Global Climate Change Impacts Attributable to Deforestation driven by the Bolsonaro Administration

Expert report for submission to the International Criminal Court.

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Oxford Sustainable Law Programme

The Smith School of Enterprise and the Environment (SSEE) at the University of Oxford has recently established the Oxford Sustainable Law Programme (SLP) in close collaboration with the Faculty of Law and the Environmental Change Institute. This new multi-disciplinary research programme examines the use of the law in addressing the most pressing global sustainability challenges that humanity faces. https://www.smithschool.ox.ac.uk/research/sustainable-law/

Executive Summary

The impacts of climate change are increasing in magnitude worldwide. The global burden of climate change impacts already spans deaths, disease, the loss of livelihoods, damage to property and infrastructure, other economic losses, and the loss of biodiversity. Every tonne of carbon dioxide added to the atmosphere today compounds these impacts. Unless drastic action is taken to eliminate net emissions of greenhouse gases from human activity and remove historical emissions from the atmosphere, the impacts of climate change will persist for centuries. Some of its consequences, such as sea-level rise or glacier retreat, will become more severe over time, even if human emissions ceased today. Climate change is a global crisis, though one whose impacts will be felt unequally around the world, with the greatest harm typically affecting communities in the Global South, vulnerable individuals in society, and future generations.

The impacts of climate change manifest through changing likelihood and intensities of extreme weather events, such as floods, heatwaves, droughts and storms, and slow-onset changes, such as sea-level rise and glacial retreat. Even though the impacts of greenhouse gas emissions arise via the complex intermediary processes of the atmosphere, developments in climate science now allow causal links to be drawn between drivers of climate change (i.e. emissions) and their impacts[1]. This report summarises the latest scientific evidence that spans the causal chain from emissions of greenhouse gases as a result of human activities, through to the consequences that affect societies.

Despite global understanding of the impacts of climate change and the humanitarian crises that will occur in coming decades in the absence of rapid reductions in greenhouse gas emissions, deforestation rates – and therefore emissions – in the Brazilian Amazon have increased substantially during the government of Jair Bolsonaro. Prior to Bolsonaro's election, deforestation in the Brazilian Amazon had fallen decreased substantially from its peak in the early 2000s, and then stabilised over the decade from 2009-2018. However, the rapid increase in deforestation since 2019 has resulted in a major uptick in emissions of greenhouse gases from the Brazilian Amazon, which will have global humanitarian consequences.

This report provides a scientific evaluation of the consequences of the greenhouse gas emissions that result from the acceleration of deforestation and land-use change that can be attributed to the government of President Jair Bolsonaro.

ES.1. Greenhouse gas emissions attributable to the Bolsonaro administration

Responsible for 19% of global CO_2 emissions since 1959, deforestation is the second largest contributor to climate change after the burning of fossil fuels (section 1.3.1). Moreover, if the goals of the Paris Agreement on climate change are to be met, and global warming limited to 1.5 °C above pre-industrial levels, deforestation-related emissions must fall rapidly. According to the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Global Warming of 1.5 °C, most scenarios for emission reductions that meet the Paris Agreement's temperature target require the elimination of all forest-related emissions by 2030. Any increases in deforestation consequently jeopardise the goals of the Paris Agreement (section 1.3.2).

It is in this context that the Bolsonaro administration has overseen a systematic weakening of legal protections against deforestation, and their enforcement, and actively encouraged increasing industrial incursion into the Amazon region (section 1.4.1). Since Jair Bolsonaro took office on 1 January 2019, deforestation rates have risen sharply. In 2019, deforestation rates were higher than at any point in the previous decade, and 34% above the 2018 deforestation rate. In 2020, deforestation in the Brazilian Amazon accelerated further, to 44% above the 2018 level. Interim data indicates that deforestation rates have increased even further in 2021.

In the Brazilian Amazon, deforestation rates had remained relatively stable over the decade from 2009-2018 and, prior to the Bolsonaro administration, previous governments had pledged to cut rates to substantially lower levels. We therefore make the conservative estimate that in the absence of the Bolsonaro government, deforestation would have continued at the average rate for 2009-2018, and attribute surplus deforestation above this level to the Bolsonaro administration. Based on these approximations, 3,985 km^2 of Amazon deforestation is attributed to the Bolsonaro administration per year, for 2019 and 2020, the years for which deforestation data is already available. To estimate the likely deforestation in the Amazon that will be attributable to the Bolsonaro administration in 2021 and 2022, we developed three scenarios that capture the plausible range of deforestation rates over the remainder of the current Bolsonaro administration: a 'low' deforestation scenario that holds deforestation rates at 2020 levels; a 'medium' deforestation scenario that continues the increase in deforestation rate observed between 2019-2020 in 2021 and 2022; and a 'high' deforestation scenario, in which deforestation rates explode, increasing linearly to reach, in 2022, the peak levels observed in 2002-2004 (Figure 3; section 1.4.2).

Based on our estimates of attributable deforestation, we then assess the carbon dioxide and methane emissions attributable to the Bolsonaro administration by considering three emissions sources: (1) reductions in carbon sequestration due to deforestation; (2) carbon dioxide emissions released through burning of deforested land; and (3) methane emissions released by replacing forested land with cattle. Across the 4 years of the Bolsonaro administration (2019-2022) the combined contribution made by these three emissions sources is equivalent to 1,700 $MtCO_2$ in the low deforestation scenario, rising to 1,900 $MtCO_2$ and 3,400 $MtCO_2$ in the medium and high deforestation scenarios, respectively (all values given to the nearest 100 $MtCO_2$; Table 1). In addition to the emissions occurring over 2019-2022, the loss of forest carbon sequestration and ongoing emissions from cattle will result in a further 6 $MtCO_2$ emitted annually even after the end of the Bolsonaro administration, unless reforestation takes place and cattle rearing ceases. The values given above relate only to the emissions from Amazon deforestation that are attributable to the Bolsonaro administration (section 1.5).

