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TOPICAL REVIEW

Climate change-related risks and adaptation potential in Central and South America during the 21st century

I Hagen[1,*] ![iD], C Huggel[1] ![iD], L Ramajo[2,3,4] ![iD], N Chacón[5] ![iD], J P Ometto[6] ![iD], J C Postigo[7] ![iD] and E J Castellanos[8] ![iD]

[1] University of Zurich, Zurich, Switzerland
[2] Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Coquimbo, Chile
[3] Departamento de Biologia Marina, Facultad de Ciencias del Mar, Universidad Católica del Norte, Coquimbo, Chile
[4] Centro de Ciencia del Clima y la Resiliencia (CR2), Santiago, Chile
[5] Venezuelan Institute for Scientific Research, Caracas, Venezuela
[6] National Institute for Space Research (INPE), São José dos Campos, Brazil
[7] Indiana University, Bloomington, United States of America
[8] Universidad del Valle de Guatemala, Guatemala, Guatemala
* Author to whom any correspondence should be addressed.

E-mail: Isabel.hagen@geo.uzh.ch

Abstract

Climate-related risks in Central and South America have received increased attention and concern in science and policy, but an up-to-date comprehensive review and synthesis of risks and adaptation potential is currently missing. For this paper we evaluated over 200 peer-reviewed articles and grey literature documents published since 2012. We found that climate change in Central and South America during the 21st century may increase the risk to severe levels for the following topical risk clusters: (a) Food insecurity; (b) Floods and landslides; (c) Water scarcity; (d) Epidemics of vector-borne diseases; (e) Amazon Forest biome shift; (f). Coral bleaching; (g) Coastal risks of sea level rise, storm surges and erosion; (h) Systemic failure due to cascading impacts of hazards and epidemics. Our synthesis also identified feasible adaptation measures for each risk. The impacts of the risks will be heterogeneous throughout the region, with rural communities, Indigenous peoples, Afro-Latin Americans, women, disabled people, and migrants identified as being the most severely affected. We refer to a number of adaptation options for each risk. However, unabated climate change together with low adaptive capacity will strictly limit adaptation options. Immediate strengthening of policies for building adaptive capacity and increase of research on the risk-adaptation nexus in Central and South America are paramount. Our findings might contribute to guide the adjustment and emphasis of adaptation policies and climate risk management strategies from local to national level.

1. Introduction and background

The unprecedented speed, magnitude, and impacts of climate change are often perceived to contrast with the political responses in the making of the climate crisis (Wilson and Orlove 2021). Risks are dynamic because they involve both hazards and their impacts. Understanding dynamic climate-driven risks is fundamental to inform decision-makers (Simpson *et al* 2021). Furthermore, providing adaptation options for each risk is the next step in the science-policy interface, particularly in regions with prevalent socio-economic vulnerabilities like Central and South America that are projected to face dramatic climatic changes during the 21st century (Ranasinghe *et al* 2021).

Central America and South America are projected to experience a 1.8 °–3.9 °C and 1.9 °–5.0 °C warming by 2100, respectively (with Coupled Model Intercomparison Project 6 (CMIP6) models and depending on the emissions scenario SSP1-2.6 to SSP5-8.5), compared to pre-industrial levels (Gutiérrez *et al* 2021). Climate change is already affecting the entire region in different ways. Physical changes include increased magnitude and frequency of hazards such as landslides and floods (Alfieri *et al* 2017, Moreiras and Pont 2017, Hirabayashi *et al* 2021), increase in extreme droughts and aridification in some places

(Marengo and Bernasconi 2015, Zambrano *et al* 2016, Hannah *et al* 2017, Garreaud *et al* 2020), and extreme precipitation, including more frequent tropical cyclones and storms, in others (Galindo *et al* 2010, Bindoff *et al* 2013, Barrett *et al* 2016, Vicencio *et al* 2021). The Amazon Forest is under risk of converting into a different biome and transforming from a carbon sink into a carbon source (Aguiar *et al* 2016, Qin *et al* 2021, SPA (Science Panel for the Amazon) 2021). In the Tropical Andes glaciers are melting at an unprecedented speed, eventually leading to reduced water supply and increased water scarcity for mountain communities (Rabatel *et al* 2013, Dussaillant *et al* 2019, Masiokas *et al* 2020). The coasts are facing issues from sea level rise and storm surges (Losada *et al* 2013, Reguero *et al* 2015), and coral reefs are suffering increasing bleaching events (Li and Reidenbach 2014, de Oliveira Soares *et al* 2019, Duarte *et al* 2020). The spread of epidemics, in particular vector-borne diseases, have been observed to increase with climate change (Confalonieri *et al* 2014, Nava *et al* 2017, Garrido *et al* 2019, Ellwanger *et al* 2020, Petrova *et al* 2020). When several events occur simultaneously or after one another, they are referred to as cascading risks. Cascading risks can lead to failure of infrastructure and stress public service systems beyond their capacities (Simpson *et al* 2021). All the mentioned climate-related changes have serious impacts for the 478 million people living in Central and South America. The most severe consequences will occur for particularly vulnerable groups (Magrin *et al* 2014).

Reviews of climate-risks in the region are neither recent nor abundant. Although chapter 27 of the IPCC 5th assessment report (Magrin *et al* 2014) identified climatic stressors, adaptation opportunities and limits in Central and South America, it chiefly relied on literature published before 2013, excluding important research efforts since. Building on Schellnhuber *et al* (2014), Reyer *et al* (2017) carried out a comprehensive review of peer-reviewed literature of climate-risks and impacts in Latin America (Central and South America, and Mexico). However, the authors did not include an assessment and analysis of relevant adaptation measures available at the time for each risk.
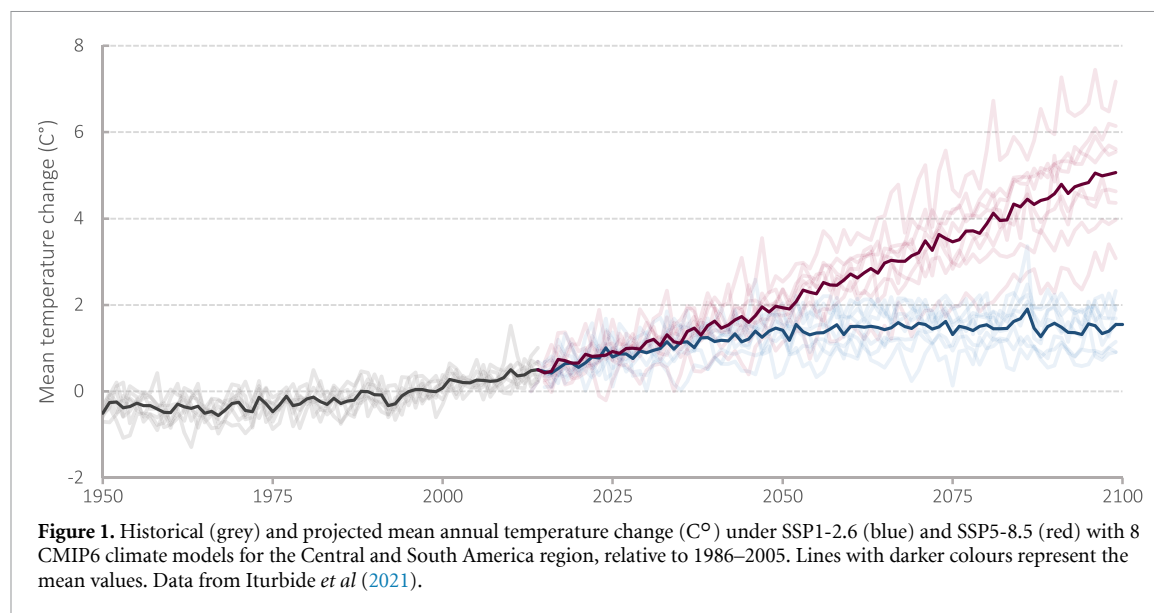
The prominence of climate change has incentivised research, leading to soaring numbers of publications. In addition to increasing peer-reviewed literature, reports from international organisations and NGOs such as CEPAL (2018) and RIOCCADAPT (Moreno *et al* 2020), and from national agencies (INAIGEM (Instituto National de Investigacion en Glaciares y Ecosistemas de Montaña) 2018, MMA (Ministerio del Medio Ambiente) 2019) are available, and there is a need for analysis and assessment of these reports in peer-reviewed literature.

Here we present a much needed comprehensive and up-to-date synthesis of current and future climate-related risks together with an analysis of the adaptation potential. This paper is timely considering the severity of climate change impacts and the urgency for action in the region. Based on a scoping process performed by experts together with a literature review, we identified eight risks in Central and South America that have the potential to become severe with climate change during the 21st century. We draw upon a review of peer-reviewed and grey literature to examine the current and projected state of each of the risks under different levels of global warming. In addition, we synthesise already implemented and feasible future adaptation measures for each of the risks. We mainly include literature published after the 5th IPCC report, to build on this report and substantially review the most recent and relevant studies of climate change risks in the region.

2. Methods

This study used a combination of a review methodology and expert knowledge to identify, characterise, and evaluate the most severe climate-risks and their status in Central and South America. The criteria for a severe risk relate to the number of people potentially affected, the severity of the negative effects of the risk, the importance of the affected systems, and the irreversibility versus potential to reduce the risk (O'Neill *et al* 2017b). First, a scoping process was performed by experts from different fields in the region. Their fields of expertise include terrestrial and marine ecosystems, natural hazards, water resources, food systems, cultural, social, and political systems. Though based upon the global key risks defined in Oppenheimer *et al* (2014) and O'Neill *et al* (2017b), our scoping adapted the risks to the specific conditions in Central and South America, resulting in eight distinct topical risk clusters: (a) Food insecurity; (b) Floods and landslides; (c) Water scarcity; (d) Epidemics of vector-borne diseases; (e) Amazon biome shift; (f) Coral bleaching; (g) Coastal risks from sea level rise, erosion and storm surges; and (h) Risk of systemic failure. Based on this, specific keywords for each risk cluster were used to complete a thorough literature search to identify relevant peer-reviewed articles. The search string was based on the following key words: 'risk', 'hazard', 'exposure', 'vulnerability', 'Central America', 'South America'. 'Latin America', and 'climate change projections', together with words specific for each risk cluster. I.e. risk 1—drought, aridification; risk 2—landslide, flood; risk 3—water scarcity, glacier retreat; risk 4—epidemic, vector-borne, disease; risk 5—Amazon, deforestation, ecologic*; risk 6—coral bleaching, sea surface temperature (SST), Mesoamerican Reef; risk 7—sea level rise, storm surge, erosion; risk 8—cascading, compound risk, systemic, infrastructure, public service system. The academic search engines used were Google Scholar, Scopus and Science Direct. Relevant journals included Nature, Science, Regional

Figure 1. Historical (grey) and projected mean annual temperature change (C°) under SSP1-2.6 (blue) and SSP5-8.5 (red) with 8 CMIP6 climate models for the Central and South America region, relative to 1986–2005. Lines with darker colours represent the mean values. Data from Iturbide *et al* (2021).

