focus projects. Of the 51 new projects in SA and the Caribbean approved in 2018–2019, the GCF financed USD 508 million over ten projects. Amazon Fund was next with USD 81 million for 10 projects. While the GCF focuses on large and transformative projects and programmes, and in connection with broader reform of the policy framework in the region, the Amazon Fund targets smaller project interventions.

Climate financing in the region is concentrated in Brazil, which receives a third of the region's funding, with 41 mitigation activities receiving more than 6 times that of adaptation from multilateral climate funds. By the size of its GDP, Brazil receives the largest amount of financing; this leaves the poorest countries with little or no financing and therefore reinforces a vicious circle of poverty and vulnerability. Whether this is due to Brazil's being more successful at presenting eligible projects, a lack of commitment from other developing countries or some other structural factors is an open question. In any case, compensation schemes for the most vulnerable countries appear as needed, given the differences in vulnerability to climate-related damage (Antimiani et al., 2017). This is aggravated by the fact that fund management is in the hands of supranational entities while inequalities remain in regions within a country, particularly in highly centralised countries, as is the case for countries in the region.

COVID-19 recovery plans can have synergistic effects for climate-change adaptation (*medium confidence: low evidence, high agreement*). A key decision point for adaptation will be how the world responds to the pandemic. The global recovery can serve as a catalyst to increased and more equitable climate financing. Globally, recovery packages will likely have the power to change the global trajectory towards meeting the targets of the Paris Agreement and building a more just future (Forster et al., 2020). Several factors are relevant to the design of economic recovery packages: the long-run economic multiplier, contributions to the productive asset base and national wealth, speed of implementation, affordability, simplicity, impact on inequality and various political considerations (Hepburn et al., 2020). A key objective of any recovery package is to stabilise expectations, restore confidence and channel desired surplus savings into productive investment. However, 'business as usual' implies temperature increases over 3°C, implying great future uncertainty, instability and climate damage. An alternative way to restore confidence is to steer investment towards a productive and balanced portfolio of sustainable physical capital, human capital, social capital, intangible capital and natural capital assets (Zenghelis et al., 2020), consistent with global goals on climate change. Finally, any recovery package, including climate-friendly recovery, is unlikely to be implemented unless it also addresses existing societal and political concerns—such as poverty alleviation, inequality and social inclusion—which vary from country to country.

12.5.9 Adaptation Options to Address Key Risks in Central and South America

This section integrates, in Table 12.10 as follows, the sectoral assessment of adaptation options (Sections 12.5.1–12.5.8) with the eight key risks assessed in the region (Section 12.4). Table 12.10 presents a list of the summarised adaptation options, which are detailed in their adaptation sections, from Section 12.5.1 to Section 12.5.8 in this chapter.

Table 12.10 | Adaptation options addressing key risks organised by sector. See the note at the end for descriptions of the sector name abbreviations.

1. Risk of food insecurity due to frequent/extreme droughts	
T&F ecosystems	EbA: Agroecosystem resilience practices
O&C ecosystems	Not assessed (NA)
Water	Water infrastructure and irrigation; NbS and PES; participatory water management; multi-purpose water use
Food	Climate information services; EWSs; insurance; land use planning; LCA strategies; agroforestry; IKLK
Cities	NA
Health and well-being	EWS, insurance; participatory water management; water infrastructure and irrigation
Poverty and SD	CbA; government and institutional support
Human Dimension	Participatory management; incorporation of IKLK in water and crop management; education and communication
2. Risk to life and infrastructure due to floods and landslides	
T&F ecosystems	NA
O&C ecosystems	NA
Water	NbS; land use regulation; EWSs; integrated risk management
Food	NA
Cities	Urban planning; climate-adapted parameters in land use and building regulation; intersectoral and multi-level governance; slum upgrading; social housing improvement; urban control systems; CbA; risk management plans; integrated watershed management; flood control programmes; environment protected areas; household relocation; EWS; NbS; mapping tools; GGI; water storage solutions; wetland restoration; SUDSs; LID; river restoration; multi-functional landscapes; improving basic sanitation services
Health and well-being	EWS; GGI; community-led and managed relocation; insurance
Poverty and SD	Secure location; social housing policies; EWS
Human dimensions	Education and communication
3. Risk of water insecurity	
T&F ecosystems	Monitoring systems; EbA; forest protection and restoration; watershed protection
O&C ecosystems	CbA; land use and development regulation
Water	Water infrastructure and irrigation; NbS and PES; participatory water management; multi-purpose water use
Food	Management and planning; NbS; soil and water conservation
Cities	Intersectoral and multi-level governance; CbA; risk management plans; integrated watershed management; environment protected areas; NbS; GGI; wetland restoration; improving basic sanitation services; reservoir system
Health and well-being	Protection and restoration; NAPs; participatory water management
Poverty and SD	NbS: water harvesting; equitable water distribution
Human dimensions	Participatory management; incorporation of IKLK in water management; education and communication
4. Risk of severe health effects due to increasing epidemics	
T&F ecosystems	NA
O&C ecosystems	NA

Water	Water infrastructure; sanitation improvement
Food	NA
Cities	NA
Health and well-being	EWS; health-climate surveillance systems; national plans on health; communal management; GGI; protection and restoration
Poverty and SD	CbA; transparent democratic governance; equitable services; education
Human dimensions	Education and communication
5. Systemic risks of surpassing infrastructure and public service systems	
T&F ecosystems	NA
O&C ecosystems	EWS; EbA; territorial planning; CbA; land use and development regulation; GGI
Water	Water infrastructure; land use regulation; water retention capacity; EWS; capacity building
Food	NA
Cities	Urban planning; climate-adapted parameters in land use and building regulation; intersectoral and multi-level governance; slum upgrading; social housing improvement; CbA; improving basic sanitation services; micro wastewater treatment plants
Health and well-being	EWS; vulnerability and risk maps; NAPs; GGI
Poverty and SD	Transparent, democratic governance
Human dimensions	NA
6. Risk of large-scale changes and biome shifts in Amazon	
T&F ecosystems	Monitoring systems; EbA; protected areas; forest protection and restoration; watershed protection
O&C ecosystems	NA
Water	IWRM
Food	Territorial planning
Cities	NA
Health and well-being	Protection and restoration
Poverty and SD	Insurance; micro-credits; PES; CbA
Human dimensions	Participatory management; incorporation of IK and LK in forest management; education and communication
7. Risk to coral reef ecosystems due to coral bleaching	
T&F ecosystems	NA
O&C ecosystems	Zoning schemes; MPAs; EbA; CbA; adherence to international treaties
Water	NA
Food	NA
Cities	NA
Health and well-being	Protection and restoration
Poverty and SD	NA
Human dimensions	NA
8. Risks to coastal socioecological systems due to sea level rise, storm surges and coastal erosion	
T&F ecosystems	NA
O&C ecosystems	EbA; planned relocation; GGI
Water	NA
Food	NA
Cities	Urban planning; climate-adapted patterns in land use and building regulation; intersectoral and multi-level governance; CbA; risk management plans; household relocation; NbS; GGI
Health and well-being	GGI; communal management; protection and restoration
Poverty and SD	Secure location; CbA relocation
Human dimensions	Participatory management; education and communication

Notes:

Some sectors are represented by abbreviations: Terrestrial and freshwater ecosystems and their services (T&F ecosystems); ocean and coastal ecosystems and their services (O&C ecosystems); food, fibre and other ecosystem products (food); cities, settlements and key infrastructure (cities); poverty, livelihood and sustainable development (poverty and SD); cross-cutting issues in the human dimension (human dimensions).

Table 12.11 | Feasibility assessment of selected adaptation options for CSA region.

System	Adaptation option	Evidence	Agreement	Dimension assessed					
				Economic	Technological	Institutional	Social	Environmental	Geophysical
Food, fibre and other ecosystem products	Agroforestry	*Medium*	*High*	Insignificant barriers	Mixed effect	Significant barriers	Mixed effect	Insignificant barriers	Mixed effect
Health and well-being	EWSs	*Robust*	*High*	Insignificant barriers	Mixed effect	Significant barriers	Mixed effect	Insignificant barriers	Mixed effect
Water	Multi-use of water storage approaches	*Robust*	*Medium*	Insignificant barriers	Mixed effect	Mixed effect	Mixed effect	Mixed effect	Insignificant barriers
Freshwater and terrestrial ecosystems	EbA	*Medium*	*High*	Insignificant barriers	Mixed effect	Mixed effect	Insignificant barriers	Insignificant barriers	Insignificant barriers

12.5.10 Feasibility Assessment of Adaptation Options

This section assesses the feasibility of selected adaptations options by sector, relevant for CSA, in five dimensions (economic, technological, institutional, social, environmental and geophysical), according to the methodology developed by Singh et al. (2020a). Table 12.11 shows the summary of results and Table SM12.7 the details of the assessment and the supporting literature.

12.5.10.1 Food, fibre and other ecosystem products: agroforestry

For agrifood systems, the adoption of agroforestry provides for more diverse and sustainable agricultural production, where farmers maintain or improve their current production by incorporating suitable trees that ameliorate climatic conditions. Thus, in the same unit of land, these systems incorporate exotic tree species or managed native forests into farming systems allowing for the simultaneous production of trees, crops and livestock with different spatial arrangements or temporal sequences. On the other hand, it is recognised that the initial investment and time until trees start to produce may create an economic vulnerability. Therefore, there is a need to design adequate programmes and allocate resources for agroforestry system implementation and technical assistance and training (*medium confidence*). Also, some market schemes such as PES and certification can help to reduce this vulnerability.

12.5.10.2 Health and Well-being: Early-warning Systems

For the health sector, we assessed the barriers and facilitators for the implementation of climate-driven EWSs under natural extreme events and epidemic situations. We found institutional dimensions to be potential barriers. These included the legal and regulatory feasibility, institutional capacity and administrative feasibility, transparency and political acceptability (*high confidence*). The fewest barriers were identified for the economic and environmental dimensions.