The increase in deforestation-related emissions during the Bolsonaro administration alone is estimated to account for approximately 1% of global greenhouse gas emissions each year, or roughly the same as the total emissions of the UK. Based on a recent estimate of the global heat-related deaths expected over the next 80 years due to each tonne of emissions produced today, over 180,000 excess heat-related deaths will occur globally before 2100 due to the deforestation-related emissions caused by the Bolsonaro administration, even if global emissions are cut substantially (section 1.6). This estimate accounts only for a subset of the climate-related harm caused by these emissions but is indicative of the magnitude of humanitarian consequences of the deforestation of the Brazilian Amazon as a result of global climate change.

ES.2. Attributed impacts of climate change

The latest assessment of the Intergovernmental Panel on Climate Change is that 'it is unequivocal that human influence has warmed the atmosphere, ocean and land'[2]. Virtually all observed global warming is due to human emissions of greenhouse gases and aerosols. This global warming has driven the retreat of glaciers, rising sea levels, and increasing frequencies and intensities of many extreme events, some of which are occurring with intensities unprecedented in the observational record. Nevertheless, it remains the case that not all climate-related harms occur due to climate change. In recent years, growing numbers of scientific studies have evaluated the role of climate change in a range of extreme events around the world, demonstrating the substantial role played by climate change in many of these events and therefore the gravity of climate change impacts experienced around the world. While we cannot provide a complete summary of the impacts of climate change that have occurred to date, since the role of climate change has only been assessed for a subset of climate-related impacts, the examples that we provide indicate the severity of global climate-related harms occurring due to deforestation-related emissions. In section 2 of the report, we summarise this evidence base.

The key climate change impacts assessed in our report are those related to heat (section 2.1.1), heavy rainfall and flooding (section 2.1.2), drought (section 2.1.3), wildfires (section 2.1.4), tropical cyclones (section 2.1.5), sea-level rise (section 2.2), glacial retreat (section 2.3), and the mental health impacts of climate-related disasters (section 2.4).

ES.3. Projected impacts of climate change

The impacts of climate change will continue to worsen in coming years, and the extent to which this is the case is determined by the rate at which global greenhouse gas emissions are reduced. In section 3 of the report, we summarise projections of future climate change impacts at different levels of future warming. Limiting the rise in global temperatures to 1.5 °C above pre-industrial levels will result in less severe impacts than those that will occur if rapid cuts to greenhouse gas emissions are not made. Further, the impacts of climate change will increase exponentially with subsequent warming beyond 1.5 °C. We summarise the projected impacts of climate change on extreme heat (section 3.2.1), extreme rainfall and flooding (section 3.2.2), drought (section 3.2.3), wildfire (section 3.2.4), tropical cyclones (section 3.2.5), sea-level rise and other marine impacts such as coral bleaching and marine heatwaves (section 3.3), and glacial retreat and mass loss (section 3.4).

ES.4. Impacts of climate change in Brazil and Latin America

Substantial climate change impacts are already occurring in Brazil and the wider Latin American region. These impacts are projected to worsen over coming decades if emissions continue unabated. In section 4, we focus on the impacts of climate change in Brazil (section 4.1) and the wider Latin America region (section 4.2). In addition to the impacts of climate change, the deforestation of the Amazon directly affects the local temperatures and rainfall. Increasing forest fires, occurring as part of the process of clearing forest for agricultural development, or due to the increasingly dry and hot conditions in Amazonia, due to climate change, also cause substantial local health impacts through dangerous air pollution.

Throughout Latin America, climate change alters rainfall patterns, increases the prevalence of extreme heat (section 4.2.1), compromises the availability of freshwater due to declining glacial water towers and seasonal snowpack in the Andes (section 4.2.2), threatens some of the world's most biodiverse ecosystems with habitat loss, disease outbreaks, wildfires, and ultimately causes species extinctions (section 4.2.3), and causes a range of coastal impacts due to sea-level rise, ocean warming and acidification, and the decline of fisheries (section 4.2.4). These impacts compromise food security (section 4.2.5) and human health (section 4.2.6).

The impacts noted above and discussed in detail throughout the main sections of the report are largely those that can be linked confidently to climate change and produce negative humanitarian consequences. However, there are also risks of further impacts associated with abrupt changes to the Amazon region, known as the Amazon tipping point. This tipping point describes a possible shift of the Amazon rainforest to savanna or seasonally dry forest. While the likelihood of reaching this tipping point is considered to be low in coming decades, continued climate change and deforestation of the Amazon increase the likelihood of such an eventuality. Were a tipping point in the Amazon to be crossed, the transition away from rainforest would lead to a substantial release of stored carbon, amplifying climate change, and a drying of the surrounding region, threatening agriculture, hydropower generation, and biodiversity (section 4.3).

ES.5. Climate change as a stress multiplier for conflict and population displacement

In addition to the direct impacts of climate change, greenhouse gas emissions also increase the risks associated with socio-political instability that may lead to conflict or refugee flows. In particular, growing water stress in regions that are drying as a result of climate change drives food and financial insecurity, and may increase political instability. Since there are a broad range of factors that contribute to the risk of armed conflict or population displacement, no one crisis of this type is likely to be linked exclusively to climate change. Nevertheless, by creating the conditions in which such events are more likely to occur, the United States Department of Defense[3], The World Bank[4] and other researchers[5] have concluded that climate change will contribute to increases in the risk of food insecurity, armed conflict and higher rates of internal displacement over the twenty-first century.

ES.6. Linking impacts to individual emitters of greenhouse gases

The overwhelming findings of climate research demonstrate that climate change is already causing substantial harm to communities around the world, and that these harms will increase over coming decades if greenhouse gas emissions continue unabated. The scale of deforestation-related emissions is substantial and their contribution to the harms of climate change can be demonstrated. These harms include increases in deaths and hospitalisations from extreme heat, increasing ranges of vector-borne diseases, and stronger and more frequent storms; food insecurity due to crop failure resulting from extreme weather events; loss of property and cultural practices, due to extreme weather events and sea-level rise; and increasing the risk of conditions that foment political instability, migration, and war. The gravity of the impacts associated with the recent acceleration of Amazon deforestation in Brazil should not be in dispute.