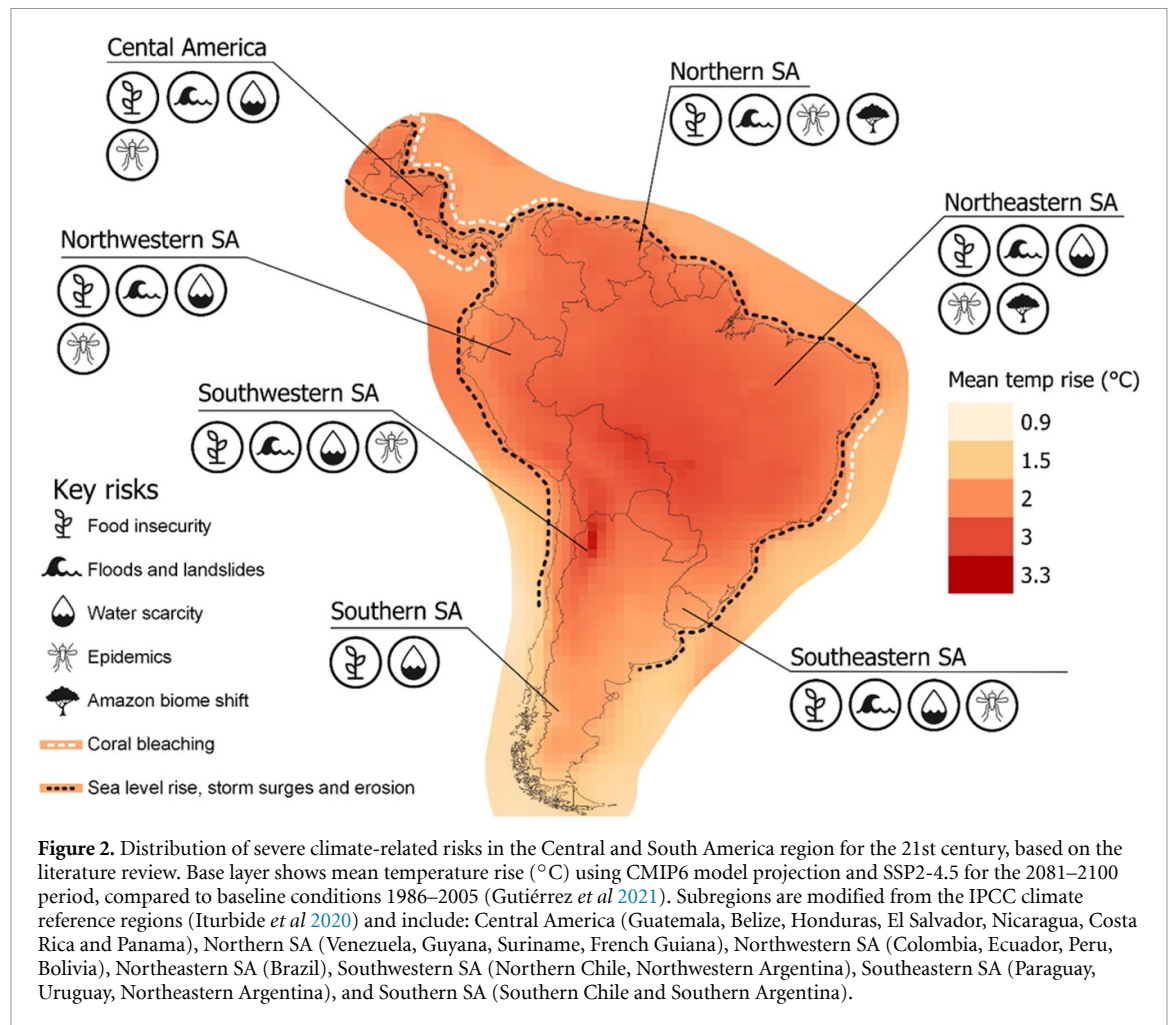Environmental Change, PLOS, Global and Planetary Change, among others.

Many subregions, particularly Central America, had a limited number of peer-reviewed articles. Considering that a large fraction of the information about these subregions was published in grey literature, we decided to include this type of documents in addition to peer-reviewed articles. To select grey literature, we elaborated a list of relevant international, regional, and national organisations and government agencies, and systematically searched for relevant reports on the topic. This was complemented by systematic Google Scholar searches with inclusion of the same search strings used for the peer-reviewed articles. The date of the last literature search was 2021-08-31 and the search was executed from Switzerland. Where literature did not use the geographical boundaries of the Central and South America region but rather Latin America or Meso-America (southern Mexico, Belize, Guatemala, El Salvador, Honduras, Nicaragua, and Costa Rica), we have included this information.

Some inclusion and exclusion criteria were adopted before and after the literature search. The peer-reviewed articles and grey literature had to be published between 2012 and 2021 (exceptions were made where the literature had substantial influence and/or was still highly relevant), cover at least one of the eight risk clusters, have a specific focus on the region Central and South America or a subregion, and mention climate change. A specific focus was also brought to risks under climate projections for the 21st century. After the search process, titles and abstracts were first reviewed, and unsuitable papers were removed before a second review of the full article was done. In total, 184 peer-reviewed articles and 25 grey literature documents were ultimately identified and utilised in the study.

Data extraction focused on information about (a) the geographic region, (b) hazard metric covered (e.g.

mm yearly sea level rise, % decline in annual precipitation, % increase in max 5 day precipitation), (c) climate scenarios used (see section 3). (d) If a climate model was used, the projected global warming level relative to pre-industrial temperatures was extracted. Also, (d) socio-economic conditions in the region (or subregion), (e) current and/or future adaptation measures, (f) risk metrics, (g) exposure metrics, (h) vulnerability metrics, and, (i) risk or impact outcome (quantitatively or qualitatively) were extracted. The information extracted from all studies was systematically compiled in matrices with risks in the rows and the above categories (a–i) in the columns. Then, the studies were systematically compared per category and risk, and quality and confidence assessed. Based on which a consistent synthesis was produced. In each of the eight risk sections, the first paragraph covers an introduction of the risk and its socio-economic implications, the second paragraph the current risk conditions on a global, regional and local scale, and the last paragraph(s) the projected risk landscape on a global, regional and local scale (if data was available).

Climate data of mean temperature change until 2100 in Central and South America, including historical data and from climate scenarios SSP1-2.6 and SSP5-8.5 from eight CMIP6 models, was retrieved from Iturbide *et al* (2021) and utilised in figure 1. In creating figure 2, mean temperature change projections from CMIP6 models from Gutiérrez *et al* (2021) were used, and the distribution of risks across the region was derived from a combination of expert knowledge and information that emerged from the literature review. Subregions were modified from the IPCC climate reference regions (Iturbide *et al* 2020), to preserve country borders (with the exception of Chile and Argentina). Icons were used from the Noun project (https://thenounproject.com/). The adaptation measures included in table 1 were derived from the literature review. The literature supporting the

Figure 2. Distribution of severe climate-related risks in the Central and South America region for the 21st century, based on the literature review. Base layer shows mean temperature rise (°C) using CMIP6 model projection and SSP2-4.5 for the 2081–2100 period, compared to baseline conditions 1986–2005 (Gutiérrez *et al* 2021). Subregions are modified from the IPCC climate reference regions (Iturbide *et al* 2020) and include: Central America (Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica and Panama), Northern SA (Venezuela, Guyana, Suriname, French Guiana), Northwestern SA (Colombia, Ecuador, Peru, Bolivia), Northeastern SA (Brazil), Southwestern SA (Northern Chile, Northwestern Argentina), Southeastern SA (Paraguay, Uruguay, Northeastern Argentina), and Southern SA (Southern Chile and Southern Argentina).

adaptation measures are included in the third column of table 1. The interconnections between risks displayed in figure 3 emerged from the literature review, as did the nine adaptation measures which can be applicable to more than one risk (figure 4). The background information, including supporting literature, for figures 3 and 4 was summarized in tables A1 and A2 in the appendix.