One of the main institutional challenges is the lack of policy with climate–health linkages. Opportunities include a national plan for the health sector to address the impacts of climate change by formalising collaborations via agreements memoranda of understanding (MOUs). Another key barrier is that relatively few institutions in the region have the human technical and administrative capacity to implement and operate an EWS. Regional platforms may provide a solution for technical assistance at national levels.

On the other hand, the economic dimensions faced relatively few barriers, although the initial costs of designing, implementing, equipping and maintaining the system are a potential barrier for health-related sectors with reduced budgets. However, the health benefits and economic savings (due to averted epidemics or damage from disasters) may offset these costs. The resilience built into the health sector by these systems may be applicable to other economic sectors that could benefit from the early warning of an immenent extreme event and associated health impacts.

12.5.10.3 Water—Multi-use Water Storage Approaches

For the water sector, geophysical and economic dimensions do not pose a major barrier thanks to the potential reduction of flood hazard exposure, physical-technical viability of project implementation, different suitable economic mechanisms for joint public-private financing and more efficient water use. However, limited institutional capacities and the social-environmental impacts of large water infrastructure (Section 12.5.3) reduce the institutional, social, environmental and, to some extent, technological feasibility. This may be a potential barrier to the adaptive approach of multi-use water storage (*medium confidence*).

12.5.10.4 Freshwater and Terrestrial Ecosystems—Ecosystem-based Adaptation

In the terrestrial and freshwater ecosystem sector, we assessed the feasibility of implementing EbA options in the CSA region. Given that EbA encompasses a wide range of projects, techniques and political and socioeconomic arrangements, extreme care should be taken when applying these general findings to particular cases. EbA can enhance food sovereignty and carbon stocks and foster SDGs by protecting and restoring ecosystems' health and productivity. EbA is a strategy that frequently involves bottom-up decision-making and local communities' empowerment and usually contributes to inequality reduction. EbA

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tends to benefit vulnerable groups, but aspects such as the impact on socioeconomic inequalities when implemented should be taken into account.

In general, EbA does not require advanced technologies for local communities. However, limitations in technical assistance and funding for specific key technologies and training may act as a barrier for EbA adoption (*medium confidence*). EbA practices can reduce risk in several ways by increasing awareness among communities and providing food diversity and production. EbA is recognised as a desirable policy for most stakeholders in CSA, particularly because as a strategy it incorporates environmental and social concerns. Nonetheless, it is important that all stakeholders agree on the goals and methods for EbA to be effective. A lack of institutional coordination, clear goals and strategies were identified as a potential barrier for EbA implementation. EbA is heavily based in local and IK, as well as academic ecological knowledge.

For the adaptation options analysed, significant barriers and mixed effects were observed for the institutional dimension, which indicates the relevance of the design and implementation of public policies and institutional arrangements for effective adaptation in the region. Considering the results, there is a need to advance initiatives, programmes and projects that facilitate adaptation to climate change. In the same way, barriers were apparent in the technological dimension, which indicates the importance of increasing access and diffusion of appropriate techniques and technologies in order to face the challenges of climate change in the region.

12.6 Case Studies

12.6.1 Nature-based Solutions in Quito, Ecuador

NbS are related to the maintenance, enhancement and restoration of biodiversity and ecosystems as a means of addressing multiple concerns simultaneously (Kabisch et al., 2016). NbS can trigger sustainability transitions. For example, the conservation and restoration of natural ecosystems are prone to promote synergy between mitigation, adaptation and sustainable development. EbA can be seen as a type of NbS deployed in response to climate-change vulnerability and risk (Greenwalt et al., 2018), combining the objectives of reducing the vulnerability of human systems and increasing the resilience of natural systems (IPCC, 2014).

The Municipal Quito District in Ecuador covers 4235 km^2 of mountainous territory that ranges from 500 to 5000 MASL. That territory has followed a pattern of urbanisation common in Latin America: its population has increased from around 500,000 people in the 1970s to nearly 3 million inhabitants by 2020, of which 80% live in urban areas (Municipio del Distrito Metropolitano de Quito, 2016). A massive inflow of people immigrated in the early 1970s due to various causes, including the search for the rents created as a result of the oil boom in the Ecuadorian Amazon, better working conditions, health, education and cultural services, in comparison with the rural areas or in mid-sized cities. As a result, the city underwent exponential growth, claiming valuable agricultural and forestry areas, as well as natural ecosystems, in the peripheries. Many of the new neighbourhoods were established through land invasions or informal markets, in many cases over steep slopes, in water sources and agricultural or conservation areas (*high confidence*) (Cuvi, 2015; Gómez Salazar and Cuvi, 2016). That exponential population growth, coupled with urban sprawl, poses many challenges to the city, including those related to climate change.

Mean air temperature and annual rainfall (measured by instruments since 1891 and inferred through historical records of rogation ceremonies since 1600), are increasing, combined with an increase in seasonality (i.e., longer periods of drought) and extreme weather events, particularly higher levels of precipitation (Serrano Vincenti et al., 2017; Domínguez-Castro et al., 2018). Two impacts related to warmer air conditions are the displacement of the freezing line currently placed at 5100 MASL (Basantes-Serrano et al., 2016), followed by glacier retreat and the upward displacement of mountainous ecosystems (*very high confidence*) (Vuille et al., 2018; Cuesta et al., 2019). The key ecosystem that regulates water provision for the city is the paramo, and only about 5% of this process is related to glaciers, so the combined effects of climate change on both systems, coupled with land use change and fires, can reduce the availability of water for agriculture, human consumption and hydropower. Other important climatic hazards and impacts are the increase of solar radiation, the heat island effect and fires (*high confidence*) (Anderson et al., 2011; Armenteras et al., 2020; Ranasinghe et al., 2021). On almost half of the days of each year, Quito's population is exposed to levels of UV radiation above 11 according to the World Health Organization scale (Municipio del Distrito Metropolitano de Quito, 2016).

Various policies, programmes and projects have been created for the promotion of urban green spaces, protected areas, water source and watershed monitoring, conservation and ecosystem restoration, air pollution monitoring and control and urban agriculture. Among those actions, three recent ones are commonly highlighted. The first is the FONAG, established in 2000 with funds from national and international organisations to promote the protection of the water basins that supply most of the drinking water. It is a PES scheme enabled through a public–private escrow. The projects include conservation, ecological restoration and environmental education for a new culture of water, in a context opposed to the commodification of natural resources (Kauffman, 2014; Bremer et al., 2016; Coronel T, 2019). FONAG was innovative in the use of trust funds in a voluntary, decentralised mechanism and has inspired more than 21 other water funds in the region; nevertheless, its narrative of success has also been said to oversimplify and misrepresent some complex interactions between stakeholders as well as within communities and their land management practices (Joslin, 2019).

The second highlighted initiative is the AGRUPAR (Participatory Urban Agriculture) programme, launched as a public initiative in 2002 initially with international cooperation funds. It was aimed at providing assistance to poorer urban and peri-urban populations, to initiate and manage orchards as well as domestic animals such as chickens and guinea pigs, with the goal of promoting self-sustenance and commerce. AGRUPAR provides and finances training, seeds and seedlings, greenhouses, certifications and marketing support and spaces where farmers can sell directly their products to consumers. In 2016, AGRUPAR gave assistance to more than 4000 farmers managing orchards of various scales that combined produce, more than 500 tonnes annually. The programme has direct impacts on nutrition, generation of work for women, production of healthy food, reduction of runoff, recycling of organic waste and social cohesion, among others (*very high confidence)* (Thomas, 2014; Cuvi, 2015; Rodríguez-Dueñas and Rivera, 2016; Clavijo Palacios and Cuvi, 2017).

A third initiative is the creation of a municipal system of protected areas, locally named Áreas de Conservación y Uso Sustentable (ACUS). This system covers an area of 1320 km^2, nearly a third of the Municipal Quito District. Half of this landscape (680 km^2) is covered by montane forests and paramos (Torres and Peralvo, 2019). These forests provide direct water, food and fibres for about 20,000 people and indirectly a rural landscape for a growing number of urban citizens and foreign tourists that practice ecotourism and look for fresh and healthy food. During the last three decades, this area has witnessed a high density of public and private conservation and restoration efforts that aim to regain ecological integrity and improve human well-being in deforested and degraded landscapes (Mansourian, 2017; Zalles, 2018; Wiegant et al., 2020). Quito's system of protected areas constitutes a primary strategy for fostering links between urban and rural citizens as a means of understanding the ecological dependence of urban metropolises to their surrounding natural landscapes. Along the same lines, these areas constitute a key element to increase the adaptive capacity of rural livelihoods and contribute to mitigating climate change through landscape restoration, sustainable production and forest conservation (*high confidence*).

Other NbS actions include the restoration of small basins, locally called quebradas, under different schemes of management and participation (*medium evidence, very high agreement*) (da Cruz e Sousa and Ríos-Touma, 2018) and the transformation since 2013 of a large portion of the old Quito airport into an urban park. Nevertheless, Quito city continues to face challenges in the social, economic, infrastructural and environmental spheres. A major pending environmental issue is air pollution; a high level of pollutants affects the city in general and especially the most vulnerable groups (*high confidence*) (Zalakeviciute et al., 2018; Alvarez-Mendoza et al., 2019; Estrella et al., 2019; Hernandez et al., 2019; Rodríguez-Guerra and Cuvi, 2019). Another major issue is the continuous sprawl of new neighbourhoods, mainly through informal processes, that diminish urban resilience because of the destruction of conservation and food production areas, sources of water and the dispersion of settlements without primary services, among other consequences (Gómez Salazar and Cuvi, 2016).