In section 6 of the main report, we explain that not only are these impacts occurring on the global scale, as a result of all greenhouse gas emissions, but that it is possible to link the emissions of individual entities, such as countries or companies to the impacts of climate change. Past studies have shown the link between individual entities' emissions and global-temperature rise[6,7], observed[7] and projected[8] sea-level rise, ocean acidification[9], and specific heatwaves[10]. These studies have demonstrated that even relatively small emissions of greenhouse gases can cause substantial impacts. As a consequence, there is robust evidence from the existing literature that the increase in deforestation-related emissions under the Bolsonaro administration is already causing, and, over coming decades and centuries, will continue to cause a global burden of harm.

Glossary

All definitions are taken from the Glossary in Annex VII of the Contribution of Working Group I to the Intergovernmental Panel on Climate Change's Sixth Assessment Report[11]*, unless otherwise stated.*

Anthropogenic	Resulting from or produced by human activities.
Attribution	The process of evaluating the contributions of multiple causal factors to a change or event.
Carbon budget	The maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other contributions to climate change (non-CO_2 greenhouse gases and aerosols). In this report, the carbon budget describes the remaining CO_2 emissions, from the present day, allowable if global temperature rise is to be limited to a specified level.
Carbon dioxide (CO_2)	A by-product of burning fossil fuels, burning biomass and of land use changes, it is the principal anthropogenic greenhouse gas that contributes to climate change.
Carbon sequestration	The process of storing carbon in a carbon pool, for instance through the uptake of carbon dioxide from the atmosphere by forests.
Carbon sink	Any process, activity, or mechanism that removes a greenhouse gas from the atmosphere.
CO_2 equivalent (CO2e)	The amount of carbon dioxide emission that would have an equivalent effect on a measure of climate change, such as global-mean temperatures, over a specified time horizon, as an emitted amount of another greenhouse gas.
Climate extreme	A weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. Extreme climate events occur when a pattern of extreme weather persists for a period of time.
Climate projection	Simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases and aerosols and changes in land use, generally derived using climate models. Climate projections depend on future changes in emissions.
Drought	An exceptional period of water shortage for existing ecosystems and the human population, due to low rainfall, high temperature, and/or wind. *Agricultural* drought describes a period with abnormally low soil moisture that impinges on crop production. *Meteorological* drought describes a period with abnormal precipitation deficit.
Greenhouse gases (GHGs)	Gaseous constituents of the atmosphere, both natural and anthropogenic, that have properties that cause the greenhouse effect. Increases in the concentration of greenhouse gases leads to a reduction in energy emitted to space from the atmosphere, and therefore warming of the earth surface temperature.

Hazard The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Heat stress A range of conditions, for instance in humans and other terrestrial or aquatic organisms when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation. Heat stress in mammals, including humans, and birds, is exacerbated by a detrimental combination of ambient heat, high humidity, and low wind speeds, causing regulation of body temperature to fail.

IBAMA The Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (Brazilian Institute of the Environment and Renewable Natural Resources) is an agency of the Brazilian Ministry of the Environment that supports protections against deforestation of the Amazon.

Impacts The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards, exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services, and infrastructure. Impacts may also be referred to as consequences.

IPCC The Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change.

INPE The Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research) is a research unit of the Brazilian Ministry of Science, Technology and Innovations and the authoritative source of data on deforestation in Brazil.

Legal Amazon The Amazônia Legal contains the nine states of the Amazon basin and includes all of the Brazilian Amazon biome, 37% of the Cerrado biome, and 40% of the Pantanal biome[12].

Paris Agreement A legally binding international treaty on climate change adopted in December 2015. The key temperature goal of the Agreement is to limit global warming to well below 2 °C, and preferably to 1.5 °C, above pre-industrial levels[13]. 190 states (including Brazil), plus the EU, have ratified or acceded to the Agreement, collectively responsible for over 95% of global greenhouse gas emissions.

Vulnerability The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Report structure

Section 1 assesses the greenhouse gas emissions that can be attributed to the increase in deforestation rates observed under the Bolsonaro administration. We present data on changes in deforestation rates before and during the Bolsonaro administration and estimate the greenhouse gas emissions attributable to the Bolsonaro administration. These emissions result from three key sources: (1) burning of deforested land; (2) the conversion of forest land to agricultural uses, including methane emissions from increases cattle farming; and (3) reduced carbon uptake by forests due to deforestation.

In sections 2 and 3, we link deforestation-related emissions to the global observed (section 2) and projected (section 3) impacts of climate change, including impacts from extreme weather events, such as heatwaves, droughts and storms, sea-level rise, and glacial retreat. Section 2 of the report provides an overview of the humanitarian impacts that have been shown to have resulted from human influence on the climate. Section 3 summarises the state-of-the-art knowledge of the projected future impacts of climate change on human societies.

The impacts assessed in sections 2 and 3 occur globally and indicate the gravity of greenhouse gas emissions in causing worldwide humanitarian consequences. In section 4, we focus on attributed (i.e., shown to already be occurring) and projected (future) impacts in Brazil and across the South American region. In section 4.3, we summarise the evidence for the existence of a tipping point in Amazonia, in which climate change and deforestation would lead to a large-scale shift in the ecosystem, accompanied by a substantial release in stored carbon, amplifying global warming. In section 5, we explain how climate change amplifies the risks of complex socio-political impacts, such as conflict and migration, through producing conditions that induce political instability, financial and nutritional insecurity, and resource scarcity.

Finally, in section 6, we explain how links can be made between individual sources of greenhouse gas emissions, such as deforestation, and the climate change impacts that occur as a result. We summarise the literature linking the emissions of individual entities, such as countries and corporations, to observed and projected climate-change impacts, and indicate the magnitude of climate-change impacts attributable to global deforestation.