3. Socio-economic and climatic conditions and scenarios for the region

Central and South America have populations of 50.7 million people and 428 million, respectively, with 63% and 84% of the populations being urban, making this region one of the most urbanised regions in the world (ECLAC (Economic Commission for Latin America and the Caribbean) 2021, United Nations 2019). Out of the urban population in Latin America (including Mexico) and the Caribbean, 21% live in slums (World Bank 2021). Despite poverty decreasing in every South American country except Venezuela, 32 million people are still living in extreme poverty, out of which 30 million live in rural areas (World Data Lab 2021). In Central America, 40% of the population live in poverty (CEPAL 2019).
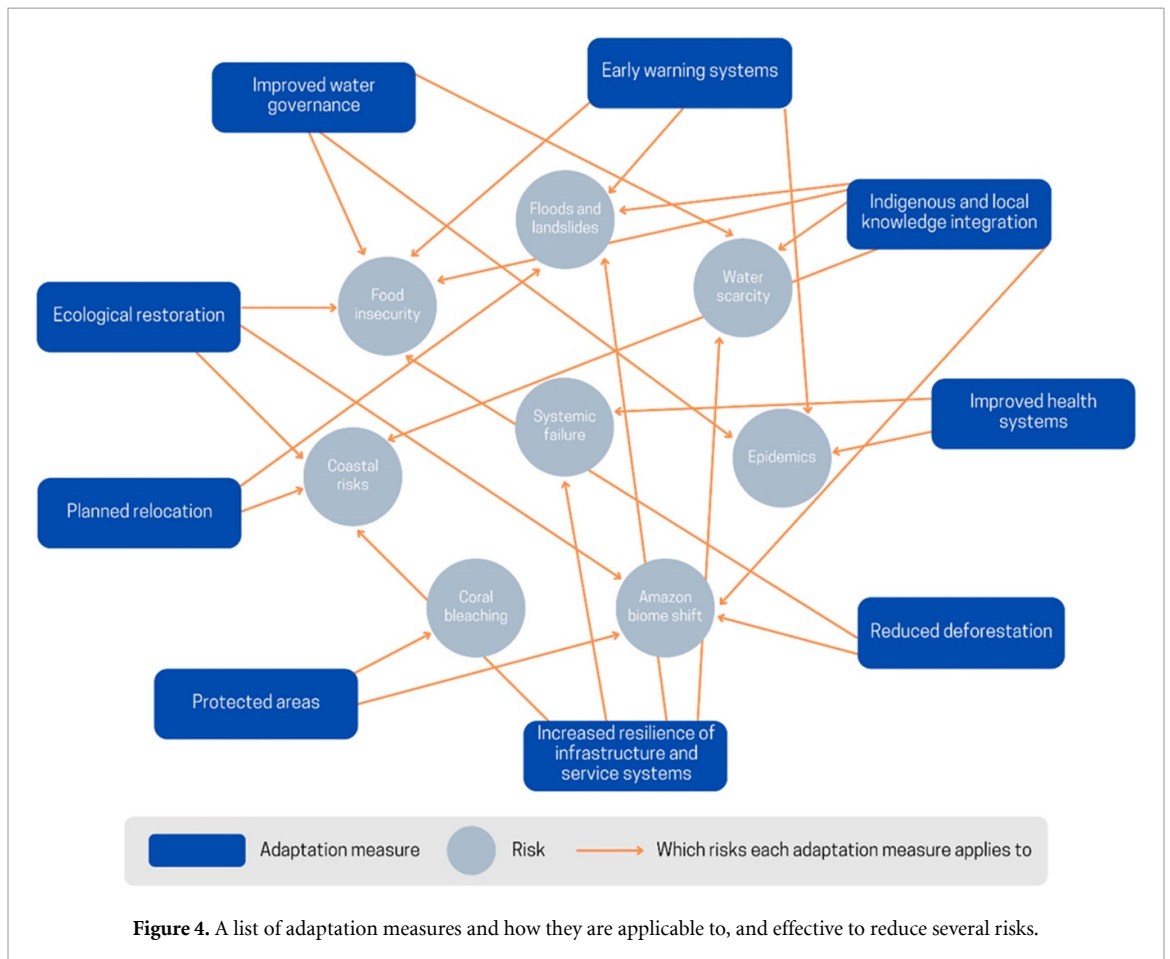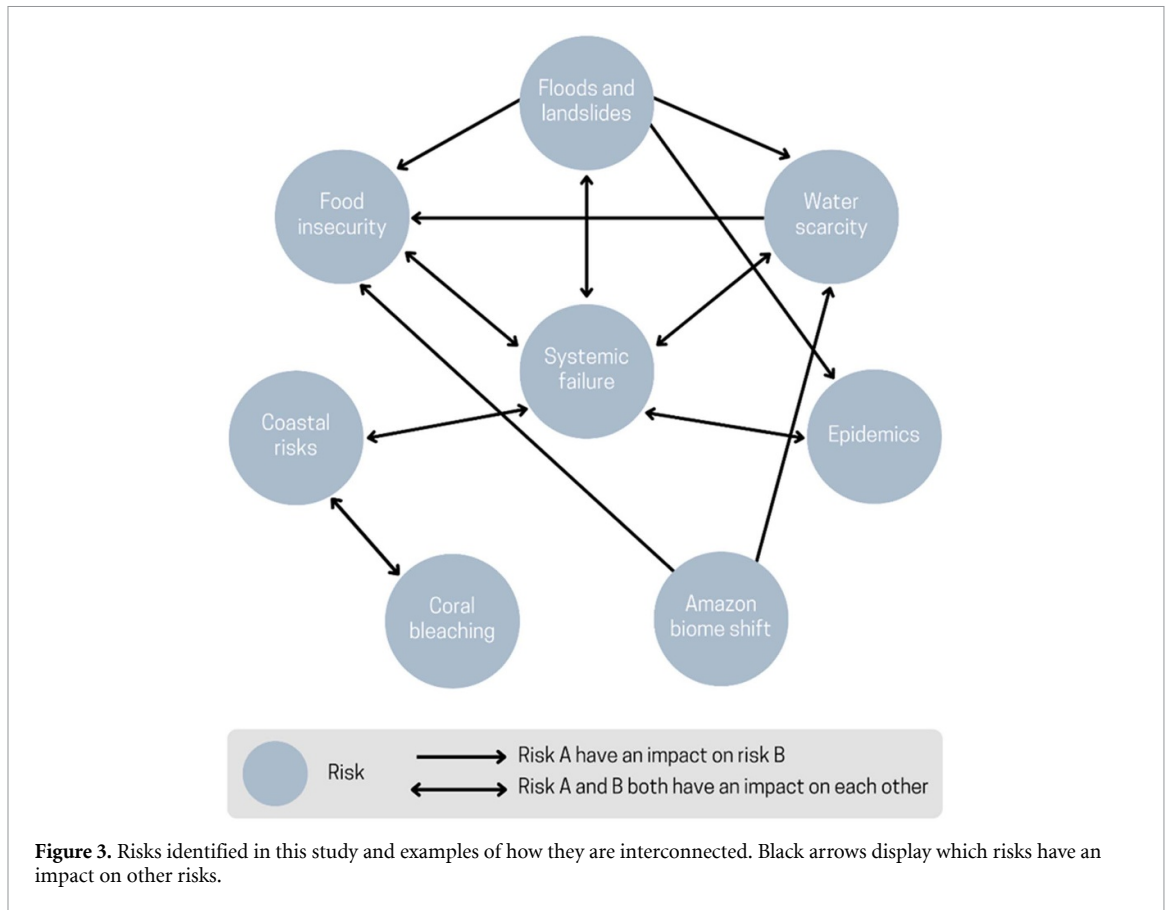
The informal employment sector is widespread, with informal employment rates of 58% in Central America and Mexico, and 51% in South America, which result in limited access to social protection and health care for a large part of workers (Bonnet *et al* 2018, Lancet 2020).

There are currently about 800 Indigenous groups in Latin America (including Mexico), making up 8% of the population. The rest of the population consists of European and African descendants since European colonisation, as well as Asian migrants (CEPAL 2014, World Bank Group 2015). Indigenous groups make up 14% of the poor and 17% of the extremely poor in Latin America. Indigenous communities often lack access to infrastructure and public service systems, as well as territorial autonomy and self-determination, and are often forced to occupy climate risk prone areas such as low-lying coastlines, steep slopes and floodplains (González 2015, World Bank Group 2015).

Severe and widespread inequalities and discrimination have led to disproportionate vulnerability to climate change for Indigenous people, Afro-Latin Americans, women, disabled people, and migrants (Yamamoto *et al* 2021, CEPAL 2019, Busso and Messina 2020). In addition, government support for

Table 1. Adaptation options for each risk and supporting literature.

Risk	Adaptation Option	References
Risk of food insecurity due to repeated and/or extreme drought conditions	• Improved water governance (storage, irrigation, recycling, reuse) • Reduced grazing pressure • Reduced deforestation and recovery of degraded land • Adoption of lucrative and drought resistant crops • Institutional support to small-scale farmers • Reduced inequalities in food production and provision systems	Barros *et al* (2015) Hannah *et al* (2017) Jat *et al* (2016) Kuzdas *et al* (2015) Marengo *et al* (2017a), Marengo *et al* (2017b) Moreno *et al* (2020) Oliveira and Hecht (2017)
Risk to life and infrastructure due to floods and landslides	• Integrated disaster risk management and land use planning • Early warning systems • Increase resilience of infrastructure and service systems • Relocation of people in high-risk areas	Aparicio-Effen *et al* (2017), Barros *et al* (2015), Drenkhan *et al* (2019), Miranda Sara *et al* (2016), Moreno *et al* (2020)
Risk of water scarcity	• Improved and just water governance considering demands from industry and domestic use • Water storage systems • Diversification of water sources (wastewater reuse, rainwater harvest) • Knowledge integration including Indigenous and local knowledge	Barros *et al* (2015), Drenkhan *et al* (2015), Gesualdo *et al* (2019), Marengo *et al* (2017a), Moreno *et al* (2020), Ostovar (2019), Rangecroft *et al* (2013), Richerzhagen *et al* (2019)
Risk of severe health effects due to increasing epidemics of vector-borne diseases	• Improved housing protection • Distributed and improved health services and infrastructure • Improved water storage and supply systems • Educational measures • Vulnerability mapping • Integrated health-climate surveillance systems	Bittencourt *et al* (2017), Colón-González *et al* (2013), Ebi and Nealon (2016), Haines and Ebi (2019), Hofmeijer *et al* (2013), Moreno *et al* (2020)
Risk of large-scale ecological transformation of the Amazon Forest	• Reduced deforestation and forest degradation, increased Reforestation • Conservation/protected areas • Community-led fire management based on Indigenous knowledge	Bebber and Butt (2017), de Moraes Falleiro *et al* (2016), Eloy *et al* (2018), Gross *et al* (2016), Moreno *et al* (2020), Nobre *et al* (2016)
Risk to coral reef ecosystems due to coral bleaching	• Managed coastal development • Reduce human stressors of pollution, fisheries, tourism • Marine protected areas	Calil *et al* (2017), Moreno *et al* (2020), Randazzo-Eisemann *et al* (2021)
Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion	• Coastal integrated management strategies • Ecological restoration, nature-based solutions • Artificial hard structures (concrete breakwaters, seawalls) • Planned relocation of people in high-risk areas	Burcharth *et al* (2015), Calil *et al* (2017), Fanning (2014), Haasnoot *et al* (2021), Moreno *et al* (2020), Morris *et al* (2018), Osorio-Cano *et al* (2019), Reguero *et al* (2019)
Risk of systemic failure by cascading impacts of hazards and epidemics overwhelming infrastructure and public service systems	• Increase of systems' resilience, based on identification of thresholds in the system and where impact cascades can be broken	Ismail-Zadeh *et al* (2016), Moreno *et al* (2020), Raymond *et al* (2020)

Figure 3. Risks identified in this study and examples of how they are interconnected. Black arrows display which risks have an impact on other risks.

Figure 4. A list of adaptation measures and how they are applicable to, and effective to reduce several risks.

climate change adaptation and recovery after climate events is not distributed fairly, and many marginalised groups are excluded from or have limited influence in political decisions surrounding climate change (Arana 2017, Moreno *et al* 2020).

The region of Central and South America has experienced a warming of 0.2 °C–0.3 °C per decade since 1980 (de Barros Soares *et al* 2017, Hidalgo *et al* 2017, Cavazos *et al* 2019). Furthermore, regional and global models in Central America show a temperature rise of 1.6 °C–2.4 °C for 2021–2050 with climate scenario representative concentration pathways (RCPs) 4.5 (Imbach *et al* 2018), and 2 °C–4 °C by 2100 for RCP 4.5 and 8.5 (Gutiérrez *et al* 2021). In South America, warming is expected to reach 2 °C–3 °C under RCP 4.5 and 3 °C–5° C under RCP 8.5 by 2100 (Llopart *et al* 2019), with strongest warming for the Amazon basin and the central Andes. Figure 1 shows projected mean annual temperature change until 2100 under climate pathways SSP1-2.6 and SSP5-8.5 for the Central and South America region.

In line with the reviewed literature, three sets of climate pathways were used in this paper. The IPCC special report on emission scenarios A1B, A2, B1 and B2 (Collins *et al* 2013); the more recently developed RCPs 2.6, 4.5, 6.0 and 8.5 (van Vuuren *et al* 2011); and for the IPCC 6th Assessment Report, RCPs were paired with shared socioeconomic pathways (SSPs) (O'Neill *et al* 2013, 2017a, Riahi *et al* 2017). The new scenarios are labelled SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (Arias *et al* 2021).

4. Risks and adaptation measures

In this section the climate-related risks are introduced, and current and projected risk conditions on a global, regional and local scale are synthesised. Moreover, the adaptation potential for each risk is reviewed.

4.1. Risk of food insecurity due to repeated and/or extreme drought conditions
4.1.1. Risk
An increased frequency and severity of droughts is observed for both Central and South America. The changes have a significant effect on agricultural activities with consecutive years of decreased harvest (Marengo *et al* 2014, Ponce *et al* 2014, Zambrano *et al* 2016, Hannah *et al* 2017). Less productivity consequently leads to negative impacts for smallholder farmers and poor communities, especially in rural areas that practise rainfed agriculture (Sanabria *et al* 2014, Zhong *et al* 2021). Impacts include lower incomes, food insecurity, increased malnutrition, and possibly forced migration (Castellanos *et al* 2013, Robalino *et al* 2015). A contested topic in South America is that of agro-industrial intensification through homogeneous monocultures, for

example soybean. While industry points towards positive effects such as increased food production (e.g. through increased productivity and efficient use of nutrients), research results show the damage of such an agricultural system, erasing entire ecosystems, decreasing resilience to drought and local food security, and marginalising small-scale farmers (Guerena and Burgos 2014, Oliveira and Hecht 2017, Moreno *et al* 2020).