12.6.2 Anthropogenic Soils, an Option for Mitigation and Adaptation to Climate Change in Central and South America. Learning from the "Terras Pretas de Índio" in the Amazon

Amazonian dark earths (ADEs), also known as Terras Pretas de Índio, are anthropogenic soils derived from the activities associated with the settlements and agricultural practices of pre-Hispanic societies in the Amazon (Woods and McCann, 1999; Lehmann et al., 2003; Sombroek et al., 2003). Most of the ADEs identified so far are 500 to 2500 years old (de Souza et al., 2019). According to Maezumi et al. (2018a), polyculture agroforestry allowed for the development of complex societies in the eastern Amazon around 4500 years ago. Agroforestry was combined with the cultivation of multiple crops and the active and progressive increase in the proportion of edible plant species in the forest, along with hunting and fishing. The formation of ADEs as a result of these activities served as the basis for a food production system that supported a growing human population in the area (Maezumi et al., 2018a).

ADEs are the result of the accumulation and incomplete combustion of waste materials such as ceramic artefacts and organic residues from harvesting, weeding, food processing (including cooking) and other activities (Lima et al., 2002; Hecht, 2003; Kämpf et al., 2003). ADEs are characterised by their increased fertility in relation to adjacent soils, with high contents of organic carbon (C) (mainly as charcoal) as well as inorganic nutrients, especially phosphorus (P) and calcium (Ca) and high carbon/nitrogen ratios (*high confidence*) (Moline and Coutinho, 2015; Alho et al., 2019; Barbosa et al., 2020; Pandey et al., 2020; Soares et al., 2021; Zhang et al., 2021). They also exhibit a high cation exchange capacity and moisture retention, among other properties (Hecht, 2003; Kämpf et al., 2003; Falcão et al., 2009). Charcoal content is a key indicator of pre-Hispanic fire activity and sedentary occupation, which is evidence of the anthropic origin of these soils (*high confidence*) (Hecht, 2017; Maezumi et al., 2018b; Alho et al., 2019; Barbosa et al., 2020; Iriarte et al., 2020; Montoya et al., 2020; Shepard et al., 2020).

Accumulation of organic residues and low-intensity fire management are recognised key elements in ADE formation. ADEs originating around settlements show a relatively high density of ceramic artefacts and are called terras pretas. They present a higher content of calcium and phosphorus than those originating from agricultural activities, which are known as *terras mulatas* (Hecht, 2003).

There is a robust and growing body of research from various disciplines that assigns a high relevance to ADEs in the region. It has been shown through archaeological and palaeoclimatic data that Amazonian societies that based their agricultural management on Terras Pretas de Índio were more resilient to the changing climate due to increased soil fertility and water retention capacity (de Souza et al., 2019). Additionally, low organic carbon degradability over long time periods, associated with high contents of charcoal or pyrogenic carbon, makes these soils an important C sink (*medium confidence*: *robust evidence, medium agreement*) (Lehmann et al., 2003; Guo, 2016; Trujillo et al., 2020), which is particularly relevant in an area like the Amazon, that could change from a net carbon sink to a net carbon source as a consequence of anthropogenic climate change (Maezumi et al., 2018b).

The Indigenous agricultural practices that led to ADEs are thought to be associated with a more sedentary agricultural model than the current slash-and-burn and shifting cultivation practices. Although this is a controversial topic, as the precise definitions of slash and burn and shifting cultivation are presently under discussion (Hecht, 2003), several present-day local and Indigenous agricultural practices, including in-field burning and nutrient additions from food processing and residue management, have been recognised as promoting high organic carbon and nutrient soil contents similar to those found in ADEs (Hecht, 2003; Winklerprins, 2009).

At present, ADEs are estimated to cover up to 3.2% of the Amazon basin and are highly valued for their persistent fertility, and they have become a key resource for sustainable agriculture for Amazon communities in a climate-change context (Altieri and Nicholls, 2013; Maezumi et al., 2018a; de Souza et al., 2019). Based on the lessons learned from the Terras Pretas de Índio, some researchers have proposed the development of technologies to promote a new generation of anthropogenic soils (e.g., Kern et al. 2009; Lehmann 2009; Schmidt et al. 2014; Bezerra et al. 2016; Kern et al. 2019). Among the technologies based on ADE findings, biochar, obtained by the slow pyrolysis of agricultural residues, is the most explored application found in the literature (Mohan et al., 2018; Matoso et al., 2019; Amoah-Antwi et al., 2020). The dual purpose of increased soil fertility and carbon sequestration is considered an important goal in connection with developing sustainable agriculture in a climate-change context (Kern et al., 2019).

Preservation of the practices and knowledge associated with these soils is vital for sustainable agriculture in a climate-change scenario in the Amazon. It will greatly contribute to the preservation of valuable IK as well as the contribution to the development of new adaptation and mitigation technologies, among other unexplored solutions.

12.6.3 Towards a Metropolitan Water-related Climate Proof Governance (Re)configuration? The case of Lima, Peru

Lima-Callao Metropolitan Area, capital of Perú, is facing recurrent climate disasters providing lessons on water-related climate-proof governance reconfiguration. The first lesson is that when disasters affect poor and rich populations, dominant actors prioritise the integral city's resilience and development and coordinate and collaborate within a *concertation* framework across institutional levels and geographical scales (Hommes and Boelens, 2017; Miranda Sara, 2021), even having different ideas, discourses, and power, recognising that no single actor has enough power. Second, water-related climate-change scenarios require comprehensive, transverse, multi-sectoral, multi-scalar, multiple types of actor knowledge (expert, tacit, codified and contextual embedded) (Pfeffer, 2018) and transparent information to manage the tensions and even conflicts when some knowledge is not shared or restricted, particularly when lower risk perception and higher risk tolerance are present. Finally, a *concertative* (processes involving a variety of actors, which has become mandatory in Peru) strategy to *localise* climate-changed-related action shows quicker, more effective and more transparent results (*medium confidence, robust evidence, medium agreement*) (Miranda Sara and Baud, 2014; Pepermans and Maeseele, 2016; Siña et al., 2016; Miranda Sara et al., 2017).

As the second driest city in the world, Lima is highly vulnerable to drought and heavy rainfall in the nearby Andean highlands (Schütze et al., 2019). Located on the Pacific coast with more than 10 million inhabitants, it suffers from flooding, mudslide disasters and water stress, and is more frequently affected by heavy rain peak events (1970, 1987, 1998, 2012, 2014, 2015 and 2017) (*very high confidence*) (Mesclier et al., 2015; Miranda Sara et al., 2016; French and Mechler, 2017; Vázquez-Rowe et al., 2017; Escalante Estrada and Miranda, 2020). In addition to unequal water distribution in quantity and pricing, one million inhabitants lack water connections (Ioris, 2016; Miranda Sara et al., 2017; Vázquez-Rowe et al., 2017) as a result of a lack of long-term city planning and lack of integration with water and risk management. Climate-change scenarios were ignored or denied, particularly when budget allocations for preventive actions were necessary (*high confidence*) (Miranda Sara et al., 2016; Allen et al., 2017a).

In 2014, the water company (SEDAPAL), together with the Lima Metropolitan Municipality (LMM), National Water Authority (ANA) and other organisations, agreed on a Lima Action Plan for Water (Schütze et al., 2019). The same year, the LMM approved a climate change strategy defining adaptation and mitigation measures (Miranda Sara and Baud, 2014) based on technical and scientific action research within interactive and iterative *concertation* multi-actor processes.

However, in 2015, municipal elections shifted Lima's and, later, Peru's political power to parties associated with climate deniers at a high cost to the people, city infrastructure and housing. In early 2017, buildings along rivers, ravines and slopes suffered from floods, *huaycos* (mudslides), and the whole city experienced potable water cuts (Vázquez-Rowe et al., 2017) and vector-borne diseases affecting especially poorer but also richer inhabitants.

A so-called coastal El Niño affected the whole country, and as a consequence, in 2018 the Peruvian government passed the Framework Law for Climate Change, Law No. 30754, a unique political decision, to assure the integration of climate-change concerns in public policies and investment projects. The law defines local government mandates on local climate action plans. The 2019 municipal elections brought new local authorities to Lima, and by 2020, 19 district municipalities had developed adaptation measures, adopting the metropolitan climate change strategy with support from Cities for Life Foro and GIZ (Foro Ciudades Para la Vida, 2021). In 2021, LMM approved its local climate change plan (LCCP), and 10 (out of 51 with Callao) more municipalities finalised their LCCP with the support of the Global Covenant of Mayors for Climate & Energy and the European Union.

The institutionalised culture of participation in Peru did lead to a broader concept of concertation, wherein practices of collaborative planning were developed to allow actors to build up socially supported agreements and decisions and take action without losing sight of their principles. These processes have been applied to reduce risks, to adapt and to anticipate uncertain and unknown futures; they also introduced climate-change concerns within a complex political and institutional environment surrounded by corruption scandals (Vergara, 2018; Durand, 2019) and growing political polarisation.

Several processes have been set in motion to engage citizen participation and promote climate action planning. First, the LMM with Climate Action Plan processes reopened the Climate Change Technical Group of the Municipal Environmental Commission, whose work ended in the approval of the Lima Local Action Plan of Climate Change (MML, 2021). Second, the River Basin Council is developing the River Basin Management Plan led by the National Water Authority.Finally, the Metropolitan Lima Urban Development Plan is finalising a citizen consultation, with the support of a high-level consultation group.

Such processes include heated discussions, conflicts and the recognition of other discourses and types of knowledge so as to build up scenarios that 'visualise' and anticipate what might happen. These processes require democratic, transparent and decentralised institutions, providing clear mandates and strong political will to support them, so that the poor and vulnerable can make their views known and are able to make themselves heard, even if their power remains limited (Chu et al., 2016). Opportunities for the reconfiguration of sociopolitical and technological water governance are emerging based on socially supported agreements (Miranda Sara and Baud, 2014; Miranda Sara, 2021). However, the water governance configuration faces the paradox that the current water demands of all users combined may no longer be feasible within ecological limits and future climate-change consequences (Miranda Sara et al., 2016; Schütze et al., 2019).