1 Attribution of greenhouse gas emissions to the Bolsonaro administration

1.1 Introduction

Deforestation is the second largest human-induced contributor to climate change, after burning of fossil fuels[14]. Coupled with the changes in land use that often accompany deforestation, such as the replacement of forest land with cattle ranches, forest loss contributes substantially to global carbon dioxide and methane emissions: the two greenhouse gases with the greatest contributions to human-induced climate change. The resulting increase in concentrations of greenhouse gases in the atmosphere raises global temperatures and leads to a wide range of impacts affecting human societies, including sea-level rise, more damaging and frequent extreme weather events, glacial retreat, climatic shifts affecting crop yields, and acidification of the oceans, damaging coral reefs. The destruction of the Amazon carbon sink, one of the world's biggest natural mechanisms for removing carbon dioxide from the atmosphere, jeopardises efforts to mitigate climate change. Pathways aligned with the goals of the Paris Agreement typically require rapid and immediate reductions in net emissions from agriculture, forestry and other land use[15]. Consequently, increases in deforestation directly contravene the globally agreed objectives of the Paris Agreement.

Human-caused greenhouse gas emissions have already elevated global-mean temperatures to 1.2 °C above pre-industrial levels[16] (Figure 1)[*] and climate change is already causing acute impacts around the world (Section 2). Continued emissions of greenhouse gases will amplify these impacts. In Section 3, we explain the state of knowledge on how the global impacts of climate change increase at warming of 1.5 °C and beyond. Limiting global warming to 1.5 °C instead of 2 °C substantially reduces its global impacts. For instance, 420 million fewer people would be frequently exposed to extreme heatwaves[17]. In light of the increased impacts projected to occur under greater levels of global warming, the Paris Agreement enshrines the political ambition of all countries to limit warming to 1.5 °C[18†]. The humanitarian consequences of failing to limit warming to 1.5 °C underline the importance of meeting this target. These consequences are discussed in more detail in sections 2-4.

[*] We note that the Intergovernmental Panel on Climate Change found that the average human-induced increase in global temperatures was 1.1 °C above pre-industrial levels in 2011-2020. By 2021, human-induced warming had reached 1.2 °C above pre-industrial levels, according to the Global Warming Index, which uses the same peer-reviewed methods as the IPCC, and so this is the value we use for this report.

[†] As of February 2021, 190 states and the EU, collectively contributing 97% of global greenhouse gas emissions have ratified or acceded to the Paris Agreement. See: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en#1

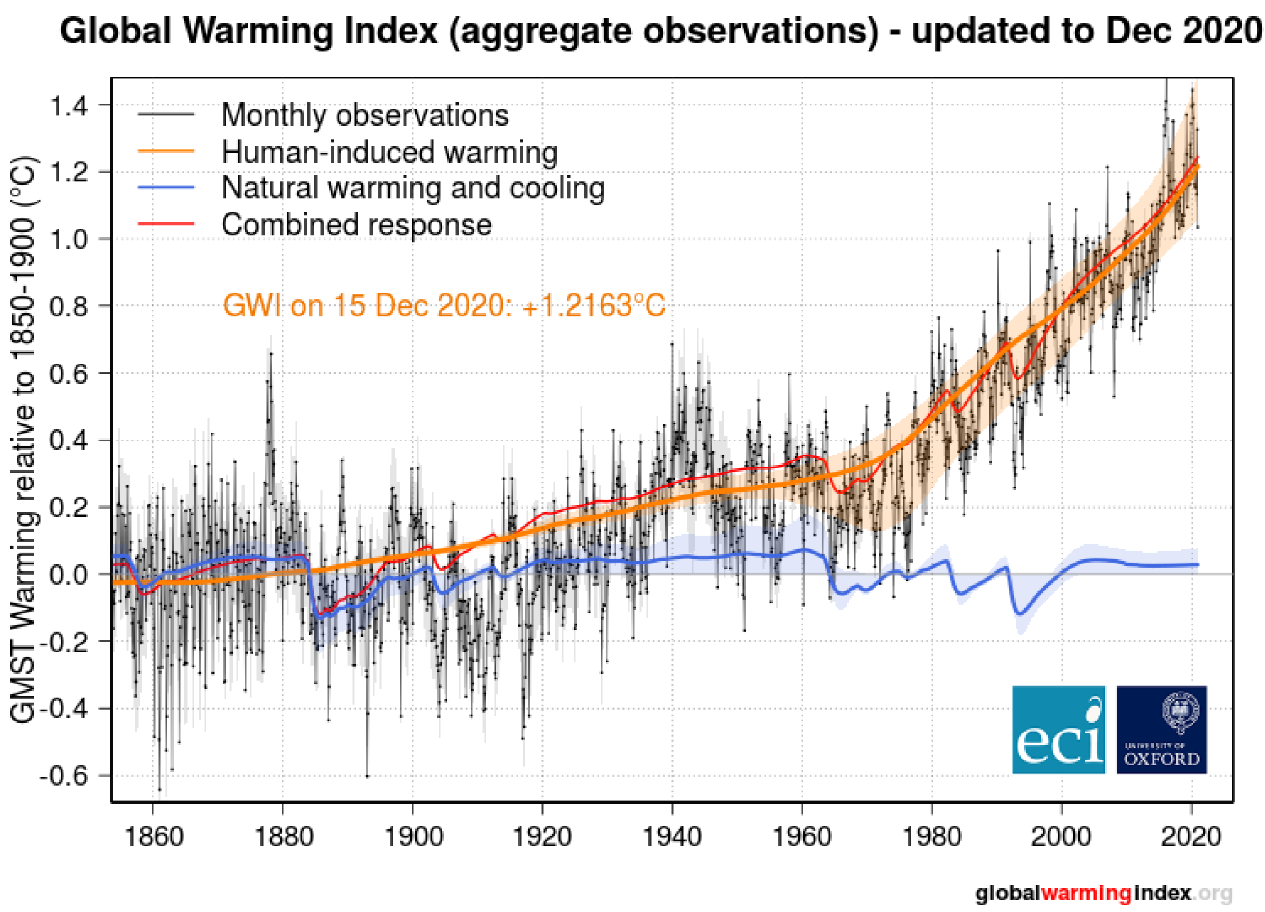

Figure 1: The human-induced (orange) and natural (blue) contributions to observed (black) temperature changes over 1850-2020. The estimated human and natural contributions are calculated as described in Haustein et al. 2017[19].