Increased aridity, intense droughts and subsequent effects on agriculture are already observed for several regions in Central and South America. In Central America, the dry corridor going through Guatemala, Honduras and El Salvador is especially exposed to droughts, and in 2016 and 2019 1.6 million and 1.4 million people were food insecure there, respectively (FAO (Food and Agriculture Organization of the United Nations) 2016, Depsky and Pons 2020). Large agricultural areas and high population density, including Indigenous communities, makes the Southeast region in South America particularly vulnerable to drought (Parraguez-Vergara *et al* 2016). Furthermore, since 2010 central Chile is suffering a mega-drought with mean rainfall deficits between 20% and 40%, affecting more than 10 million people (Garreaud *et al* 2020). Virtually the entire region of Northeast South America, the world's most populous dry land region, is susceptible to land degradation or desertification (Vieira *et al* 2020). An intense dry period in the region during 2012–2014 led to water and food scarcity for 10 million people (Marengo and Bernasconi 2015, Vieira *et al* 2015). The Amazon is increasingly exposed, and during the extreme droughts in 2010 and 2016, drought-exposed regions covered 16% and 46% of the Brazilian Amazon biome, respectively (Anderson *et al* 2018). Food security of Indigenous and rural resource-dependent communities of the Amazon has been strongly impacted due to high dependence on fishing and small-scale agriculture, two sectors highly vulnerable to extreme droughts (Pinho *et al* 2015, Camacho Guerreiro *et al* 2016).

The projected impacts of droughts on food security in Central and South America are substantial. In Central America, a considerable reduction of suitable areas for particular crops and a decreased yield for key crops including maize, coffee and sugar cane is projected for the 21st century. Smallholder farmers are regarded as especially vulnerable to the changes (Hannah *et al* 2017). Arnell *et al* (2016) projected cropland suitability until 2050, and found a decline in suitability of 188–415 000 km^2 for Meso-America, 21–193 000 km^2 for Brazil and 52–405 000 km^2 for the rest of South America, while the increase in suitability was 0–2000 km^2 for Meso-America, 0–56 000 km^2 for Brazil and 20–405 000 km^2 for the rest of South America. Furthermore, a study by CEPAL & CAC/SICA (Consejo Agropecuario Centroamericano del Sistema de la Integración Centroamericano) (2014) projected

a reduction in agricultural yield from 6.4% in 2020 to 38% in 2100 for Central America. Extreme drought conditions are projected by the end of the 21st century in the Amazon Basin, Southern Chile and Central America, following RCP 4.5 (Dai 2012). In Chile, the largest decrease in agricultural production is expected to occur for fruit producers rather than crop producers. The largest impacts are projected to occur in the northern region, where the Atacama and Coquimbo regions are expected to decrease their agricultural area by 40% (Ponce *et al* 2014). Droughts and decreasing precipitation are expected to reduce forage production of grassland systems, impacting sheep production in the semi-arid to sub-humid central region of Chile (Toro-Mujica *et al* 2017). See figure 2 for the geographic distribution of all eight risks under SSP2-4.5 for the 21st century.

4.1.2. Adaptation measures
The risk of food insecurity due to repeated and/or extreme droughts can be reduced through a combination of adaptation measures. In order to account for variability in drought years and increase resilience, farmers can, with financial support from governments especially to small-scale farmers, choose different crops depending on the year and season, including winter crops and drought resistant crops during drier years (Barros *et al* 2015, Hannah *et al* 2017). Research has found that in order to develop such a routine, improved and accessible climate and environmental forecasts are needed (Jat *et al* 2016). Installation of early warning systems can improve monitoring and prediction of droughts, and thus allow for humanitarian aid to arrive on time (Funk *et al* 2019). Evidence suggests that improved water governance including storage, water harvesting, irrigation and fair distribution is necessary (Kuzdas *et al* 2015, Marengo *et al* 2017a, 2017b). Overgrazing, deforestation and other forms of land degradation can amplify aridification and desertification. A suggested adaptation measure is therefore to set up clear regulations against deforestation and land degradation (Moreno *et al* 2020). Moving away from monocultures and towards alternative growing systems such as agroforestry can also help increase resilience (Oliveira and Hecht 2017, Lapola *et al* 2018). Moreover, local and Indigenous-led adaptation based on ecosystem-management to reduce the risk of food insecurity due to droughts has proven successful (Oviedo *et al* 2016, Vogt *et al* 2016, Moreno *et al* 2020).

4.2. Risk to life and infrastructure due to floods and landslides
4.2.1. Risk
Anthropogenic climate change will increase the frequency and severity of extreme events such as floods and landslides, mainly through changes in the hydrological cycle (Kundzewicz *et al* 2014, Alfieri *et al* 2017, Hirabayashi *et al* 2021). Changing conditions

include heavy rainfall, intensification of El Niño and La Niña Southern Oscillation, retreating glaciers, changing snow conditions and thawing of permafrost (Iribarren Anacona *et al* 2015, Emmer 2017, Wang *et al* 2017, Cai *et al* 2018, Rodríguez-Morata *et al* 2018, Poveda *et al* 2020). In Southwest South America, a positive trend in the number of wildfires, affecting forest plantations and native shrublands, have increased the potential of landslides and flooding events with an amplified risk during wet season (de la Barrera *et al* 2018). An increase in flooding events and landslides will lead to both loss of lives and large economic losses if effective adaptation measures are not adopted (Jongman *et al* 2015, Sepúlveda *et al* 2015). Floods and landslides already have severe consequences for people living in floodplains and mountain valleys. Where infrastructure is affected, it can lead to delays in transport of food supplies and water provision (Sepúlveda *et al* 2015, Emmer *et al* 2016, Aristizábal and Sánchez 2020).

Changes in the frequency and severity of extreme weather events have already been observed in Central and South America (Magrin *et al* 2014, CEPAL 2018, Grez *et al* 2020). In the La Plata Basin, the main rivers Uruguay, Paraguay and Paraná have all increased their mean flow due to a combination of land use changes and increased precipitation since the 1960s, and the rivers have experienced increased frequency of floods since 1975 (García and Vargas 1997, Genta *et al* 1998, Barros *et al* 2004, 2015). Around 1.1 million people are currently affected by river floods in South America every year, with damages of €1.5 billion, and where residential, commercial and industrial areas suffer the most damage, in that order (Alfieri *et al* 2017). In the Andes, temperature rise has intensified glacier melt, multiplying the number of glacier lakes. Glacial lake outburst floods (GLOFs) are a recurring hazard (Wilson *et al* 2018). GLOFs occur due to sudden release of large quantities of water accumulated in lakes from melting glaciers during the past decades, and have caused more than 5700 deaths in South America on record (Carrivick and Tweed 2016, Drenkhan *et al* 2019). Landslides are prominent in both Central and South America, placing millions of people at risk. People in less developed, densely populated regions are disproportionately affected, and continued settlement in high-risk areas increase exposure. For instance, in the Colombian Andes over 30 000 landslides were recorded between 1900 and 2018, with economic losses of 654 million USD, where rainfall was the predominant trigger (92%), and rising urbanisation was an important risk factor (Aristizábal and Sánchez 2020).

In response to changing hydroclimatic conditions, clear regional differences in heavy rainfall are projected across Central and South America. Reyer *et al* (2017) projected that extreme precipitation events with 20 year return period would intensify by

25% over Latin America in a +4 °C world, with hotspots of more than 30% increase in extreme precipitation in Serra do Espinhaco in Brazil, Pampas region in Argentina, and the Pacific coastline of Ecuador, Peru and Colombia. Annual rainfall reductions of up to 50% are projected for Rio de Janeiro, São Paulo and Santos in Southeast Brazil (Lyra *et al* 2017), which however is contrasted with seasonal precipitation increase exacerbating landslide risk, e.g. in São Paulo (Cavalcanti *et al* 2017).

Projections of fluvial and glacial flood risk during the 21st century show reason for concern for the Central and South America region. However, in many regions there is variability in the direction of change due to uncertain precipitation projections and differences in hydrological models, arising in part from limited meteorological data available (Reyer *et al* 2017). For the La Plata basin, a wetting trend can be seen, and projections for 2050 follow the already observed trends of an increase in frequency and duration of fluvial floods for the Parana and Uruguay rivers (Barros *et al* 2015, Reyer *et al* 2017). Alfieri *et al* (2017) project more than a ten-fold relative increase in populations disrupted by river floods in Colombia, Ecuador, Peru and Uruguay by the end of the 21st century in a +4 °C world. Hirabayashi *et al* (2013, 2021) projected river discharge changes based on CMIP5 and CMIP6 models. The authors found a majority agreement between the models, with an increase in flood frequency in practically the entire Central and South America except southern South America. Large increases in flood frequency are projected for the northern half of the Andes (Hirabayashi *et al* 2021). Glacier lakes in the Andes are projected to increase in numbers during the 21st century and GLOFs pose an imminent threat to populations downstream (Colonia *et al* 2017). For instance, in the Vilcanota-Urubamba basin in Peru, 70 out of the current 134 glacial lakes are considered highly susceptible to GLOFs. Another 14–20 glacier lakes are projected to form in the area by 2100, following RCP 2.6 and 8.5, respectively. Following RCP 8.5, 17 future lakes are highly susceptible to GLOFs (Drenkhan *et al* 2019).

4.2.2. Adaptation measures
The risk of floods and landslides can largely be alleviated with a combination of effective disaster risk management and climate change adaptation. Implementation of early warning systems at flood-prone rivers and glacier lakes and in risk zones of densely populated areas is strongly recommended (Barros *et al* 2015, Aparicio-Effen *et al* 2017, Drenkhan *et al* 2019), while integrating and taking into consideration local and Indigenous knowledge systems (Huggel *et al* 2020). Additionally, accurate hazard and risk maps are important tools to implement in land-use and urban development planning. Moreover, clear communication on needs and preferences between local government and residents has proven necessary

to avoid misunderstandings and tension, especially in cases of relocation from high-risk areas (Miranda Sara *et al* 2016). Finally, increased public awareness, improved contingency planning as well as increased resilience in infrastructure and service systems have shown to be essential for a successful risk reduction (Barros *et al* 2015).

4.3. Risk of water scarcity
4.3.1. Risk
Water resources are depleting in several regions in Central and South America. Increasing demands from agriculture, mining, hydropower and urbanisation are all contributing factors to decreased water availability and quality (Buytaert and Breuer 2013). Climate change is strongly exacerbating the risk of water scarcity. For instance, decreased annual precipitation rates, trends of decreased annual runoff and salt water intrusion into aquifers and groundwater sources due to sea level rise all contribute to water scarcity (Hidalgo *et al* 2013). Glacier shrinkage in the Andes is a key contributor to water scarcity in populated high mountain regions of South America. Increased temperatures and partly reduced precipitation have led to rapid glacier retreat, reduced river flow and increased water deficits in downstream locations (Drenkhan *et al* 2015).