12.6.4 Strengthening Water Governance for Adaptation to Climate Change: Managing Scarcity and Excess of Water in the Pacific Coastal Area of Guatemala

Guatemala experiences high climate interannual variability, now increased from the effect of climate change (INSIVUMEH, 2018; Bardales et al., 2019). Impacts on human settlements, agriculture and ecosystems result from both excess and reduced precipitation (*high confidence*) (Section 12.3.1.4). Guerra (2016) argues that deficient IWRM in the country is the main reason for those impacts. A case in point is that of the Madre Vieja and Achiguate rivers, where an intense El Niño event triggered dryer conditions and, in turn, a crisis and conflict that reached national proportions. Progress in local water governance helped to solve that crisis and helped tackle challenges posed by reduced precipitation and flood risk in southern Guatemala.

The ENSO event that started in November 2014 and ended in July 2016 (CIIFEN, 2016) was the most intense since records commenced in 1950 (NOAA, 2019). Its effects were felt in different parts of the world, and Guatemala and the rest of CA experienced intense water scarcity due to a significant reduction in rainfall (*high confidence*) (IICA, 2015; Scientific American, 2015). River flow in the dry months is related to precipitation levels in the previous rainy season, so ENSO has an effect on river flow rates. Two of the main rivers in the Pacific coast of Guatemala, Madre Vieja and Achiguate, dried out completely at the beginning of 2016, triggering a nearly violent local conflict that caught the attention of national leaders (Guerra, 2016; Gobernación de Escuintla et al., 2017). In addition to the severe drought, the rivers dried because of overextraction by multiple users (60 in the case of Madre Vieja). This had happened before to a lesser extent in the last 20 years during the critical months of the dry season. A lack of regulation, coordination mechanisms, information and other elements of water governance was the root cause of the problem, exacerbated by the drier conditions during the intense El Niño event, resulting in the intensification of an existing conflict (*high confidence*) (Guerra, 2016).

Roundtables were set up to foster dialogue between numerous stakeholders, including communities, agri-export companies, governmental organisations and municipalities, all led by the local governor (Gobernación de Escuintla et al., 2017). Agreements included keeping a minimum river flow all the way to the sea, setting up a monitoring and verification system for levels of river flow and restoring riparian forests. A system was set up to monitor river flow at different points along the rivers on a daily basis in the dry season using a simple WhatsApp-based system to communicate the warnings and monitor compliance. Four years on, the rivers had not dried out and conflict was kept to a minimum. Rural communities can use rivers for recreational purposes and for fishing all year round, while plantations (large and small) can use water for irrigation (rationally) and keep producing. Similar schemes and interactions started happening in other rivers in the Pacific coast of Guatemala, with positive results, in particular, rivers kept flowing all through the dry season, as can be seen in the report of river flows for the years 2017, 2018 and 2019 (ICC, 2019b).

A key actor in the improvement of water governance has been the private Institute for Climate Change Research (ICC). This is a unique initiative that was created in 2010 and is funded primarily by the private sector of Guatemala to help the country advance in climate-change mitigation and adaptation (Guerra, 2014). The institute works alongside local governments, communities and private companies in several areas besides integrated water management. Its role is merely technical-scientific: it oversees the water monitoring system, generating data on weather and hydrology and providing support to other stakeholders.

Local governance was also essential for the implementation of flood risk management actions (*high confidence*). Guerra et al. (2017) explained how impacts were significantly reduced in the Coyolate River watershed, as well as on the Pacific coast of Guatemala, thanks to flood protection that was designed and implemented in a technical and integrated manner. This was a result of the strong and active participation of local communities, companies and the local municipality, which demanded that the central government invest effectively. The stakeholders provided some resources (financial and in-kind) and inspected the works. Some flat areas of the lower Coyolate watershed used to flood annually, causing economic damage in communities. The areas covered by flood risk measures have not flooded and so have avoided losses and created conditions that attract investment and create jobs, improving living conditions for the locals. Other processes of participation and interaction between the authorities, the private sector and communities have taken place in other watersheds for planning, action and investment in connection with flood risk management. The ICC has played a role by studying flood-prone areas, building capacities in communities, fostering

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public–private coordination mechanisms and providing much needed technical assistance to local governments (ICC, 2019a).

Although some may argue that water governance is in the realm of development, it has made contributions in reducing direct and indirect impacts of climate events and, therefore, can be seen as a key element for climate adaptation (*high confidence*).

12.7 Knowledge Gaps

Data deficiencies and heterogeneity in quantity, quality and geographical bias in knowledge limit people's understanding of climate change, evaluation of its impacts and the implementation of adaptation and mitigation measures (Harvey et al., 2018) in CSA. The number of publications is not representative of the sensitivity to climate change and vulnerability contexts of different sub-regions and sectors. This lack of representation in the mainstream literature may lead to a bias and, therefore, an underestimation of the overall climate-related impact for some CSA sub-regions (Sietsma et al., 2021). The reason for the relatively few quantitative studies might be the complexities of socio-demographic and economic factors and the lack of long-term and reliable data in these areas (Harvey et al., 2018), along with other social, economic and technical constraints.

Most studies that assess vulnerability to climate change do not yet follow the concept adopted since AR5, which isolates exposure as an external variable (WGII AR5 Figure SPM 1) (IPCC, 2014), and many still use the A and B system of climate-change scenarios from AR4, because the adoption of the RCP models has been slow. There is still limited literature on severe risks and little specific and explicit consideration of risk drivers in the region. Moreover, limits to adaptation and the effectiveness of adaptation measures in CSA remain largely understudied.

Research on the interactions between climate change and socioeconomic processes is not extensive (Barnes et al., 2013; Leichenko and O'Brien, 2019; Thomas et al., 2019). There is limited understanding of the multi-level synergistic effects of climate change and other drivers, including economic development from the household to the country level (Wilbanks and Kates, 2010; Leichenko and Silva, 2014; Tanner et al., 2015a; Carey et al., 2017). In the region, this deficit is greater for sectors other than agriculture, water and food.

12.7.1 Knowledge Gaps in the Sub-regions

The knowledge gaps in the eight sub-regions are quite heterogeneous. In CA, climate-change research is notably insufficient in all sectors included in this report, considering that climatic change, variability and extremes are impacting and will continue to severely impact this sub-region, and the vulnerability of the social and natural systems is high. Data deficiencies must be overcome as renewed research on climate change updates models, scenarios and projected impacts across sectors and levels (i.e., household to country). In NWS, there is a lack of studies on the relationships with increased fire events, and the impacts on the infrastructure of all kinds, on certain lowland, marine and coastal ecosystems and on ecosystem functioning and the provision of environmental services. Experimental studies are rare and most necessary to identify critical ecological thresholds to support decision-making processes, linking glacier retreat to its consequences on biodiversity and ecosystems, combined with different land use trajectories. Complex interactions with processes such as peace agreements in Colombia are yet to be investigated (Salazar et al., 2018). In NSA, there remains a limited amount of peer-reviewed literature addressing the implications of climate change on Indigenous cultures and their livelihoods. In SAM, further data are needed on the vulnerability of traditional populations, impacts on water availability and soil degradation, risks to biodiversity and resilience of ecosystems in connection with climate change.

There is a knowledge gap about the likely impact of climate change on NES biodiversity, soil degradation and best adaptation measures. SES is the most urbanised sub-region of CSA, but there are severe knowledge deficits related to the design, implementation and evaluation of adaptation policy plans with respect to climate change. Forecasts related to risk prevention require new studies that address down-scaled climate-change models with concrete solutions to increase cities' resilience. In SWS, there is a lack of long-term studies addressing climate-change impacts on terrestrial, freshwater and marine ecosystems, which is mainly due to the lack of integrated observational systems. There is a lack of studies projecting future impacts of climate change on the cryosphere, water resources, hazards, risks and disasters on natural and human systems. This is mainly due to the lack of systematic documentation, analysis and evaluation of adaptation strategies adopted, as well as their limitations and the lessons learned from maladaptation processes. There is scant evidence about transformational adaptation to climate change and system resilience. In SSA, there is a need for information related to the cities' vulnerability to climate change and the impacts of the direct effects of future climate change on cities, energy infrastructure and health. Also, there is a knowledge gap about the financing of climate-change adaptation in SSA.

12.7.2 Knowledge Gaps by Sector

12.7.2.1 Terrestrial and Freshwater Ecosystems and their Services

Advances in scientific knowledge on the risks of climate-change impacts and the vulnerability and resilience of ecosystems to climate change are needed (Bustamante et al., 2020). Persistent climate change in tropical rainforests requires deeper study and understanding, overall in connection with the role of nutrients, deep-water availability and biodiversity. Further research is needed to understand feedback to climate systems of large-scale changes in the land surface in SA biomes. The region has important freshwater Global 200 Ecoregions, including the Orinoco River and Flooded Forests, Upper Amazon River and streams, and Amazon River and Flooded Forests, which represent a priority for freshwater biodiversity conservation at a global scale (Manes et al., 2021) (Cross-Chapter Paper 1; Figure 12.8). There is, however, a clear knowledge gap on the impacts of climate change on freshwater biodiversity in the region (Section CCP1.2.3; Manes et al.,

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2021). Lastly, more interdisciplinary research is needed regarding conservation strategies and stable financial resources focusing on adaptation of ecosystems in the region (Mistry et al., 2016; Gebara and Agrawal, 2017; Ruggiero et al., 2019; To and Dressler, 2019).

12.7.2.2 Ocean and Coastal Ecosystems and Their Service

There is an important lack of knowledge about the state of health of the ocean and coastal ecosystems along CSA (i.e., social-ecological data integration, poor sampling efforts, lack of information about the value of ecosystem services, lack of information about ecosystems cover and distribution, lack of studies about climate-change perceptions and social concerns), including marine fisheries (i.e., landing statistics not available, lack of reliable information on the scope of resource extraction, among others). Poor or absent monitoring programmes (physical, environmental and biological variables) that feed alert and surveillance systems are lacking in CSA. There is a general absence of a continuous line of scientific research or adequate baseline information about the impacts of climate change, as well as continuous monitoring of the adaptation plans adopted in ocean and coastal ecosystems that limit the formulation of adequate conservation and management programmes. When studies are performed, inadequate access to data limits the analyses of the existing information, making difficult to detect climate-change trends and impacts and develop effective adaptation strategies.