1.2 Deforestation: the global picture

Forest loss includes deforestation, the complete removal of trees to convert forest land for agriculture, mining, or urban development, and forest degradation, which describes the thinning of canopy without conversion to an alternative land use. Between 2001-2015, 27% of global forest loss was due to deforestation. However, in tropical regions, deforestation is the key driver of forest loss, accounting for 56-72% in the tropical forests of Latin America, and 48-78% in Southeast Asia, depending on the method used to estimate deforestation drivers[20]. 95% of global deforestation occurs in tropical forests, of which one third is in Brazil[21]. Tropical deforestation is driven primarily by the expansion of land for agricultural uses. 41% of tropical deforestation, including 72% in Brazil, takes place to create pastureland for cattle farming. Indeed, such is the extent of deforestation in Brazil that 24% of tropical deforestation worldwide is due to the expansion of Brazilian cattle farming alone[21].

1.3 Global deforestation and climate change

Tropical forests hold approximately one-third as much carbon as is contained in the atmosphere[22]. Consequently, tropical forests are an important store of carbon, and their deforestation has the potential to contribute substantially to climate change. The Amazon contains 50% of the world's remaining tropical forest area[23] and is therefore a globally-significant carbon sink.

1.3.1 The contribution of deforestation to climate change

Tropical forests' effect on the climate is determined by the balance between their sequestration of carbon dioxide from the atmosphere and the release of carbon dioxide and other greenhouse gases through land use, logging and forest degradation, and secondary forest regrowth. Intact and recovering tropical forests sequester substantial amounts of carbon dioxide, globally. However, rapid deforestation in tropical and extra-tropical regions means that the emissions associated with deforestation and forest degradation approximately counterbalance all forest carbon sequestration. This is the case for global tropical forests[22] and all global forests[24]. The contribution of deforestation to climate change includes (1) direct emissions from deforestation (and forest degradation), (2) emissions associated with land use introduced following deforestation, such as cattle farming, and (3) reduced carbon sequestration as a result of deforestation reducing the size of carbon sinks.

Deforestation reduces the ability of the world's forests to sequester carbon dioxide. Consequently, atmospheric carbon dioxide concentrations, and therefore global temperatures, rise. Globally, 19% of CO_2 emissions between 1959 and 2019 were caused by land-use change, including deforestation[25]. The majority of carbon emissions to the atmosphere resulting from changes in land cover is due to tropical deforestation, with smaller contributions from land degradation[26]. Tropical deforestation was responsible for emissions of 2.9 ± 0.5 GtC yr^{-1} (= 10.63 $GtCO_2$ yr^{-1}) over the period 1990-2007, partially compensated by forest regrowth of 1.6 ± 0.5 GtC yr^{-1}. This gives a net source of 1.3 GtC yr^{-1} (4.77 $GtCO_2$ yr^{-1}) from tropical land-use change[27]. This was larger than the emissions of the EU, which stood at 3.16 $GtCO_2$ in 2016[28]. Over 2010-2014, the net emissions from tropical deforestation fell to 2.6 $GtCO_2$[29].

In addition to its global impacts on the climate, Amazon deforestation has also induced increases in fires[30], and local reductions in rainfall and increases in temperature (section 4). When regional deforestation exceeds around half of land cover, substantial decreases in rainfall occur, compromising the largely rainfed agricultural systems of Brazil[31].

1.3.2 Deforestation and climate change mitigation

To achieve the Paris Agreement goal of limiting global warming to well below 2 °C above pre-industrial levels, and ideally to 1.5 °C, substantially reducing deforestation rates is essential. Scientific modelling of emission reduction pathways that meet the goals of the Paris Agreement prioritises reducing deforestation as one of the first steps in cutting emissions. There are no scenarios in which deforestation rates remain high and the goals of the Paris Agreement are achieved.

The IPCC's recent Special Report on Global Warming of 1.5°C finds that limiting warming to 1.5 °C above pre-industrial levels requires emissions from agriculture, forestry and other land use to fall rapidly, with CO_2 emissions reaching zero by 2050 at the latest. Most scenarios that meet the Paris goals require all forest-related emissions to be eliminated by 2030[32]. After 2050, in these scenarios, agriculture, forestry and other land use becomes a net carbon sink, absorbing more carbon than it emits. This underlines the damaging consequences of the recent acceleration of deforestation under the Bolsonaro administration. The need to prioritise reducing deforestation-related emissions is opposed by these increases in deforestation, jeopardising global efforts to mitigate climate change.

1.4 The Bolsonaro administration contribution to deforestation

1.4.1 How has the Bolsonaro administration caused increases in deforestation and forest degradation?

Since the Bolsonaro Government entered office on 1 January 2019, the enforcement of legal protections against deforestation have been all-but eliminated and political rhetoric has undermined efforts to moderate deforestation. In response, deforestation rates have accelerated, including an 290% increase in July-September 2019, compared to the rate in the same months of the preceding year[33].

In the Brazilian Amazon, key drivers of deforestation include expanding cattle grazing and soy plantations. Prior to the Bolsonaro government, deforestation of the Brazilian Amazon had declined substantially (Figure 2), including a 79% drop in the annually deforested area between the peak deforestation rate in 2004 and 2013[33]. Key drivers of this reduction in deforestation included state and federal government actions to establish new protected areas, initiate law enforcement campaigns, and impose credit restrictions on landowners who contribute to illegal deforestation. These actions brought the annual deforested area of the Brazilian Amazon to 5,000 km^2 in 2012-15. This rate was the lowest for decades and down from an average of 18-19,000 km^2 over 1990-2010[34]. In 2016, prior to Jair Bolsonaro's election, Brazil submitted pledges to further reduce deforestation in support of their Intended Nationally Determined Contribution to achieving the goals of the Paris Agreement, including eradicating illegal deforestation in the Amazon by 2030[35]. Meeting the goals of the Paris Agreement requires near-term and rapid cuts in deforestation, both legal and illegal.