In the tropical Andes, glaciers have lost substantial amounts of mass over the past decades. Glaciers in Bolivia, Ecuador and Colombia have decreased by 35%, 54% and 56% in area between 1980s–2013, 1980s–2017, and 1986–2017, respectively (Ramírez 2014, Cáceres 2018, IDEAM (El Instituto de Hidrología, Meteorología y Estudios Ambientales) 2018). Peruvian glaciers lost 54% of their area between 1962 and 2016 (INAIGEM (Instituto National de Investigacion en Glaciares y Ecosistemas de Montaña) 2018). Glacial contributions to the water supply strongly decrease downstream, as glacier runoff becomes a smaller part of the total water supply. However, in southern Peru and Bolivia where precipitation levels are low, glacier runoff continues to be an important water source downstream, particularly in the dry season (Drenkhan *et al* 2015, Buytaert *et al* 2017). Many cities in the arid Bolivian Andes are situated above 2500 m where rainfall is limited, and consequently strongly rely on high-altitude water sources of glaciers and lakes. In Bolivia, only 56% of the rural population have access to safe water (Jeschke *et al* 2012). Hotspots with high glacier contribution to water use are found mostly in rural areas of south Peru and Bolivia, where adaptation capacities are limited. During drought conditions, glacier contributions to freshwater demand increase dramatically (Buytaert *et al* 2017). In fact, increased water stress has already been perceived by the local population in both the Santa River in Cordillera Blanca and the Vilcanota River in Cordillera Vilcanota (Peru) (Motschmann *et al* 2020).

Projections for the next decades foresee that up to 112 million people in Meso-America, up to 28 million in Brazil and up to 31 million in the rest of South America could be exposed to increased water resources stress in 2050 with a 2.7 °C temperature rise (following the A1B climate scenario), compared to pre-industrial levels (Arnell *et al* 2016). On the other hand, projected populations with decreased water resources stress for the same scenario were up to 53 million for Meso-America, no decrease for Brazil and up to 18 million for the rest of South America (Arnell *et al* 2016). Veldkamp *et al* (2016) projected that about 40% of Latin America could be exposed to absolute water scarcity in 2080 following RCP 6.0-SSP3.

With further warming, seasonal snow (especially in Southwestern South America) will melt earlier and cause a rise in runoff during early spring and a drop during the summer dry season when irrigation is crucial for agriculture (Vicuña *et al* 2013, Barros *et al* 2015). Tropical glaciers in the Andes are projected to almost completely disappear under high warming levels, while the ice masses in the Southern Andes would persist to about 50% by the end of the century as compared to current extents (Reyer *et al* 2017, Drenkhan *et al* 2018, Hock *et al* 2019). A study projected water balance in 11 hydrologic basins in Bolivia for 2050, and found that only for one basin a surplus of water is expected, while two basins showed substantial water deficits. It is worth mentioning that the analysis did not consider water consumption for domestic use (Escurra *et al* 2013).

While regional and global modelling studies are important tools to understand future water availability, local modelling studies with high spatial resolution can give a more precise idea of water availability for specific regions. For instance, Gesualdo *et al* (2019) assessed future streamflow from the Jaguari Basin and the subsequent water security for 9 million people in São Paulo until 2095 following RCP 4.5 and 8.5. Dry periods were projected to extend from currently July–September to July–November, and the driest month shifted from September to October. While water scarcity was close to zero during austral winter, the period from August to November was insecure, with a 100% water scarcity reached in November following RCP 4.5 for 2041–2070 and a projected 40% increase in demand (Gesualdo *et al* 2019).

4.3.2. Adaptation measures
During the seasonally dry period, adaptation options and water management against water scarcity are especially important. It is advised that integrated water resource management is pursued in participatory approaches, i.e. community-based with consideration of Indigenous and local knowledge (Rangecroft *et al* 2013). Moreover, efficient water storage during wet season, as well as diversification of water sources, including wastewater reuse and rainwater harvesting, can reduce scarcity during dry season (Gesualdo *et al* 2019). Further, improvement of infrastructure can reduce leaks and improve efficiency and water quality (Marengo *et al* 2017a). Governments are advised to consider fair distribution of water resources between agriculture, mining, hydropower plants and community usage (Gesualdo *et al* 2019). Lastly, research has found that ecosystem-based adaptation projects including water supply and watershed management, e.g. through restoration and protection measures, have the potential to reduce the risk of water scarcity (Ostovar 2019, Richerzhagen *et al* 2019).

4.4. Risk of severe health effects due to increasing epidemics of vector-borne diseases
4.4.1. Risk
Changes in precipitation patterns and temperature caused by climate change have a clear impact on the distribution and magnitude of vector-borne diseases such as malaria, leishmaniasis, dengue, Zika and Chagas disease (Carvalho *et al* 2015, Pino *et al* 2015, Ali *et al* 2017, Ryan *et al* 2019) in the Central and South America region. Minimum and maximum temperatures help determine the geographical distribution of the vectors carrying the pathogen. The amount and frequency of rainfall can potentially cause overflowing of breeding sites and disturb hatching of eggs. Increase in air humidity can on the other hand lead to an increased hatching (Bittencourt *et al* 2017). Sensitivity to vector-borne diseases differs vastly between different population groups, and access to health care, intact infrastructure and clean drinking water increases resilience. For instance, Indigenous populations in Panaillo and Nuevo Progreso in the Peruvian Amazon experience high sensitivity to vector-borne diseases, due to stagnant pools of water and a lack of access to a community health post. Moreover, deforestation has made traditional remedies less accessible (Hofmeijer *et al* 2013).

Plasmodium falciparum is transmitted by Anopheles mosquitoes, and can cause malaria. The parasite is currently restricted to the tropics. However, predictable niche models of habitat suitability during the 21st century show an increased distribution, with *P. falciparum* covering up to 46% of South America by 2070. The primary malaria vector *Anopheles darlingi* did not respond well to the associated change in water availability and is predicted to reduce its coverage from 21% to 8%–11%. However, mosquitoes in the Albitarsis Complex, for example *Anopheles deaneorum*, were less dependent on changes in precipitation and were projected to increase their coverage (Laporta *et al* 2015). Another projection for 2069–2099 showed a consistent increase in the malaria transmission season over the highlands in Central America and southern Brazil, and a consistent decrease over tropical regions in South America (Caminade *et al* 2014).

Carvalho *et al* (2015) used ecological niche models to explore the distribution of *Lutzomyia flaviscutellata*, the vector for leishmaniasis, in South America under the impact of climate change. The coverage increased by 12.8% ($\sim$1 million km^2) in the RCP 4.5 scenario and 10.7% (0.9 million km^2) in the RCP 8.5 scenario, and maximum elevations vent from 1545 m to 2213 m and 2265 m for the RCP 4.5 and 8.5 scenario, respectively. The expansion was expected in Southeast and Central southern Brazil, Eastern Paraguay and into the Amazonian areas of Colombia, Venezuela, Ecuador, Peru and Bolivia (Carvalho *et al* 2015).

Dengue, and Zika are both transmitted through the *Aedes aegypti* mosquito. Climate projections for South America for 2061–2080 show an increase in land surface area occurrence of the *Aedes aegypti* by 0.4 million km^2 for RCP 4.5 and 0.5 million km^2 for RCP 8.5, over a 15 million km^2 area for 1950–2000 (Monaghan *et al* 2016). Another study found an additional 50.5–69.5 million and 47.5–99.2 million people at risk in 2050 and 2080 respectively in Latin America, following RCP 2.6–8.5 (from current 416.2 million), with the largest increase in Central America (Ryan *et al* 2019).

The dengue virus is most likely to occur in average monthly air temperatures between 5 °C–32 °C (with rapid increase at temperatures above 18 °C); below and above this range of temperatures the risk declines rapidly (Colón-González *et al* 2013). A field study in Belo Horizonte, Brazil found that projected temperature increases in 2030 would favour the dengue vector also in winter, while increase or redistribution in rainfall could increase the number and quality of vector breeding sites (Bittencourt *et al* 2017). Limiting global temperature rise to 1.5 or 2 °C above pre-industrial levels is projected to limit expansion of dengue and reduce 3.3 or 2.8 million dengue cases per year in Latin America by 2100, respectively, compared to a temperature rise of 3.7 °C (Colón-González *et al* 2018). The Zika virus first emerged in South America in Brazil in 2015 and has since then spread rapidly throughout Central and South America (Colón-González *et al* 2017). The surface climate conditions produced by the extreme El Niño of 2015–2016 was thought to provide exceptional conditions for the *Aedes aegypti* vector (Rao *et al* 2019). Ali *et al* (2017) identified 'climate variation, land use change, poverty, and human movement' as main drivers for the rapid spread of the Zika virus.

Projections for the spread of Chagas disease with climate change are not unanimous over the Central and South America region. Increasing the temperature from 26 °C to 30 °C caused increased infective forms and decreased development time of the vector (Tamayo *et al* 2018). However, projections for Venezuela and Argentina for 2050 show a decreasing trend of suitable areas for the two main Chagas disease vectors, especially in currently high transmission areas in Venezuela (Medone *et al* 2015). Moreover, authors of a study of five Chagas disease vectors following A1B and B1 climate scenarios for 2020, 2060 and 2080 projected a slightly decreasing human vulnerability to geographic exposure to Chagas disease (Ceccarelli and Rabinovich 2015). On the other hand, in Chile, the potential distribution of two Chagas disease vectors for 2070 was found to be larger than their current ranges. However, the distribution depended on whether modelling a higher or lower public health risk situation (Garrido *et al* 2019).

4.4.2. Adaptation measures

With vectors and pathogens projected to reach both higher latitudes and altitudes during the 21st century, investments in distributed and well-equipped public health facilities, with a special regard to areas with low socio-economic status, can help reduce risk (Hofmeijer *et al* 2013, Moreno *et al* 2020). Another option is investment in surveillance systems to monitor vector development and reproduction, and possible disease outbreaks (Haines and Ebi 2019). Studies have suggested that adaptation on community level should include protection in housing and schools, vaccination campaigns, capacity building and education (Ebi and Nealon 2016, Bittencourt *et al* 2017). Improved water storage, wastewater management and access to treated water are other adaptation measures proven effective to cope with epidemics in the region (Colón-González *et al* 2013, Hofmeijer *et al* 2013, Moreno *et al* 2020). Finally, increased investments in in-depth studies on spread of vector-borne diseases with regards to climate change and socio-economic development, especially in remote areas (Ebi and Nealon 2016, Moreno *et al* 2020), followed by updated management policies and measures in light of these studies (Haines and Ebi 2019) can help reduce risks.

4.5. Risk of large-scale ecological transformation of the Amazon Forest

4.5.1. Risk

The Amazon is going through massive changes due to climate warming, forest degradation and deforestation (Qin *et al* 2021). Deforestation rates of the Brazilian Amazon peaked in 2004 when 27 000 km^2 were clear-cut. In 2012, deforestation rates were reduced by 84% compared to 2004. However, since 2012 rates have increased alarmingly, and the relative reduction compared to 2004 was a mere 44% in 2020 (Silva Junior *et al* 2021), leading to 648 million tons of CO_2 y^{-1} emitted to the atmosphere (Aragão *et al* 2018). Recent data indicate a 22% increase in deforestation in 2021, reaching 13 235 km^2 (INPE (Instituto Nacional de Pesquisas Espaciais) 2021). The added impact of climate change to deforestation and wildfires has severe consequences both regionally and globally. Tropical forests are large carbon sinks, and the Amazon currently stores 150 PgC to

200 PgC (Pan *et al* 2011, Feldpausch *et al* 2012, SPA (Science Panel for the Amazon) 2021). Moreover, the forest is an important part of the hydrological cycle (Reyer *et al* 2017) within the world's largest hydrographic basin (Richey *et al* 1989). The river system includes 20 000 km of waterways and is essential for transportation, connecting the many communities in the region (CEPAL (Comisión Econômica para a América Latina e o Caribe) 2007). Amazon deforestation has the potential to change the local and regional hydrologic cycle through decreased moisture transport and precipitation (Ruiz-Vásquez *et al* 2020).