12.7.2.3 Water

As in other sectors and environmental systems, for the water sector there are important limitations in terms of monitoring and data collection. High-quality, long-term hydrological data are unevenly available for different sub-regions and limit the possibility of obtaining a deeper understanding of changes in river runoff and lake or groundwater changes. Groundwater data are particularly scarce. There are important gaps related to the projections of water resources for the future. Much of current knowledge on future changes in water resources and water scarcity and flood risks is based on information from global-scale studies because studies specific to this region are scarce. Several elements that are important for IWRM, such as water quality, water demand, privatisation and other economic dynamics, and nutrient, pollutant and sediment flux are poorly known currently due to missing data and insufficient efforts to monitor them.

12.7.2.4 Food, Fibre and Other Ecosystem Products

Integrative evaluation on impacts on food security, including agricultural production, distribution and access, leading to adaptation strategies is limited within the region. Limited information regarding cost-benefit analyses of adaptation in the food production sector is available in the region. It is also important to obtain a better understanding of adaptation effects to avoid maladaptation and promote site-specific and dynamic adaptation options considering available technologies. Compiling and systematising existing scientific and local knowledge on the relationship between forests, land cover/use and hydrological services is a gap that must be filled from a broader perspective in the region, which could contribute to formulating recommendations and inform restoration practices and policies. The literature also highlights widespread gaps between farmers' information needs and services that are routinely available. There is evidence that when climate information services are created with farmer input and targeted in a timely and inclusive manner, they are a positive determinant of adaptation through the adoption of more resilient farm-level practices. However, current assessments of the economic impacts of climate information services are scarce; hence, more such studies are needed.

12.7.2.5 Cities, Settlements and Infrastructure

Despite the high level of urbanisation in the region, studies on urban adaptation initiatives are still underreported by municipalities, and several practical results have not yet been demonstrated (Araos et al., 2016). This issue is particularly relevant to medium-sized cities because most of the literature and data available on adaptation refer to the major capital cities. The potential of applying new resilient parameters in building and land use regulations for adaptation is underreported. The same can be said about the impact of housing improvement and slum upgrading on climate resilience, even when initiatives are focused on reducing environmental and climate risk. Also relevant in the region is a gap in research about NbS applied to urban area adaptation, as in the case of the urban forestry potential for adaptation (Barona et al., 2020). Even though the importance of urban ecological infrastructure in providing ecosystem services, such as flood control, is reasonably well documented, its practical application in urban planning in CSA remains limited (Romero-Duque et al., 2020). Added to this is the lack of monitoring data on adaptation initiatives in general and, in particular, on adaptation initiatives in water systems that have already been implemented and their effects on risk reduction. A lack of monitoring data contributes to the lack of information about maladaptation in urban areas and its consequences. Mobility and transport system adaptation options remained virtually entirely unexplored, while mitigation options receive significant attention.

12.7.2.6 Health and Well-being

There is a growing body of evidence that climate variability and climate change (CVC) cause harm to human health in CSA. However, there is a lack of information about the current and future projected impacts of CVC events on overall illness and death in this region. It is challenging to attribute specific health outcomes to CVC in models and field experiments due to multiple factors, including the following:

- lack of long-term, high-quality health surveillance data
- multiple interacting infectious disease and chronic health issues
- mismatch in the spatial and temporal scales of CVC and health measurements
- complex climate and human system dynamics, including non-linear time lags
- limited longitudinal data on non-climate factors that influence health outcomes (e.g., public health interventions, migration of human populations, seasonal patterns in livelihoods).

The uncertainty inherent in predictive models also makes it challenging to expand current localised knowledge on the impacts of infectious diseases associated with CVC to other regions or future climate scenarios (UNEP, 2018).

Improved risk assessments based on better models and empirical research are needed to bridge the knowledge gap and inform the design of adaptation strategies. A systematic multi-scalar analysis of the impact of CVC on human health is needed across distinct social-ecological contexts. Data collection systems need to be strengthened to accurately estimate the burden of mortality and morbidity from heat and extreme events. The data deficit is a common problem in functioning civil registration and vital statistics systems, including lack of information on causes of death (UNEP, 2018). In addition, there is a lack of consensus on globally accepted and operational definitions for both climate-related extremes and exposures/outcomes.

For infectious disease (vector-borne and water-borne), the technology available to estimate current and future risk areas is often limited by human or financial resource constraints in developing countries. There is a geographical mismatch between the areas producing the technology and knowledge (in the global north) and the areas most affected by CVC (in the global south). User-friendly tools that bring together climate and health information—without the need for modelling or GIS expertise—are needed for health sector decision makers.

There is a lack of studies that assess the feasibility of health adaptation measures (Section 12.5.10), thereby limiting the ability of decision makers to compare different health interventions and identify bottlenecks for implementation. The growing field of implementation science could help to address barriers to mainstreaming climate information in the health sector as an adaptation strategy.

Finally, there is an almost complete absence of studies that address relationships of climate change with well-being in CSA, broadly understood as including emotions and moods, satisfaction with life, sense of meaning and positive functioning, including the capacity for unimpaired cognitive functioning and economic productivity (Section 7.1.4.1).

12.7.2.7 Poverty, Livelihood and Sustainable Development

Climate change is becoming a major obstacle to poverty reduction and overcoming poverty traps. There is a need to better understand how poor and vulnerable communities are affected and the more effective ways to prevent it. The large majority of the poor in the region are living in urban areas (UNDESA, 2019); extreme urban poverty is increasingly more relevant, including the needs and priorities of informal settlements and economies, but less studied within the interaction with climate change. There is little reporting of major adaptation options implemented by or for vulnerable and poor urban dwellers (Ryan and Bustos, 2019; Berrang-Ford et al., 2021).

Adaptation options are being increasingly documented for poverty-related impacts, despite the fact that the uncertain context from climate impacts is not uniform across communities and the very local scale of the type of adaptation responses needed (Miranda Sara et al., 2016; Rosenzweig et al., 2018; Dodman et al., 2019). There is a huge gap in understanding how the poor respond to climate change, what is needed to support them and the interconnections among development policies, poverty and risk reduction with climate-change actions (Ryan and Bustos, 2019; Satterthwaite et al., 2020).

The literature to assess the effectiveness of pro-poor or low-income adaptation options continues to be weak; a very small proportion shows results associated with adaptation efforts (Magrin et al., 2014; Berrang-Ford et al., 2021). Without this kind of approach and in-depth understanding there is the risk that top-down climate-change adaptation options could reinforce poverty cycles and neglect cultural values, even eroding them (Bartlett and Satterthwaite, 2016; Walshe and Argumedo, 2016; Allen et al., 2017a; Hallegatte et al., 2018; Kalikoski et al., 2018; UN-Habitat, 2018).

The impacts of climate change on vulnerable groups remain understudied. There are little or no climate data on the remote mountain regions of CSA as well as research measuring the vulnerability of smallholders living there, making it hard to assess the expected changes or the possible adaptation measures (Pons et al., 2016; Donatti et al., 2019).

12.7.2.8 Cross-Cutting Issues in the Human Dimension

A significant number of studies address the impacts of climate change on the Amazon rainforest (Brienen et al., 2015; Doughty et al., 2015; Feldpausch et al., 2016; Rammig, 2020; Sullivan et al., 2020); however, assessment of the tangible and intangible impacts of climate change on Indigenous Peoples' cultures and livelihoods in this forest need to be further advanced (Brondízio et al., 2016; Hoegh-Guldberg et al., 2018).

Studies on the perception of climate change in rural and urban populations throughout the region have increased, but there is a lack of more specific research on the perception of specific groups, such as economic or political actors, that influence public institutions and policies at the local, regional and national levels.

While studies on climate-change gender-differentiated impacts have grown over the past 10 years in CSA, studies on how gender intersects with other dimensions such as race, ethnicity, age or rural/urban setting are still needed. This will help to further understand how gender inequalities are connected to broader power structures in society and, thus, to produce evidence on the importance of an intersectional approach to climate change.

Regarding the relation of social movements and climate-change adaptation, institutions and politics, two major issues stand out: youth movements for climate change and the resistances, mainly urban, to climate-change adaptation policies. Little connection is found in research concentrating on resistance to climate-change adaptation policies and their interaction with the politics of place. Conflictivity related to climate change is another understudied issue.

Although there are several case studies on migrations and displacements caused by strong and immediate climatic threats, such as hurricanes or floods, and on slow-onset impacts, such as droughts or temperature increase, there are gaps in the attribution or relative weight of climate change in these processes.

Still important to note is that synergies between mitigation, adaptation, risk reduction and sustainable development have not been jointly explored, which would better facilitate adaptation policy approaches.

There are critical knowledge gaps in the interlinkages between social and environmental dynamics that are important for climate-change adaptation, as in Andean forest landscapes. A salient knowledge gap in this thematic area is the need to characterise how multi-level and multi-actor governance systems can enable sustainable land management practices, including ecosystem restoration (Mathez-Stiefel et al., 2017). More capacities are needed to increase the generation of relevant knowledge. Even small grant programmes can sustain research projects that target the linkages between knowledge and decision-making at multiple scales (Báez et al., 2020).

12.8 Conclusion

CSA is a broadly heterogeneous region with respect to topography, ecosystems, urban and rural territories, demography, economy, cultures and climates. The region relies on a strong agrarian economy in which small producers and large industries participate, but also large industrialised urban centres, oil production and mining. The region is one of the most urbanised areas of the world and home to many Indigenous Peoples, some still in isolation, and exhibits one of the highest rates of inequality, which is a structural and growing feature of CSA. Poverty and extreme poverty rates are higher among children, young people, women, Indigenous Peoples and migrant and rural populations, but urban extreme poverty is also growing (*very high confidence*). Socioeconomic challenges are being intensified by the COVID crisis. Most countries in CA are already ranked as the highest risk level worldwide due to the region's high vulnerability to climate change and low adaptive capacity; the lack of climate data and proper downscaling are challenging the adaptation process (*high confidence*).