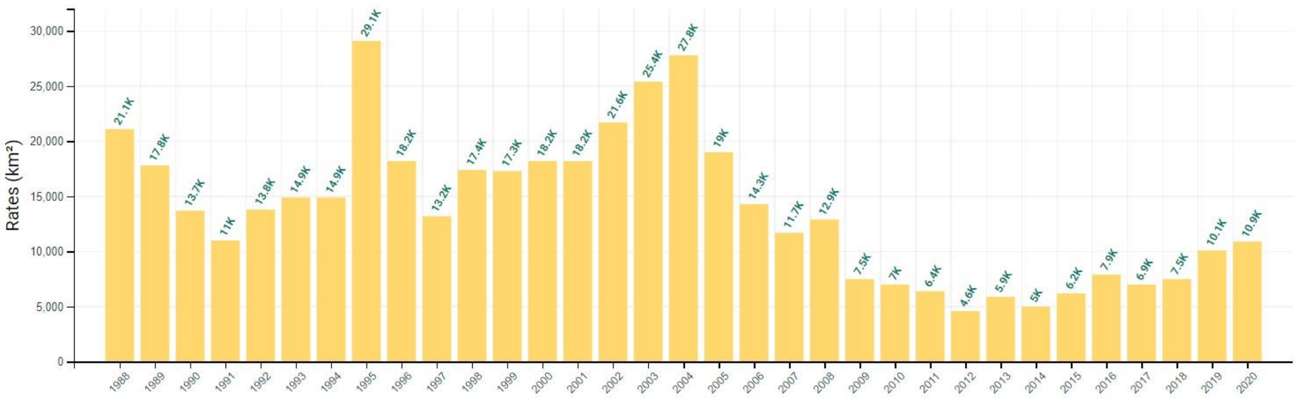

Figure 2: Annually deforested area in the Legal Amazon of Brazil, 1988-2020. Data from the PRODES deforestation dataset compiled by INPE[33].

Since the election of Jair Bolsonaro, deforestation of the Amazon has increased substantially. Bolsonaro has stated his desire to weaken environmental licensing and remove licensing authority from IBAMA, the federal environment agency, and has removed the IBAMA superintendents of 21/27 Brazilian states, replacing many of them with inexperienced military. IBAMA's enforcement capabilities have been weakened substantially, and IBAMA now gives advance notice of where it will carry out inspections for illegal deforestation. Further, 99.8% of Brazilian deforestation occurring in 2020 showed signs of being illegal, but only 2% had any action taken by IBAMA[36]. However, there is a trend in IBAMA not punishing deforestation offenders[37], facilitating deforestation with impunity.

The government has stated that agriculture and mining should be permitted in protected areas ('conservation units') and on indigenous lands. Further, the Brazilian Forestry Service, which oversees deforestation in private land through the Rural Environmental Registry, was moved from the Environment Ministry to the Agriculture Ministry and the department addressing climate change abolished. In addition to the direct impacts of policy changes and reductions in their enforcement, vandalism and attacks on indigenous and environmental agencies have increased, spurred on by Bolsonaro's rhetoric, leading to seizing of indigenous lands and repelling of environmental inspectors[37].

Weak legal frameworks for protecting land and the environment have been shown to result in large-scale forest destruction[38]. The absence of action against illegal logging by the Brazilian government has strengthened and emboldened the criminal networks driving illegal deforestation, accelerating the rate of forest destruction. The reduction of Amazonian protection has continued in Brazil in 2021, with a series of new bills that would legalise land-grabbing and loosen controls on new deforestation projects on public lands proposed[39]. One bill, known as PL-2633 would facilitate the obtaining of titles to, and provide amnesties to illegal occupants of, public rainforest land[40].

Further to the increases in deforestation that have taken place under the Bolsonaro administration to date, Brazil has submitted an updated Nationally Determined Contribution (NDC) to the Paris Agreement that weakens its emission-reduction targets for 2025 and 2030 by increasing the base year emissions against which emissions cuts are calculated. As a result of these accounting changes, Brazil's 2030 emissions would be 27% higher than those pledged when ratifying the Paris Agreement in 2016. Brazil's updated NDC also removes all commitments to stopping illegal deforestation, forest restoration and supporting native forest management. As a result of the undermining of (already insufficient) climate targets, one widely used estimate places Brazil's emissions trajectory in line with warming of up to 4 °C if other countries made similar efforts to reduce their carbon emissions. Consequently, Brazil's NDC is rated 'highly insufficient' by the Climate Action Tracker, an independent scientific analysis of national greenhouse gas emission pledges in the context of the Paris Agreement[41].

1.4.2 Evidence of changes in deforestation and land degradation

Following the start of the tenure of the government of Jair Bolsonaro, a step change in deforestation rates in the Amazon occurred and deforestation rates have since continued to rise. This contrasts with Brazil's 2009 National Policy on Climate Change, which includes a commitment to an 80% reduction in Amazonian deforestation by 2020, against a baseline of the mean rate over 1996-2005[42]. This is equivalent to a maximum extent of deforestation of 3,925 km^2. Between August 2019 and July 2020, 10,851 km^2 of rainforest were deforested, a rate 7% higher than the previous year (10,129 km^2), and the highest level since 2008[33] (Figure 3). The 2019 and 2020 deforestation extents represented 34% and 44% increases on 2018, respectively[42] and were 2.6 and 2.8 times higher than the maximum rates stipulated by the 2009 National Policy. Further, the 2019 and 2020 deforestation rates were 3,620 and 4,350 km^2 above the average deforestation rates over 2009-2018. In the calendar year 2020, Brazil's forest loss was the 15,000 km^2, 13% more than in 2019[43]. Although a small rise in deforestation levels was seen prior to the election of Jair Bolsonaro, the increase in deforested area since 2019 still represents a major change in deforestation rates, as shown in Figure 3, below.

The trend of increasing deforestation appears to be continuing, and potentially accelerating in 2021. In May 2021, deforestation of 1,180 km^2 was recorded in the Legal Amazon, with rates 41% higher than in May 2020, according to the DETER database of the Instituto Nacional de Pesquisas Espaciais (INPE)[33]. The more accurate annual (August – July) deforestation assessment, PRODES, typically assesses the deforested area as 1.54 times higher than DETER[44‡]. We also

‡ The DETER and PRODES databases are both produced by INPE, the Instituto Nacional de Pesquisas Espaciais. PRODES provides annual deforestation data and is considered to be the official dataset and most reliable for scientific use, and have been assessed to be 95% accurate. We therefore primarily use PRODES data for our deforestation calculations as the most robust and reputable source of

note that the PRODES deforestation data are likely to be conservative as they exclude loss of secondary forest – forests regrown on abandoned agricultural land[45] – in their calculations. The increase in deforestation under the Bolsonaro administration is clear for the Legal Amazon (Figure 3). While our analyses of the deforestation-related emissions attributable to the Bolsonaro administration in section 1.5, below, focus on the Legal Amazon, it is likely that increased deforestation rates have also occurred in regions outside of the Legal Amazon since 2019, and therefore that our assessment is conservative.