Combined pressures from deforestation, wildfires and climate change have resulted in the tropical forest biome of the Amazon being under threat. Projections of the tropical forest distribution for 2050 following RCP 2.6 and 8.5 show a 15% reduction in the biome for RCP 8.5 compared to 2.6 (Nobre *et al* 2016). When accounting for deforestation and forest fires, a reduction of 60% of tropical forest is projected, centred in eastern and southern Amazon, and exchanged with seasonal forest and tropical savannah biomes (Nobre *et al* 2016, Brando *et al* 2020, Malhi *et al* 2021). Two tipping points have been identified, and if exceeded, large-scale savannization of the southern and eastern Amazon can take place. The two tipping points are estimated at a temperature increase of 4 °C, and of deforestation exceeding 40% of the forested area (Nobre *et al* 2016). The change from tropical forest to savannah would imply large scale alterations in ecosystem services (e.g. food production and climate regulation) as well as loss of biodiversity (Sampaio *et al* 2019). Lapola *et al* (2018) explored the consequences of an Amazon forest dieback (AFD), i.e. an abrupt change in biome towards drier vegetation with lower biomass. The authors estimated that the net-present value of socioeconomic damage, primarily from changes in ecosystem services, over a 30 year period after an AFD was 957–3589 billion USD. This can be compared with the Brazilian Amazon Gross Product of 150 billion USD per year. Moreover, an AFD could result in massive migration to Amazonian cities, due to a lack of transportation paths, food security and health systems (Lapola *et al* 2018). Poverty and poor adaptive capacity are the strongest contributors to the current vulnerability in the Brazilian state of Amazonas. Decreased mobility due to changes in the hydrological basin together with food insecurity are the main concerns (Pinho *et al* 2014, Menezes *et al* 2018).

Projections of changes in the hydrological cycle in the Amazon are somewhat inconclusive, with some showing a drying trend, and others a wetting trend for the region (Seiler *et al* 2013). However, following the scenario SSP3-7.0 for the 21st century, a drying trend was projected for most of Amazonia in 10 out of 12 months (Parsons 2020). Nobre *et al* (2016) found, during the wet season, a wetting trend in the

north-western part of the basin, and a drying trend in the southern and south-eastern part. A lengthening of the dry season could be catastrophic as the Amazon humid forests require that the dry season, with less than 100 mm precipitation per month, is no longer than four months. Moreover, lianas and larger trees are the most vulnerable species to droughts. Increased drought conditions could therefore change species composition, and result in less shading over lower canopy, enhancing temperature and dryness even more while increasing the vulnerability to droughts and wildfires (Nobre *et al* 2016, Costa *et al* 2021).

Recent research show how parts of the Amazon Forest are turning from a net carbon sink to a carbon source (Gatti *et al* 2021). Harris *et al* (2021) found that the Brazilian Amazon was a net carbon source of 0.22 Gt CO_2e yr^{-1} from 2001 to 2019, while the larger Amazon River basin remained a net sink of -0.10 Gt CO_2e yr^{-1}. Brienen *et al* (2015) analysed the evolution of the Amazon rainforest as a carbon sink over three decades and found that while the Amazon was indeed acting as a long-term net biomass sink, the capacity had decreased by ⅓ since 1990. Lapola *et al* (2018) concluded that the Amazon could become a carbon source in less than ten years.

4.5.2. Adaptation measures

The Amazon Forest is undergoing large changes that, if left unaltered, can ultimately lead to a shift in biome from tropical rainforest to seasonal forest. There are a number of adaptation measures that have the potential to reduce the risk, the most substantial ones are reducing deforestation and increasing reforestation. This would in turn have a positive effect on precipitation, and therefore change the course of forest fires and droughts (Nobre *et al* 2016). In a recent study, Poorter *et al* (2021) analysed the patterns of recovery in forest attributes after deforestation which, under low intensity land use, were recovered at levels of ¾ of the pre-disturbance conditions. Stricter policies, surveillance and monitoring in the Amazon countries on logging, agriculture expansion and slash-and-burn are also impactful. An increase in protected areas, with inclusion of positive socio-economic outcomes for Indigenous and local communities, is recommended. Management of such protected areas should be diverse and secure Indigenous rights to forest (Gross *et al* 2016, Bebber and Butt 2017), to avoid 'fortress conservation' (Montgomery *et al* 2020, Murdock 2021). Research suggests that all levels of decision-making about forest and land should include Indigenous knowledge systems in order to improve fire management (Mistry *et al* 2016, Bilbao *et al* 2019), soil health, and ecosystem restoration. Community-owned fire management practices are disappearing and undermined, though approaches incorporating Indigenous fire management into market and incentive-based

mechanisms for climate change mitigation are emerging. Community Indigenous fire management has already been adopted in Venezuela, Brazil and Guyana to prevent large-scale and destructive wildfires, reducing the vulnerability to climate change (de Moraes Falleiro *et al* 2016, Mistry *et al* 2016, Eloy *et al* 2018, Bilbao *et al* 2019).

4.6. Risk to coral reef ecosystems due to coral bleaching

4.6.1. Risk

Coral reefs are important ecosystems, and store more than one million of the world's marine species (Wilkinson 2006, Wagner *et al* 1999). The Mesoamerican Reef (MAR), also known as the Great Mayan Reef, stretching 1000 km from Mexico to Honduras, is the second largest reef in the world (Bland *et al* 2017). The reef is already under stress due to increased SST and lowered seawater pH and carbonate levels, as a consequence of increased levels of atmospheric CO_2 (Baumann *et al* 2019, Helmuth *et al* 2020, McField *et al* 2020). Lower abundance in coral cover as well as diversity has already been observed (Baumann *et al* 2016, 2019). The MAR is further threatened by sea level rise, hurricanes, overfishing, coastal development, pollution from wastewater and solid waste, tourism as well as lionfish invasions and disease outbreaks (Jackson *et al* 2014, Renfro and Chadwick 2017, Suchley and Alvarez-Filip 2018). The reef is currently considered critically endangered and at risk of ecosystem collapse (Bland *et al* 2017). An evaluation of the ecosystem health in 286 sites made by Healthy Reefs showed an overall decline in the Reef Health Index from 2.8 (fair) in 2016 to 2.5 (poor) in 2018. The evaluation covered live coral (% cover), fleshy macroalgae (% cover), commercial fish (g/100 m^2) and herbivorous fish (g/100 m^2) (McField *et al* 2020). Further degradation of the reef would lead to severe damage to the habitat of numerous fish species, species of mollusc as well as sharks, crocodiles, turtles and manatees. Moreover, various ecosystem services such as fisheries and coastal tourism (Alva-Basurto and Arias-González 2014, Hoegh-Guldberg *et al* 2017), as well as crucial shoreline protection (Osorio-Cano *et al* 2019, Reguero *et al* 2019) are at risk. Besides the MAR, coral reefs in Panama and Brazil are also experiencing coral bleaching events and declines in coral cover (Li and Reidenbach 2014, de Oliveira Soares *et al* 2019, de Oliveira *et al* 2019, Duarte *et al* 2020).

Corals require specific temperatures, salinity, light availability and aragonite saturation, and are therefore vulnerable to change (van Hooidonk *et al* 2013). SST anomalies can cause coral bleaching to occur (Baker *et al* 2008, van Hooidonk *et al* 2013). Bleaching starts when a warming of 1 °C above typical regional warm season maxima is reached for over four weeks. The longer the anomalies stay the

worse the conditions for corals (Hoegh-Guldberg 2011, Meissner *et al* 2012). Changes in environmental conditions has produced a change in species composition (Baumann *et al* 2016), with growing populations of opportunistic species, which on the one hand have high tolerance to environmental disturbance but on the other hand contribute little to reef structural complexity (Alvarez-Filip *et al* 2013, González-Barrios and Álvarez-Filip 2018), affecting the reef ecosystem resilience and surrounding ecosystem services (Hughes *et al* 2017, Randazzo-Eisemann *et al* 2021).

Surface seawater carbonate saturation (Ω) and pH levels are important factors modulating physiological rates as calcification and biomineralization in corals (Mollica *et al* 2018, Kawahata *et al* 2019). Increased CO_2 levels in seawater (pCO_2) causes a decrease in availability of carbonite ions and pH levels in a process known as ocean acidification (Wolf-Gladrow *et al* 1999, Caldeira and Wickett 2003, Feely *et al* 2008). Meissner *et al* (2012) showed that no coral reefs exist in environments with aragonite saturation below 3. The authors found that only RCP scenario 3PD projected a recovery for SST anomalies and an aragonite saturation above 3, whereas for RCP 4.5 and 8.5 mean aragonite fell below 3 by 2050 and 2040, respectively. Mean SST anomalies exceeded 2 °C after 2100 and 2070 for RCP 4.5, and 8.5, respectively (Meissner *et al* 2012). Scenarios project that for RCP 4.5 by year 2050, virtually the entire MAR will experience annual severe bleaching events (van Hooidonk *et al* 2013, 2019).

Changes in species composition and functional traits are projected to continue during the 21st century, with certain coral species being more resilient to warming and acidification (Bove *et al* 2020). Recovery of reefs does not guarantee full recovery in functional traits and composition (McWilliam *et al* 2020). Moreover, the entire MAR reef food web has the potential to shift with the combined stresses of coral bleaching, deoxygenation and acidification, resulting in an overall decrease in biomass (Alva-Basurto and Arias-González 2014). The adaptive capacity of corals is not fully established, and it is highly dependent on corals' exposure to stress. Shortening of return periods between bleaching events, and other factors causing additional stress, increase the rates of reef degradation (van Hooidonk *et al* 2013). Further bleaching is projected also for Panama, especially in shallow reef areas (Li and Reidenbach 2014). A loss of suitable areas by 46%–59% by 2100 is projected for a Brazilian endemic coral following RCP 4.5 and 8.5 (de Oliveira *et al* 2019).

4.6.2. Adaptation measures

The adaptation potential for coral reefs is limited and hard limits are approaching rapidly (Mechler *et al* 2020). A combination of rapid global greenhouse gas

(GHG) emission reduction and reduction of non-climatic stressors are the most effective way to preserve coral reefs and their socio-ecological functions. Corals are long lived and adapt relatively slowly to environmental changes, with large interspecies differences (Hoegh-Guldberg *et al* 2017). However, reducing bleaching events to every five years could be sufficient enough for most reefs to recover. Nonetheless, with the current climate trajectory bleaching could occur yearly as early as 2050 in the MAR (van Hooidonk *et al* 2013, 2019). The best chance of survival is therefore ensured by reducing CO_2 emissions rapidly in order to limit global warming (e.g. Meissner *et al* 2012). Moreover, local human stressors from pollution both from untreated wastewater and solid waste, coastal development, fishing and tourism can be reduced in order to increase resilience of the reef. This can be accomplished through marine protected areas, especially in hotspot areas with high structural complexity (Randazzo-Eisemann *et al* 2021). This can be done in combination with better access to and integration of scientific knowledge in decision-making processes and management plans (Cvitanovic *et al* 2015). In general, climate change adaptation strategies in Central and South America are based on protection, conservation, and restoration (Cruz-Garcia and Peters 2015, Alvarado *et al* 2017, Bayraktarov *et al* 2020), with some strategies incorporating community-based adaptation (Alvarado *et al* 2017).