Many extreme events are already impacting the region and are projected to intensify; such events include warming temperatures and dryness, SLR, coastal erosion and ocean and lake acidification, resulting in coral bleaching and an increasing frequency and severity of droughts in some regions, with a concomitant decrease in water supply, which impact agricultural production, traditional fishing, food security and human health (*high confidence*). In CA, 10.5 million people are living in the so-called Dry Corridor, a region with an extended dry season and, now, more erratic rainfall patterns. A water crisis in Brazil affected the major cities of the country between 2014 and 2016, having become more frequent since then. Severe droughts have also been reported in Paraguay and Argentina. In contrast, the urbanised areas of NSA are highly exposed to extreme floods (41% of urban population in the Amazon Delta and Estuary). Urban areas in the region are vulnerable for many reasons, notably high rates of poverty and informality, poor and unevenly distributed infrastructure, housing deficits and the recurrent occupation of risk areas (*high confidence*).

Socioecological systems in the region are highly vulnerable to climate change, which acts in synergy with other drivers such as land use change and deep socioeconomic inequalities. Most biodiversity hotspots in the region will be negatively impacted. The Cerrado and the Atlantic Forest (two important biodiversity hotspots where about 72% of Brazil's threatened species can be found) are exposed to different hazards (extreme events, mean temperature increase) due to climate change. Many coastal areas and their concentrated urban populations and assets are exposed to SLR. Climate change is threatening several systems (glaciers in the Andes, coral reefs in CA, the Amazon rainforest) that are already approaching a critical state at risk of irreversible damage.

Extreme heat, droughts and floods will seriously affect CSA terrestrial and freshwater ecosystems. The high poverty level increases the region's vulnerability to droughts, both in cities and rural areas, where people already suffer from natural water scarcity (*high confidence*). The conversion of natural ecosystems to other land uses exacerbates the adaptation challenges. IKLK play an important role in adaptation but are also threatened by climate change (*high confidence*). EbA and CbA have increased since AR5, with an emphasis on freshwater ecosystems and forests, including protected areas. Inadequate access to finance and technology is widely identified as an adaptation barrier (*high confidence*).

Climate change is expected to have many impacts on the economy. Subsistence farmers and the urban poor are expected to be the most impacted by droughts and variable rainfall in the region (*high confidence*). The increasing water scarcity is and will continue to impact food security, human health and well-being. The impacts of the many landslides and floods affect mainly the urban poor neighbourhoods and are responsible for the majority of the deaths related to disasters. SLR and intense storm surges are expected to impact the tourism and hospitality industry in general. Internal and international migrations and displacements are expected to increase (*high confidence*). Climatic drivers, such as droughts, tropical storms and hurricanes, heavy rains and floods, interact with social, political, geopolitical and economic drivers (*high confidence*).

The common patterns and problems, however, also highlight the possibilities for collaboration and learning among the countries and institutions in the region in order to strengthen the interface between knowledge and policy in climate-change adaptation. All countries in the region have submitted their first and updated NDCs, and many have published their NAPs, establishing priorities and formulating their own policies to cope with climate change.

Various adaptation initiatives have been launched in various sectors that focus on reducing poverty, improving livelihoods and achieving sustainable and resilient development. An increasing number of planned and autonomous initiatives has been seen, led by communities, governments or a combination of the two, involving engineering or NbS. Climate-smart agriculture is an effective option, in several conditions and regions, to mitigate the negative impacts of climate change. Disaster reduction solutions are increasingly being used, such as EWSs. Many and diverse initiatives are still poorly reported and evaluated in the scientific literature, leading to challenges in assessing and improving them, including consideration of tacit IKLK. The lack of climate data and proper downscaling, weak governance, obstacles to financing, and inequality constrain the adaptation process (*high confidence*).

Adaptation measures have been increased and improved since AR5 in ocean and coastal ecosystems. The majority of these measures are focused on EbA application through the application of protection and recovery of already impacted ecosystems. Another battery of measures is focused on the management and sustainability of marine resources managed in fisheries; however, these measures do not assess current and future climate-change impacts but rather focus on decreasing the impact of other non-climate factors, such as overfishing or pollution. To date, throughout CSA there is an important lack of long-term research addressing ocean and coastal ecosystem health and their species through continuous monitoring, which is one of the main barriers to adaptation. The number and type of adaptation measures for ocean and coastal ecosystems and their contributions to humans are very different among CSA countries, which highlights the number of measures related to increasing scientific research and monitoring followed by the conservation of biodiversity and changes in legislation (*high confidence*). On the other hand, those measures that include changes in financing (an important barrier) or the incorporation of traditional knowledge are not always considered in NAPs by CSA countries.

In the water sector, a lack of systematic analysis and evaluation of adaptation measures predominates, although important progress has been made since AR5 in terms of understanding the interlinkages among climate change, human vulnerabilities, governance, policies and adaptation success (*high confidence*). NbS, PES, IWRM and integration of IKLK hold great potential for success, in particular if adopting approaches with inclusive negotiation formats for water management with clear, just and transparent rights and responsibilities.

Climate change poses several challenges to the agri-food sector, impacting agricultural production and productivity and posing a risk to food security and the economy (*high confidence*). Adapting agriculture while conserving the environment represents a challenge for sustainable and resilient food production (*high confidence*). Adaptation in the region presents persistent barriers and limitations (Table 12.8) associated with investments and knowledge gaps (*medium confidence*). Climate change urges advances in initiatives to improve education, technology and innovation in farming systems in the CSA region.

Urban adaptation is limited by financing constraints, weak intersectoral and multi-level governance and deficits in the housing and infrastructure sectors, the overcoming of which represents an opportunity for transformative adaptation (*high confidence*). Short-term interventions are more common than long-term planning (*high confidence*). Adaptation has taken place throughout the region in planning, land use and building regulation, urban control systems and risk management. Initiatives in social housing focus on reducing risk and overcoming urgent deficits but also adding to a transformative adaptation pathway (*high confidence*). Hybrid (green-grey) infrastructure has been adopted for better efficiency in flood control, sanitation, water scarcity and landslide prevention and coastal protection (*high confidence*). NbS, including GI and EbA, are increasing in urban areas (*high confidence*), although isolated engineering solutions are still widely practiced. The integration of transport and land use plans and the improvement of public transport are key to urban adaptation; mitigation prevails over adaptation in the sector (*high confidence*).

There is a growing body of evidence that climate variability and climate change are causing harm to human health in CSA—including the increasing transmission of vector-borne and zoonotic diseases, heat stress, respiratory illness associated with fires, food and water insecurity associated with drought, among others (*medium confidence*). In response, countries in the region are developing innovative adaptation strategies to inform health decision-making such as integrated climate-health surveillance systems and observatories, forecasting of climate-related disasters and epidemic forecast tools. However, institutional barriers (limited resources, administrative feasibility and political mandates) need to be addressed to ensure the sustained implementation of adaptation strategies (*high confidence*).

Poor and vulnerable groups exert limited political influence; the fewer channels and opportunities that exist to participate in decision-making and policymaking make these groups less able to leverage government support to invest in adaptation measures (*very high confidence*). Participatory processes spur adaptation measures strengthening local capacities, though the literature assessing the success of such initiatives remains limited. Limits to adaptation include access to land, territory and resources, labour and livelihood opportunities, knowledge gaps and poor multi-actor coordination. Social organisation, participation and governance reconfiguration are essential for building climate resilience (*very high confidence*).

Social organisation, participation, governance, education and communications to increase perception and knowledge are essential for building the resilience to adapt and overcome expected and unexpected climate impacts (*very high confidence*). The focus on inclusion and enrolling of the full range of actors in adaptation processes, including vulnerable populations, have yielded good results in the region (*high confidence*). However, existing poverty and inequality, imbalances in power relations, corruption, weak governance and institutions, structural problems and high levels of risk tolerance may reinforce poverty and inequality cycles (*high confidence*). In addition, the continued exposure of critical infrastructure and valuable assets are signs of persisting maladaptation.

The development model prevalent in the region in recent decades has proven to be unsustainable, with the emphasis on financial sources based on natural resource depletion and extraction and the persistence and growing inequality. It is widely recognised that climate adaptation measures, if carefully selected considering coupled human-environment systems, will provide significant contributions to the sustainable development pathways of the region and to achieve the SDGs if implemented together with comprehensive strategies to reduce poverty, inequality and risks (*high confidence*). Adaptation and the construction of resilience offer not only an opportunity to reduce climate-change impacts but also an opportunity to reduce inequality and development gaps, to achieve dynamic economies and to regulate the sustainable use and transformation of the territory.

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Frequently Asked Questions

FAQ 12.1 | How are inequality and poverty limiting options to adapt to climate change in Central and South America?

Poverty and inequality decrease human capacity to adapt to climate change. Limited access to resources may reduce the ability of individuals, households and societies to adapt to the impacts of climate change and variability because of the narrow response portfolio. Inequality limits responses available to vulnerable segments as most adaptation options are resource-dependent.

Though poverty in Central and South America has decreased over the last 12 years, inequality remains as a historic and structural characteristic of the region. In 2018, 29.5% of Latin America's population (including Mexico) were poor (182 million) and 10.2% were extremely poor (63 million), more than half of them living in urban areas. In 2020, due to COVID crisis Gini coefficient projection of increases is ranging from 1.1% to 7.8%, poverty increased to 33.7% (209 millions) and extreme poverty to 12.5% (78 millions).

Poor populations have little or no access to good-quality education, information, health systems and financial services. They have fewer chances to access resources, such as land and water, good-quality housing, risk-reducing infrastructure, and services, such as running water, sanitation and drainage. Their lack of political clout and endowments limits their access to assets for withstanding and recovering from shocks and stresses. Poverty, inequality and high vulnerability to the impacts of climate change are interrelated processes. Poor populations are highly vulnerable to the impacts of climate change and are usually located in areas of high exposure to extreme events. The constant loss of assets and livelihoods in both urban and rural areas drives communities into chronic poverty traps, exacerbating local poverty cycles and creating new ones.