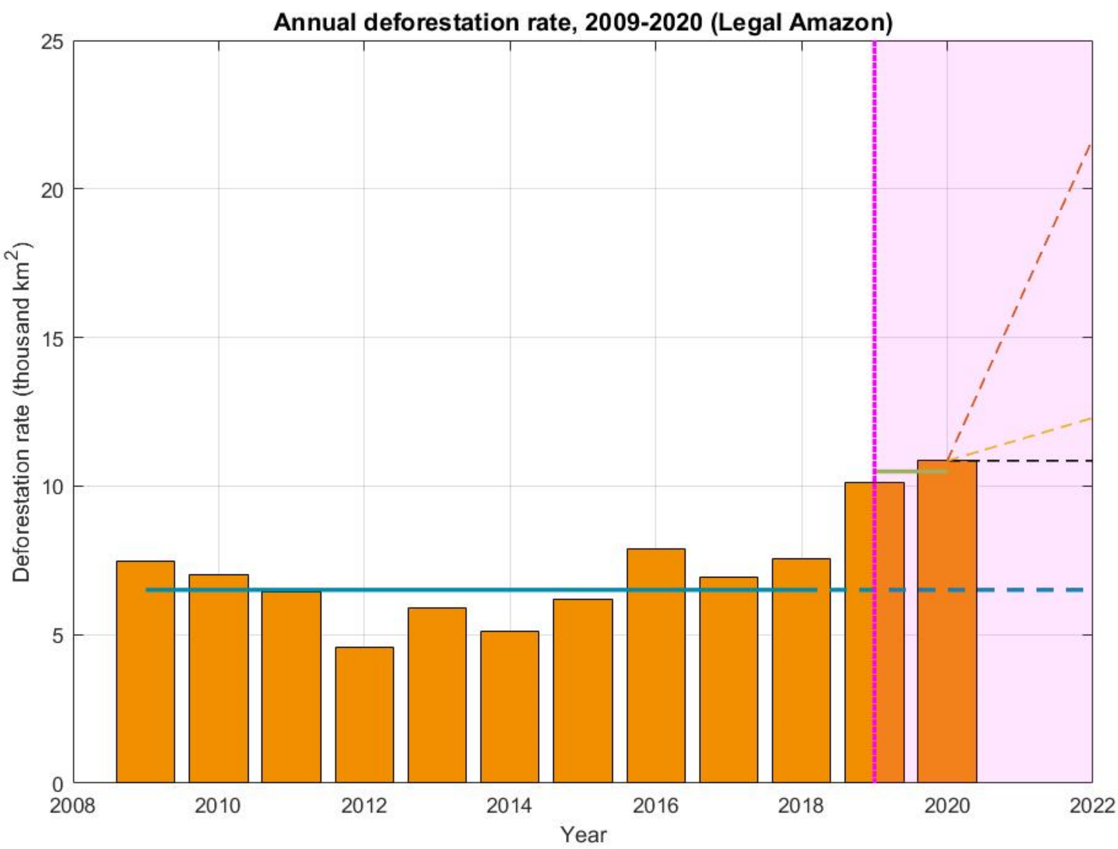

Figure 3: Annual deforestation in the legal Amazon of Brazil (orange bars). The mean deforestation rate during the Bolsonaro administration, to date (green line) is compared to the counterfactual deforestation rate: a continuation of the mean deforestation rate for the previous decade (2009-2018, blue line). The period of the Bolsonaro administration is shaded in magenta. Three future deforestation scenarios are included: a continuation of the 2019/20 deforestation rate (black dashed line), a continuation of the deforestation-rate increase observed over 2018/19-2019/20 (orange dashed line), and a 'high deforestation scenario' in which the deforestation rate doubles by 2022 to the rates observed in 2002-2004. Data from PRODES[33].

Fire plays a central role in deforestation, including in the conversion of previously forested land to pasture for cattle farming. The expansion of cattle farming is the leading driver of illegal land seizure on Reserves and Indigenous territories in the Brazilian Amazon. Between 1988-2014, 63% of the area deforested was converted to pasture for cattle[46,47] and in recent years this has risen to over 70%[21,48]. The process of converting tropical rainforest to pasture typically involves cutting down existing trees and lighting fires to remove vegetation, before planting grass and introducing cattle[46].

deforestation data for Brazil. DETER is a monthly alert system for deforestation that uses lower resolution sensors and is more affected by data limitations due to cloud cover than the annual PRODES dataset. Since PRODES data is not yet available for August 2020-July 2021, we use the lower-resolution DETER data to facilitate an indicative comparison between deforestation rates in 2020/21, with the previous year, but do not rely on DETER for our quantitative assessment. For more information on PRODES and DETER, see http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes

In August 2019, incidence of forest fires in the Brazilian Amazon was double the month's average of the previous decade[30], and there were three times more fires in August 2019 than August 2018[44]. Fires in the Amazon typically include (1) fires involved in clearing of primary forest, with vegetation felled, left to dry, and then burned, (2) agricultural processes including burning of weeds by cattle ranchers, and as part of farm-fallow systems by smallholders, traditional and Indigenous peoples, and (3) fires affecting standing forests[44]. While drought can lead to increased fire in the Amazon, peer-reviewed research has shown that the devastating 2019 fires in the Brazilian Amazon were driven by deforestation[30] and not by weather conditions such as drought[44,49]. Indeed, 2019 saw greater forest loss than the extreme El Niño drought year of 2015, indicating the role of government policy changes on top of the effect of any contributing climatic factors[23]. In 2020, fires in the Amazon were even more intense than 2019[50]. The encroachment of deforestation-driven fires onto non-deforested land further increases emissions associated with deforestation.