4.7. Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion
4.7.1. Risk
Coastal flooding, erosion and subsidence is a recurring issue in the Central and South America region. Coastal flooding is strongly impacted by climatic changes in mean sea levels, El Niño Southern Oscillation (ENSO) events, and extreme sea levels from sea level rise and storm surges (Reguero *et al* 2015, Wahl *et al* 2020). Consequences of coastal flooding include loss of lives, destruction of infrastructure, erosion, infiltration of ocean water in aquifers and groundwater, and severe damage to ecosystems and nature-based coastal protection (Leatherman *et al* 2000, Carretero *et al* 2013, Fanning 2014, Saleh and Weinstein 2016, Zanetti *et al* 2016, Hu *et al* 2018), where subsidence can compound the effect (Wong *et al* 2014). Extensive development and population growth is occurring in coastal regions, increasing the exposure of people to these risks. Poor planning and limited adaptation options, especially for poor communities, increase the vulnerability to coastal hazards.

The low-elevation coastal zone (LECZ) covers over 400 000 km² in Central and South America (Neumann *et al* 2015) and is in South America occupied by at least 6% of the population (Villamizar *et al* 2017), i.e. 25 million people. In the year 2000, 32 million people in Central and South America and

the Caribbean together lived in the LECZ. Brazil and Argentina were the two countries with the highest number of people living in the LECZ, with 12 million and 3.6 million, respectively (Neumann *et al* 2015). Extreme sea levels are events driven by mean sea level, storm surges and tides combined (Oppenheimer *et al* 2019). About 7.5 million people and capital goods worth 299 billion USD are currently exposed to 100 year extreme sea level events in Latin America and the Caribbean (Reguero *et al* 2015).

Virtually the entire coastal zone of Central and South America is projected to be exposed to either storm surges, risks from mean sea level rise or erosion, or a combination thereof. ENSO events are projected to compound the risk of sea level rise through induced sea level changes especially in Peru, Ecuador, Panama, El Salvador, Costa Rica and Guatemala. Highly populated areas most exposed to 100 year extreme sea level events include Fortaleza, Natal, Recife, Rio de Janeiro and Florinapolis in Brazil, Montevideo in Uruguay, Buenos Aires in Argentina, La Libertad and Guayaquil in Ecuador, Lima in Peru and Valparaiso in Chile (Reguero *et al* 2015). Calil *et al* (2017) identified hotspot locations of coastal risk in El Oro, Ecuador and Usulutan, El Salvador. The Chilean government projected that 49 000 people in Chile will be affected by floods from storm surges and sea level rise by 2045 (MMA (Ministerio del Medio Ambiente) 2019). Zanetti *et al* (2016) assessed the coastal vulnerability of Santos, Brazil and found that 70% of the area is highly vulnerable.

Projections for the 21st century show continued coastal population growth, together with mean sea level rise and increased storm surges. In 2030 and 2060, the total LECZ population of Central and South America and the Caribbean is projected to reach up to 42 million and 52 million, respectively. The South America LECZ population could reach up to 38 million by 2060, with up to 19 million in Brazil and 7.6 million in Argentina (Neumann *et al* 2015). Global mean sea level rise is projected to reach 0.29–0.59 m for RCP 2.6 and 0.61–1.10 m under RCP 8.5 by 2100, relative to 1986–2005 (Oppenheimer *et al* 2019). Reguero *et al* (2015) projected that with increased extreme sea levels and growing population and without adaptation, 9.9 million people in Latin America and the Caribbean will be exposed to flooding from 100 year extreme sea levels by 2050. When taking El Niño into account, the threats will be more frequent and intense in several of the countries at the Pacific coast.

4.7.2. Adaptation measures
Restoring and increasing resilience of coral reefs will not only have beneficial effects for coral reefs themselves but also have large co-benefits on coastal socio-ecological systems, due to reefs providing coastal protection against hurricanes, storm surges and erosion (Osorio-Cano *et al* 2019, Reguero *et al* 2019). Other

nature-based protection measures include protection and restoration of mangroves, dunes, seagrasses and marshes. However, large habitats are needed to substantially reduce storm surge risk (Saleh and Weinstein 2016). Nonetheless, lagoon ecosystems in Uruguay have proved to provide flood and storm protection as well as limit erosion (Fanning 2014). Artificial protection structures such as concrete breakwaters, groins, revetments and seawalls provide further alternatives (Burcharth *et al* 2015, Morris *et al* 2018). Other than improving coastal protection, coastal management strategies can take into consideration appropriate infrastructure, urban development and agricultural land use in order to limit future coastal risk (Calil *et al* 2017, Osorio-Cano *et al* 2019), and can involve local stakeholders in defining adaptation actions (Villamizar *et al* 2017). Beyond protection measures, the emerging discussion about managed retreat will continue to grow in importance. Haasnoot *et al* (2021) thereby emphasise that retreat, or relocation, should be community-led and self-determined, focusing on justice and equity.

4.8. Risk of systemic failure by cascading impacts of hazards and epidemics overwhelming infrastructure and public service systems

4.8.1. Risk

Though impacts of individual climate-related risks are detrimental on their own, compound or cascading events have a particularly high potential to exceed the capacity of public systems and infrastructure, leading to widespread social, economic and environmental loss (Cutter 2018, Simpson *et al* 2021). Recent attention has been brought to the combined impact of climate hazards and epidemics, and the potential of extensive displacement of people and disruption of public service systems. This is already acknowledged for the Covid-19 pandemic (Phillips *et al* 2020). Central and South America is highly climate-suitable for infectious diseases, and the Covid-19 pandemic has hit the region hard (Ramírez and Lee 2020), with Brazil, Peru, Colombia and Argentina particularly heavily affected. By June 2021 there were 36 million confirmed Covid-19 cases (20% of total cases) and over 1.2 million deaths (32% of total deaths) in the region of Latin America and the Caribbean (Sullivan and Meyer 2021).

The ability of countries to tackle a widespread epidemic, simultaneously with sending emergency response to climate-related disasters varies drastically depending on the socio-economic conditions of the country. Moreover, extreme events such as floods, landslides and hurricanes can cause population displacement and environmental change, further leading to poor water and sanitation conditions, poor nutritional status and limited access to health care. Forced migration to cities due to natural hazards and consequential overcrowding and limited access to clean water in slum-like conditions further increases the

spread of diseases. As a result, exposure and vulnerability to pathogens and transmission of infectious diseases increase (Kouadio *et al* 2012). In the region of Latin America and the Caribbean, an estimated 20.9% of the urban population lived in slum-like conditions in 2018 (Ramírez and Lee 2020). In Peru, Ecuador and Brazil there is a severe lack of handwashing facilities in healthcare centres, homes and schools (UNICEF (United Nations Children's Fund) 2020). Informal workers, accounting for about half of the total workers in Central and South America and over 70% in Peru, do not receive reimbursements and cannot stay at home during disease outbreaks, and are therefore disproportionately affected (Bonnet *et al* 2018, The Lancet 2020). Health systems are severely underfunded in the Latin America region, with some countries only spending 4% of their gross domestic product (GDP) on health care (Litewka and Heitman 2020). These factors combined pose a great risk for public systems to be overburdened in the occurrence of cascading events.

Outbreaks of diseases have been observed to follow ENSO events and related heavy rainfall. After the ENSO in 1997–1998, the El Oro province in Ecuador was affected by 300 cases of malaria and 200 cases of dengue fever (Vos *et al* 1999). Petrova *et al* (2020) used a dengue model and an ENSO forecast and successfully estimated the magnitude of dengue outbreaks in El Oro in 1998 and 2010 through the use of ENSO predictions, clearly showing the relationship between the two. Pools of water, formed due to heavy rains in the ENSO event of 1982–1983, acted as breeding sites for mosquitoes and increased cases of malaria in Peru by 250% from the year before (CAF (Corporación Andina de Fomento) 2000). During El Niño years, dengue cases in Brazil were 2.9% higher than during neutral years for the period 2000–2016 (Anyamba *et al* 2019). Moreover, flooding from ENSO events have a large impact on sanitation and water quality, in turn leading to increased waterborne illnesses such as cholera. After the ENSO in 1998, there were 41 000 confirmed cases of cholera in Peru, which equates to an 1000% increase from the two previous years (CAF (Corporación Andina de Fomento) 2000). Additionally, ENSO events have been observed to have a detrimental effect on sensitive infrastructure. E.g. the 1998 ENSO destroyed thousands of homes in Ecuador, Peru and Bolivia (CAF 2014). Extreme El Niño events are projected to increase in frequency linearly with global mean temperatures, reaching double the current frequency at 1.5 °C warming. A higher risk of extreme El Niño events during the 21st century is expected, even after a hypothetical stabilisation of the temperature (Wang *et al* 2017). Simultaneously, the spatial distribution of vector-borne diseases such as malaria, leishmaniasis, dengue and Zika is projected to increase during the 21st century (e.g. Carvalho *et al* 2015, Ali *et al* 2017, Ryan *et al* 2019). The evidence suggests that compound

risks of increasing epidemics and hazards will have the capacity to overwhelm infrastructure and public service systems unless adaptation measures are implemented.

4.8.2. Adaptation measures

Climate change-related risks will increase in frequency and magnitude during the coming century. Multiple hazards occurring simultaneously or in a cascade will exacerbate the impacts of the risks, ultimately causing severe damage to infrastructure and public service systems. In order to account for the impacts of compound or cascading risks, a systems thinking approach is necessary, moving away from individual risks (Ismail-Zadeh *et al* 2016, Raymond *et al* 2020). Adaptation measures should centre on increasing systems resilience and identifying thresholds and where impact cascades can be broken. Inclusion of both biophysical hazards and socio-economic consequences is key, as well as a joint focus on disaster risk reduction and climate change adaptation, together with more inclusive development.

5. Discussion

In this review we comprehensively synthesised current and future climate-related risks and assessed the adaptation potential in Central and South America. Considering the general lack of reviewed articles on the subject in this region, contrasting the prevailing climate urgency, this paper can provide a substantial contribution on the matter.

This paper shows that the region of Central and South America will be increasingly affected by climate change-related risks during the 21st century, also under lower warming scenarios. We were able to identify eight risks which all have the potential to become severe in the near future, contingent on mitigation and adaptation efforts. While climate change plays a key role in the future trend of all eight risks, other human-induced dynamics will be crucial as well. These include socio-economic development, pollution, land-use, deforestation and migration. Moreover, our assessment shows that the risks do not unfold in an isolated way, but have a great influence on each other. For example, an Amazon biome shift can increase aridification and therefore food insecurity, and more frequent and magnified flooding events can destroy water storage systems or other critical infrastructure, increasing water scarcity in certain areas. See figure 3 for some of the existing relationships between risks, and table A1 in the appendix for a list of how the risks impact each other, and the supporting literature.