For instance, climate-related reduced yields in crops, fisheries and aquaculture have a substantial impact on the livelihoods and food security of families and affect their options for coping with and adapting to climate change and variability. The impact of climate change in agriculture for CSA depends on determinants such as the availability of natural resources, access to markets, diversity of inputs and production methods, quality and coverage of infrastructure and socioeconomic characteristics of the population. Impacts from climate change on small-scale farmers compromise the livelihoods and food security of rural areas and, consequently, the food supply for urban areas.

Governments in the region have implemented several poverty-reduction programmes. However, policies of income redistribution and poverty alleviation do not necessarily improve climate risk management, so complementary policies integrating both social and material conditions are required. A study in northern Brazil showed that risk management strategies for droughts and food insecurity did not change poverty rates between 1997–1998 and 2011–2012. Major shocks, such as climate and extreme weather events (e.g., floods, heavy rains, droughts, frost), reduce and destroy public and private property. For instance, the ENSO event of 2017 in Peru caused losses estimated between USD 6 and 9 billion, affected more than a million inhabitants and generated 370,000 new poor. In total, losses by unemployment, deaths, destruction and damage to infrastructure and houses were around 1.3% of the GDP of Peru.

Low government spending on social infrastructure (e.g., health, education), ethnic discrimination and social exclusion reduce healthcare access, leaving poor people in entire regions mostly undiagnosed or untreated. In a context of privatisation policies of healthcare systems, research shows that marginal people lack identifying documents needed to access public services in Buenos Aires (Argentina), Mexico City (Mexico) and Santiago de Chile (Chile), some of the most developed cities in the region. The consequences of this situation are underreporting, low diagnosis and low treatment of diseases such as vector-borne diseases such as dengue and risk of diarrhoeal diseases originating from frequent flooding in Amazonian riverine communities. Bias in reporting on access to healthcare and the incidence of diseases in marginal populations is usually region-dependent. For example, in Brazil's Amazonian north in 2018, there were 2.2 medical doctors per 1000 inhabitants, while 4.95 medical doctors per 1000 inhabitants and 9.52 doctors in São Paulo and Santa Catarina respectively. Another example is pregnant women in remote Amazonian municipalities, who receive less prenatal care than women in urban areas. These social inequities underlie systemic biases in health data quality, hindering reliable estimation of disease burdens such as the distribution of disease or birth and death registrations. For example, in Guatemala, alternative Indigenous healthcare systems are responding to local needs in Mayan communities. However, this remains unrecognised. The existence of health institutions based on IK can reinforce the lack of universal coverage by central government healthcare, addressing the miscalculation of morbidity, mortality and cause of death among disadvantaged groups.

FAQ 12.1 (continued)

Inequality, informality and precariousness are particularly relevant barriers to adaptation. A significant part of the construction sector in the region is informal and does not follow regulations for land use and construction safety codes, and there is a lack of public strategies for housing access. Adaptive construction is based on up-to-date regulation and codes, appropriate design and materials, and access to infrastructure and services. Decreasing inequality and eradicating poverty are crucial for achieving proper adaptation to climate change in the region. Some anti-poverty initiatives, such as savings groups, microfinance for improving housing or assets and community enterprises, may also support specific adaptive measures. These mechanisms should be widely accessible to poor groups and be complemented by comprehensive poverty alleviation programmes that include climate-change adaptation.

Frequently Asked Questions

FAQ 12.2 | How have urban areas in Central and South America adapted to climate change so far, which further actions should be considered within the next decades and what are the limits of adaptation and sustainability?

Cities are becoming focal points for climate-change impacts. Rapid urbanisation in CSA, together with accelerating demand for housing, resource supplies and social and health services, has put pressure on the already stretched physical and social infrastructure. In addition, migration is negatively affecting the opportunities of cities to adapt to climate change.

CSA is the second most urbanised region in the world after North America, with 81% of its population being urban. In addition, 129 secondary cities with 500,000 inhabitants are home to half of the region's urban population (222 million). Another 65 million people live in megacities of over 10 million each. The population migrates among cities, resulting in more secondary cities and creating mega regions and urban corridors.

Rapid growth in cities has increased the urban informal housing sector (e.g., slums, marginal human settlements and others), which increased from 6% to 26% of the total residences from 1990 to 2015. Coastal areas in CSA increasingly concentrate more urban centres. Researchers indicate that between 3 and 4 million inhabitants will experience coastal flooding and erosion from SLR in all emission scenarios by 2100 considering South America alone.

A study on cities with more than 100,000 inhabitants showed that the number of coastal cities significantly increased from 42 to 420 between 1945 and 2014; they are located close to fragile ecosystems such as bays, estuaries and mangrove forests, resulting in higher concentrations of population and economic activities. This process degraded the ability of coastal ecosystems, such as mangroves, to reduce risks and provide essential ecosystem services, which help to prevent coastal erosion or maintain fish stocks. Moreover, it reduced ports and tourism, along with income opportunities.

Climate-change impacts on cities in CSA are strongly influenced by ENSO, which is associated with an increase in more-extreme rainfall events. Urban areas are increasingly dealing with floods, landslides, storms, TCs, water stress, fires, spread of vector-borne and infectious diseases, damaging infrastructure, economic activities, built and natural environments and the population's overall well-being.

Glacier retreat in the mountains will affect water runoff and water provision to metropolitan areas such as Lima, La Paz, Quito and Santiago, which rely on rivers that originate in the high Andes. Lima, the second driest capital city in the world, is vulnerable to drought and heavy rain peak events associated with climate change. In Bogota, lower precipitation levels and a tendency towards increasing extreme events are expected in the coming decades. Hence, the protection of fragile ecosystems such as paramo (fields at 3000 to 4000 MASL) will be crucial for supplying water to the city.

SLR impacts cities located in LECZs, not only because of direct coastal flooding, coastal erosion and subsidence, but also because it aggravates the impact of storm surges, heat wave energy and saltwater intrusion. In Suriname and Guyana 68% and 31% of the population respectively live below 5 MASL, while many sectors of Georgetown, the capital of Guyana, are below sea level. Floods with increased frequency and severity of storm surges will also impact the River Plate estuary and lower delta of the Parana River where metropolitan Buenos Aires is located.

FAQ 12.2 (continued)

Over 80% of losses associated with climate-related risks are concentrated in urban areas, and between 40% and 70% of losses occur in cities with less than 100,000 inhabitants, most likely as a result of limited capacities to manage disaster risks and low levels of investment.

Despite consistent political and economic barriers, many cities in the region have adopted sustainable local development agendas, which work to bring about balanced urban development. The shortcomings of poor development patterns remain prominently on display in cities and present important obstacles to adaptation investment, as public investment in basic needs (mainly housing and sanitation) must be prioritised.

Cities struggle to address the immediate needs of their population while addressing longer-term needs associated with climate adaptation, emissions reduction and sustainable development. Some cities are moving forward to transformative adaptation, addressing drivers of vulnerability, building robust systems and anticipating impacts. Besides government-led adaptation planning and action, individuals, communities and enterprises have been incrementally adapting to climate change autonomously over time. Municipalities from Argentina, Peru, Chile, Equator, Brazil and Costa Rica are developing and implementing their Local Climate Action Plans, experimenting with and revealing best practices in adaptation. Both anticipatory adaptation measures—choosing safe locations, building structurally safe houses, choosing elevated places to store valuables, building on stilts—and reactive adaptation measures are used, the latter incorporating measures such as relocation, slope stabilisation, afforestation and greening of riverbanks. With variations, these cities have included mechanisms to work across sectors and actors on the understanding that it is collective planning and actions that will ensure that long-term programmes continue independently of particular city administrations.

Cities are interconnected systems operating beyond administrative boundaries. Improved collaboration and coordination are needed for integrated responses. Aside from good planning, cities need access to external adaptation funds. Climate-change adaptation requires long-term funding and investments, which are beyond cyclical political considerations. It is crucial to rethink how to ensure that international adaptation funds will reach cities and innovate. For example, member cities of Global Covenant of Mayors for Climate & Energy in the region, together with Cities for Life Forum in Peru, the Red Argentina de Municipios por el Cambio Climático (RAMCC), the Capital Cities of the Americas facing Climate Change (CC35) and others, are pursuing this goal and applying directly for international grants. New funding sources are required to help local governments and civil society. Cities and locally driven adaptation initiatives can be funded by national governments and international organisations.

Frequently Asked Questions

FAQ 12.3 | How do climatic events and conditions affect migration and displacement in Central and South America, will this change due to climate change, and how can communities adapt?

Migration and displacements associated with climatic hazards are becoming more frequent in CSA, and they are expected to continue to increase. These complex processes require comprehensive actions in their places of origin and reception, to improve both adaptation in more affected places and the conditions of mobilisation.

The migration, voluntary and involuntary, of individuals, families and groups is common in CSA. People migrate nationally and internationally, temporarily or permanently, predominantly from rural areas—often immersed in poverty—to urban areas. Common social drivers of migration in the region are the economy, politics, land tenure and land management change, lack of access to markets, lack of infrastructure, and violence; environmental drivers include loss of water, crops and livestock, land degradation and sudden or gradual onset of climate hazards.

The increasing frequency and magnitude of droughts, tropical storms, hurricanes and heavy rains producing landslides and floods have amplified internal movements, overall rural to urban. For instance, rural-to-urban migration in northern Brazil and international migration from Guatemala, Honduras and El Salvador to North America are partly a consequence of prolonged droughts, which have increased the stress of food availability in these highly impoverished regions. Diminished access to water is also a result of privatisation of that resource. In CA, the majority of migrants are young men, reducing the labour force in their places of origin. However, the

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FAQ 12.3 (continued)

migrants send back substantial amounts of money, which have become the main source of foreign exchange for their countries and the main source of income for their families.