Evidence suggests that several risks occurring simultaneously or after one another could have the potential to cause systemic failure. The potential, occurrence and severity of cascading risks depends partly on climate hazards (such as floods, landslides and droughts) exceeding thresholds and tipping points of socio-economic systems, and partly on the vulnerability and resilience of these systems (e.g. health, sanitation and energy systems). Countries with low adaptive capacity are prone to an increase in cascading risks with potentially severe and long enduring consequences.

The extent of the severity of risks will not only depend on the level of warming, but also on the region's exposure, vulnerability and adaptive capacity. Adaptation options become increasingly limited for high warming scenarios, and unabated climate change will increase the likelihood of adaptation limits being reached, especially for groups and populations with low socio-economic status. Additionally, because of their socio-economic and marginal conditions, these groups are more exposed and vulnerable to the impacts of climate change and have less access and control of assets required to adapt. Still, various adaptation options are available for each risk (see table 1), with the exception of coral bleaching, where adaptation options mainly focus on protection and conservation, and hard limits are approaching.

Our analysis suggests that adaptation measures can be applicable to more than one risk. For example, efforts to reduce deforestation will have an impact on both food insecurity and an Amazon biome shift. See figure 4 for nine adaptation measures which can be applicable to more than one risk in the region, and table A2 in the appendix for details of how the adaptation measures can apply to each risk, and the supporting literature.

Our review revealed critical knowledge gaps for the region's capacity to address climate change-related risks, and may guide future research efforts. A salient gap is the large heterogeneity in availability and quality of data and information, which do not necessarily correlate with risk levels. For instance, Central America is highly prone to several analysed risks, with important uncertainties related to poor data availability. Improved capacity to address risks should be based on the nexus among sustained collection of quality data, analysis, and policy. Moreover, precipitation affects almost all of the risks analysed (food insecurity, floods and landslides, water scarcity, epidemics, Amazon biome shift, systemic failure), however, precipitation projections were largely based on global models. Thus, increasing efforts to develop reliable and high-resolution precipitation models should be a priority. Active and up to date research is crucial to support adaptive responses and policies. Moreover, there is a lack of studies that test and evaluate adaptation measures. Efforts to thoroughly research further adaptation measures and their feasibility and effectiveness should be of the highest priority. This will undoubtedly save both lives and severe economic loss as Central and South America face the

impacts of climate change. In addition to strengthening scientific knowledge of climate-risks and how to adapt, an inclusion of other knowledge systems such as traditional (e.g. Indigenous) and local knowledge is strongly advisable (Moreno *et al* 2020, Iwama *et al* 2021). Finally, the large-scale and massive impacts of cascading risks make integrated research on the interactions between all climate-risks and their impacts crucial for the adaptation and resilience of Central and South America.

6. Conclusions

We identified eight risks that are or have the potential to become severe with climate change during the 21st century. The critical evaluation of peer-reviewed and grey literature led to a synthesis of climate-related risks and adaptation options for Central and South America. Understanding the severity of current and future risks and their geographic and social distribution can benefit developing robust, well-aimed, and feasible adaptation measures. As such, rural communities, Indigenous peoples, Afro-Latin Americans, women, disabled people, and migrants are likely to be the most severely affected.

Communities most critically impacted by climate-risks often also have low adaptive capacity and limited means to respond to and recover from climate-risks. Although there are adaptation options available for all eight risks, socio-economic conditions disrupt implementation in some of the most critical areas. Therefore, immediate strengthening and increase of research as well as policies that build adaptive capacity in Central and South America are crucial for managing severe climate-risks in the future.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

Appendix

Tables A1 and A2 provide background information and traceable evidence for figures 3 and 4, respectively.

Table A1. Listing which risks have an impact on which other risks and how, and the supporting literature.

Risk impacting	Risk impacted	Impact	References
Food insecurity	Systemic failure	Increased food insecurity will lead to more strain on service systems to provide assistance	Depsky and Pons (2020)
Floods and landslides	Food insecurity	Agricultural land destroyed and crops lost from inundation, access roads for food transportation blocked.	Barros *et al* (2015), Huggel *et al* (2020)
Floods and landslides	Water scarcity	If infrastructure or water storage systems are destroyed and water supplies cannot be accessed	Aristizábal and Sánchez (2020), Emmer *et al* (2016), Sepúlveda *et al* (2015)
Floods and landslides	Epidemics	Pools of water can lead to increased spread of diseases. Ruined infrastructure makes it harder to reach health facilities.	CAF (Corporación Andina de Fomento) (2000), Hofmeijer *et al* (2013)
Floods and landslides	Systemic failure	Ruined infrastructure/service systems, more strain on public service/health systems	Alfieri *et al* (2017)
Water scarcity	Food insecurity	No/limited/fluctuating access to water will heavily impact agricultural yields	Barros *et al* (2015), Vicuña *et al* (2013)
Water scarcity	Systemic failure	Increased water scarcity will lead to more strain on service systems	Marengo *et al* (2017a)
Epidemics	Systemic failure	More strain on and possibility to collapse public service/health systems	Kouadio *et al* (2012), Litewka and Heitman (2020)
Amazon biome shift	Food insecurity	Aridification can have large implication for food production	Lapola *et al* (2018), Sampaio *et al* (2019)
Amazon biome shift	Water scarcity	Changes in hydrological cycle, decreased moisture transport and precipitation	Ruiz-Vásquez *et al* (2020)
Coral bleaching	Coastal risks	Without healthy coral reefs less protection against sea level rise and storm surges	Osorio-Cano *et al* (2019), Reguero *et al* (2019)
Coastal risks	Coral bleaching	Storm surges can damage coral reefs	Osorio-Cano *et al* (2019)
Coastal risks	Systemic failure	Storm surges, erosion will lead to more strain on infrastructure and health systems	Hu *et al* (2018), Zanetti *et al* (2016)
Systemic failure	Food insecurity	Collapse of infrastructure/service systems will increase risk of food insecurity	Depsky and Pons (2020)
Systemic failure	Floods and landslides	Collapse of infrastructure/service systems will increase risk of floods and landslides	Alfieri *et al* (2017)
Systemic failure	Water scarcity	Collapse of infrastructure/service systems will increase risk of water scarcity	Kouadio *et al* (2012), UNICEF (United Nations Children's Fund) (2020)
Systemic failure	Epidemics	Collapse of infrastructure/service systems will increase risk of epidemics	Litewka and Heitman (2020)
Systemic failure	Coastal risks	Collapse of infrastructure/service systems will increase risk of storm surges, sea level rise and erosion	Hu *et al* (2018), Kouadio *et al* (2012), Zanetti *et al* (2016)

Table A2. Listing adaptation measures which are applicable to more than one risk, which risks they apply to and how, and the supporting literature.

Adaptation measure	Risks	Application	References
Early warning system	Food insecurity	Warning prior to drought	Funk *et al* (2019)
	Floods and landslides	Warning prior to flood/landslide	Aparicio-Effen *et al* (2017), Barros *et al* (2015), Drenkhan *et al* (2019)
	Epidemics	Warning prior to epidemics outbreak	Haines and Ebi (2019)
Indigenous and local knowledge integration	Food insecurity	Indigenous-led adaptation based on ecosystem management can reduce food insecurity	Moreno *et al* (2020), Oviedo *et al* (2016), Vogt *et al* (2016)
	Floods and landslides	Integrating local and Indigenous knowledge systems in adaptation measures to avoid maladaptation	Huggel *et al* (2020)
	Water scarcity	Integrated water management in participatory approaches, community-based	Rangecroft *et al* (2013)
	Amazon biome shift	Local/indigenous knowledge of fire-management	de Moraes Falleiro *et al* (2016), Eloy *et al* (2018), Mistry *et al* 2016
	Coastal risks	Local stakeholders integrated in defining adaptation actions, including relocation	Villamizar *et al* (2017)
Improved health systems	Epidemics	Investments in distributed and well-equipped public health facilities will help stop spread of diseases	Hofmeijer *et al* (2013), Moreno *et al* (2020)
	Systemic failure	Better health systems mean it is less likely for system to collapse under compound risks	
Reduced deforestation	Food insecurity	To avoid aridification and desertification	Moreno *et al* (2020)
	Amazon biome shift	Reduced deforestation would have a positive effect on precipitation, and also change course of forest fires and droughts	Nobre *et al* (2016)
Increased resilience of infrastructure and service systems	Floods and landslides	For risk reduction, avoiding bridges/houses/roads to get damaged or destroyed	Barros *et al* (2015)
	Water scarcity	Improvement of infrastructure can reduce leaks and improve efficiency and water quality	Marengo *et al* (2017a)
	Coastal risks	Artificial structures like seawalls can protect against storms and floods	Burcharth *et al* (2015), Morris *et al* (2018)
	Systemic failure	Better infrastructure/service systems mean it is less likely for system to collapse under compound risks	
Protected areas	Amazon biome shift	Avoiding excessive logging/slash-and-burn and other types of deforestation and degradation in certain areas will give forest time to recover	Bebber and Butt (2017), Gross *et al* (2016)
	Coral bleaching	Avoiding human stressors from pollution, coastal development, fishing, tourism especially in hotspot areas	Randazzo-Eisemann *et al* (2021)
Planned relocation	Floods and landslides	Relocating people where adaptation limits have been reached will avoid loss of lives, damage to infrastructure	Miranda Sara *et al* (2016)
	Coastal risks	Relocating people where adaptation limits have been reached will avoid loss of lives, damage to infrastructure	Haasnoot *et al* (2021)

(Continued.)

Table A2. (Continued.)

Adaptation measure	Risks	Application	References
Ecological restoration	Food insecurity	Avoiding monocultures as well as overgrazing and degradation will lead to less risk of aridification and desertification, and reduce risk for small-scale farmers	Lapola *et al* (2018), Moreno *et al* (2020), Oliveira and Hecht (2017)
	Amazon biome shift	Avoiding excessive logging/slash-and-burn and other types of deforestation and degradation in certain areas will give forest time to recover. Larger trees also give shaddow to smaller canopy, decreasing fire risk.	Bebber and Butt (2017)
	Coastal risks	Restoration of coral reefs, mangroves, dunes, sea grasses and marshes can reduce storm surge impacts and limit erosion.	Fanning (2014), Osorio-Cano *et al* (2019), Reguero *et al* (2019), Saleh and Weinstein (2016)
Improved water governance	Food insecurity	Better storage, water harvesting, irrigation and fair distribution will reduce risk	Kuzdas *et al* (2015), Marengo *et al* (2017a), Marengo *et al* (2017b)
	Water scarcity	Better storage, water harvesting, irrigation and fair distribution will reduce risk	Gesualdo *et al* (2019), Kuzdas *et al* (2015), Marengo *et al* (2017a), Marengo *et al* (2017b), Ostovar (2019), Richerzhagen *et al* (2019)
	Epidemics	Improved water storage, wastewater management and access to treated water are effective adaptation measures to avoid spread.	Colón-González *et al* (2013), Hofmeijer *et al* (2013), Moreno *et al* (2020)

ORCID iDs

I Hagen https://orcid.org/0000-0002-7829-7751
C Huggel https://orcid.org/0000-0001-9299-2665
L Ramajo https://orcid.org/0000-0001-6707-685X
N Chacón https://orcid.org/0000-0001-8825-9743
J P Ometto https://orcid.org/0000-0002-4221-1039
J C Postigo https://orcid.org/0000-0003-0272-8348
E J Castellanos https://orcid.org/0000-0001-9775-0518

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