Because poor people have fewer resources to adapt to changing conditions, they are usually the most impacted by climate hazards since they are already struggling to survive under normal conditions. These populations are the most likely to migrate, chiefly because of the loss of their livelihoods, their precarious housing and settlements and the lack of money and international aid. Other important factors are the minimal governmental support and assistance through social safety nets and extension services, the scarcity and low quality of education and health services, their isolation and marginality and the insecurity of land rights. These same conditions, though, may hinder their mobility or even render them immobile. Nevertheless, in some cases, despite worsening conditions, people decide not to move.

The magnitude and frequency of droughts and hurricanes are projected to keep increasing by 2050, which may force millions of people to leave their homes. Climate models show some dry regions becoming even dryer in the coming decades, increasing the stress on small farmers who rely on rainfall to water their fields. Glacier retreat and water scarcity are becoming strong drivers of migration in the Andes. SLR affects activities such as fishing and tourism, which will foster further migration. In Brazil, at least 0.9 million more people will migrate interregionally under future climate conditions.

Addressing migration and displacement requires diverse interventions: in dry regions it is recommended to improve water management in the places of origin of migration, including storage, distribution and irrigation. Wet regions, lowlands and floodplains will benefit from preventing construction in areas prone to landslides and flooding. Government and international aid are also important for improving people's options to adapt and enhance their resilience to climate impacts. In northern Brazil, for example, government financial support has significantly reduced drought-related migration. There exists between Guatemala and Canada a temporary migration programme to bring in migrant workers during the harvest season. The United States is also increasing these types of legal temporary migration.

Frequently Asked Questions

FAQ 12.4 | How is climate change impacting and how is it expected to impact food production in Central and South America in the next 30 years, and what effective adaptation strategies are and can be adopted in the region?

Agriculture is a fundamental sector in the development of societies from economic and social perspectives, and so it is a major component of CSA countries' adaptive strategies. Implementation of sustainable agriculture practices, such as improved management on native grasslands or agroforestry systems for crop and livestock production, can increase productivity while improving adaptability.

Over the last two decades, countries throughout CSA have been developing rapidly. The agricultural sector is fundamental to this development from economic and social perspectives. Some countries in the region are major global food exporters:

- Corn: three of the top 10 exporters are Brazil, Argentina and Paraguay;
- Soybean exports: Brazil and Argentina are among the top 5 and Paraguay and Bolivia rank in the top 12;
- Coffee exports: 5 of the top 10 export countries are Brazil, Colombia, Honduras, Peru and Guatemala;
- Fruits: 2 of the top 10 fresh fruit exporting countries are Chile and Ecuador;
- Fishmeal exports globally are led by Peru, Chile and Ecuador;
- Beef: four of the top exporting countries are from this region: Brazil, Argentina, Uruguay and Paraguay.

CSA is among the regions with the highest potential to increase food supplies, particularly to more densely populated regions in Asia, the Middle East and Europe. A better understanding of the impact of the economy on the environment and the contribution of the environment to the economy is critical for identifying opportunities for innovation and promoting activities that could lead to sustainable economic growth without depleting natural resources and increasing sensitivity to climate change and climate variability. The consideration of food as a commodity instead of a common resource leads to the accumulation of underpriced food resources at the expense

FAQ 12.4 (continued)

of natural capital. Without serious emissions reduction measures, climate models project an average 1°C to 4°C increase in maximum temperatures and a 30% decrease in rainfall up to 2050, across CSA. Tropical SA is projected to warm at higher rates than the southern part of SA. Given these circumstances, some regions in CSA (Andes region and CA) will just meet or fall below the critical food supply/demand ratio for their population. Meanwhile, the temperate southern-most region of SA is projected to have agricultural production surplus. The challenge for this region will be to retain the ability to feed and adequately nourish its internal population as well as make an important contribution to food supplies available to the rest of the world.

The NDCs of most CSA countries expressly include agriculture as a major component of their adaptive strategy. From the recommendations presented, five general adaptive themes, or imperatives, emerge: (a) inclusion of climate-change projections as a key element for ministries of agriculture and research institutes in their decision-making processes, (b) support of research on and adoption of drought- and heat-tolerant crop varieties, (c) promotion of sustainable irrigation as an effective adaptive strategy, (d) recovery of degraded lands and sustainable intensification of agriculture to prevent further deforestation, and (e) implementation of climate-smart practices and technologies to increase productivity while improving adaptability.

Climate-smart practices provide a framework to operationalise actions aimed at understanding synergies among productivity, adaptation and mitigation. A significant amount of evidence supports the potential for climate-smart-practice technologies to produce such triple wins as natural pastoral systems in the southern region of SA. Such systems allow for the combination of food production and environmental sustainability. The production of meat based on native grasslands with grazing management that optimises forage allowance can achieve high production levels while providing multiple ecosystem benefits. Optimal forage allowance means offering animals enough forage in order to meet requirements while avoiding overgrazing. This management practice simultaneously increases productivity, reduces GHG emissions while improving soil carbon sequestration and minimises other environmental impacts such as excess of nutrients, fossil-based energy use and biodiversity loss. Pastoral farming systems that manage grazing and feeding efficiently are an example of the integration of food security, environmental conservation and nature-based adaptation to climate change.

Agroforestry systems are present in the tropical region of CSA. Trees are present in a large part of the agricultural landscape of this region, either dispersed or in lines, supporting the production of coffee, cocoa, fruits, pastures and livestock in various agroforestry configurations. In CA, shade-grown coffee reduces weed control and improves the quality and taste of the product. Agroforestry uses nitrogen-fixing trees (*Leguminosae*), such as *Leucaena* in Colombia and *Inga* in Brazil, to restore soil nitrogen fertility. Tropical forest soils are generally nutrient-poor and unsuited to long-term agricultural use. Land converted to agriculture by cutting and burning natural vegetation tends to remain productive for only a few years. Agroforestry and so-called silvopastoral systems, which incorporate trees into crop and livestock systems, have been shown to have a dramatic impact on the maintenance and restoration of long-term productivity in agricultural landscapes, including degraded and abandoned land. Agroforestry systems can provide major benefits through enhanced food security, stronger local economies and increased ecosystem services such as carbon storage, regulation of climate and water cycles, control of pests and diseases and maintenance of soil fertility. Because of these multiple goods and services, agroforestry practices are considered one of the key strategies for the development of climate-smart agriculture.

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Frequently Asked Questions

FAQ 12.5 | How can Indigenous knowledge and practices contribute to adaptation initiatives in Central and South America?

Indigenous Peoples have knowledge systems and practices that allow them to adapt to many climatic changes. Adaptation initiatives based on IK and practices are more sustainable and legitimate among local communities. It is important to build effective and respectful partnerships among Indigenous and non–Indigenous researchers to co-produce climate-relevant knowledge to enhance adaptation planning and action in the region.

There are 28 million Indigenous Peoples in CSA (around 6.6% of the total population of the region). They belong to more than 800 groups living in territories covering a wide range of ecosystems—from drylands to tropical rainforests to savannahs, coasts to mountains—and that share the land with many other cultural and ethnic groups. In the region, Indigenous Peoples are often categorised as groups that are highly vulnerable to climate change because they are frequently affected by socioeconomic inequalities and the dominance of external powers. They often experience internal and external pressures on their communal lands in the forms of pollution, oil and mining, industrial agriculture and urbanisation. On the other hand, it is important to recognise that Indigenous Peoples have knowledge systems and practices that allow them to adapt to many climatic changes. Increasing scientific evidence shows that adaptation initiatives based on Indigenous knowledge and practices are more sustainable and legitimate among local communities.

The wide range of adaptation practices based on IK in the region include, among others, increasing species and genetic diversity in agricultural systems through community seed exchanges; promotion of highly diverse crop systems; ancient systems to collect and conserve water; fire prevention strategies; observing and monitoring changes in communal ecological–agricultural calendar cycles; recognising changes in ecological indicators like migration patterns in birds, the behaviour of insects and other invertebrates and the phenology of fruit and flowering species; and systematisation and knowledge exchange among communities. These practices represent a valuable cultural and biological heritage.

The Kichwa in the Ecuadorian Amazon cultivate Chakras (plots) within the rainforest. These plots combine crops and medicinal herbs for both self-consumption and selling. Similar systems, like the Chakras in the high Andes, the Milpas in CA, and the Conucos in northern SA, have been resilient to social and environmental disturbances due to their outstanding agrobiodiversity (more than 40 species and varieties can be present in one plot), microhabitat management and the associated knowledge and institutions.

Traditional fire management among Indigenous Peoples of Venezuela, Brazil and Guyana is another adaptation strategy based on a fine-tuned understanding of environmental indicators associated with their culture and worldviews. In these countries, Indigenous lands have the lowest incidence of wildfires, significantly contributing to maintaining and enhancing biodiversity. These traditional practices have helped to prevent large-scale and destructive wildfires, reducing the risks posed by rising temperature and dryness due to climate change.

The traditional agriculture of Mapuche Indigenous Peoples in Chile includes a series of practices that result in a system that is more resilient to climate and non-climate stressors. Practices include water management, native seed conservation and exchange with other producers (trafkintu), crop rotation, polyculture and tree–crop association. Similar practices can be found in Mayan communities in Guatemala at the other end of the sub-continent.

Despite the increasing recognition and integration of IK in adaptation practices and policies in the region, important barriers for a more effective and transformative integration remain. Some of the most relevant barriers include limited participation of Indigenous Peoples and local communities in adaptation planning and the lack of sufficient consideration of non-climatic socioeconomic drivers of vulnerability such as poverty and inequality. Also, scientific knowledge is commonly prioritised over traditional IKLK. However, some transformative efforts are emerging. Bolivian Indigenous organisations represent a notable example by contesting normative conceptions of development as economic growth and replacing them with more comprehensive views like harmony with Mother Earth and 'Sumak Kawsay' or 'Good Living'.

Several strategies have been proposed to overcome existing barriers, including building effective and respectful partnerships among Indigenous and non-Indigenous researchers, co-producing climate-change-relevant knowledge and recognising Indigenous Peoples as active participants in the continual development of autonomous strategies to preserve their practices, beliefs and knowledge. The implementation of these and other strategies can significantly enhance adaptation planning and action in the region.

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