Nevertheless, not all aboveground biomass loss is the result of deforestation. Even though Amazonian forests are relatively resilient to drought due to their deep root systems, some tree mortality and degradation is attributable to climate-related factors. Loss of aboveground biomass has been attributed to direct human-induced deforestation, selective logging, forest fragmentation and associated edge effects, forest fires[51], and mortality from climatic disturbances.

Globally, forest degradation, which describes all mechanisms that do not result in deforestation but that result in forest loss, is the largest driver of forest-related carbon emissions, contributing 73% to the loss of aboveground biomass in the Brazilian Amazon, in 2010-2019, with deforestation contributing the other 27%[23]. Forest area coverage is affected only by deforestation and afforestation, whereas aboveground biomass may also be altered by forest degradation. In 2019, gross forest area loss totalled 3.9 x 10^6 ha, as compared with 3.0 x 10^6 ha in 2015, including both deforested and degraded land[23] (Figure 3). While deforestation, rather than forest degradation, dominates forest losses in the Brazilian Amazon, forest degradation is also a substantial contributor to forest-related carbon emissions[23]. In section 1.5, we focus primarily on carbon emissions from Amazonian deforestation alone due to greater uncertainty in calculating emissions associated with forest degradation. Our calculations therefore represent a conservative estimate of overall deforestation-related emissions attributable to the Bolsonaro administration. Estimates of the portions of overall aboveground biomass loss attributable to deforestation and forest degradation vary, with ratios of deforestation:degradation ranging from 1:2.7[23] to 5:1[52].

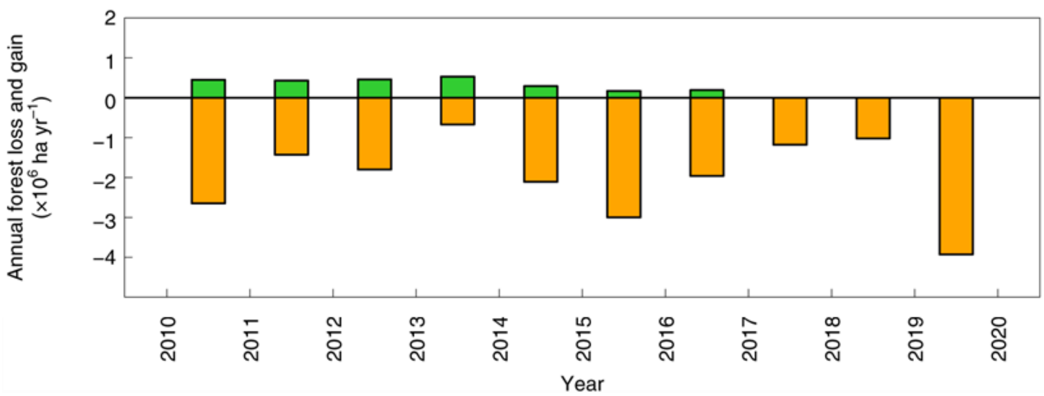

Figure 4: Annual forest-area loss (orange) and gain (green) in the Brazilian Amazon over 2010-2019. The area of forest loss was greatest in 2019, with no compensation by forest area gain in that year[23].

1.5 Calculating emissions associated with deforestation.

Deforestation-related emissions occur over two timescales. Firstly, at the time of deforestation, burning of biomass (fire is the primary method by which forest land is cleared[53]) and the introduction of cattle result in immediate greenhouse gas emissions. Subsequently, over the ensuing decades, continuing methane emissions from cattle and an ongoing deficit in carbon sequestration from deforested land increases the contribution made by deforestation to climate change. Here we estimate the contribution made by the Bolsonaro government to deforestation-related emissions as the excess in estimated deforestation-related emissions above the average rate over 2009-2018. We also present three scenarios of changes in deforestation rates in the Legal Amazon over the remaining two years of Bolsonaro's tenure (2021 – 2022): a low deforestation scenario, in which deforestation rates are held at 2020 levels in 2021 and 2022, a medium deforestation scenario, where deforestation rates increase year-on-year in line with the increase observed between 2019-2020, and a high deforestation scenario, in which deforestation accelerates linearly to double the 2020 rate by 2022, reaching similar levels to the Amazon deforestation rate observed in 2002. We note that early indications of deforestation in 2020/21 from the DETER dataset suggest that deforestation rates are likely to be most in keeping with the low or medium scenarios. The high scenario is provided to indicate the increase in emissions that would occur if substantial and rapid increases in deforestation were to happen, beyond the already high levels of the first two years of the Bolsonaro administration.

We use these three scenarios to assess the plausible range of deforestation-related emissions from the Legal Amazon over the full duration of the Bolsonaro administration. The deforested area in each of these three scenarios is shown in Figure 3. We also assess the long-term emissions commitment incurred due to deforestation and land-use change during the Bolsonaro administration. These results are presented in full in Table 1 and Figure 5, below. In sections 1.5.1, 1.5.2, and 1.5.3, all emissions data is the estimated emissions attributable to the Bolsonaro administration, and not the total emissions associated with Amazon deforestation.

1.5.1 Reduced carbon sequestration due to Amazon deforestation

The Amazon is one of the world's largest carbon sinks, accounting for one quarter of the terrestrial carbon dioxide removals from the atmosphere. Between 1990-2007, annual carbon sequestration was 0.42-0.65 GtC yr^{-1} in the Amazon[54]. This is equal to 1.54 – 2.38 $GtCO_2$, or 3.7 – 5.7% of annual global emissions[15]. Reductions in the size of the Amazon carbon sink consequently lower the rate of carbon uptake by forests and therefore increase atmospheric carbon dioxide concentrations and therefore global temperatures. We quantify this effect below (see Table 1 and Figure 5).

Given that the values stated above for Amazon carbon sequestration are based on an estimated area of intact forests in tropical South America of 6.29×10^8 ha[54], based on the Global Land Cover map 2000[54,55], the mean sequestration rate for the Amazon is 2.45 – 3.78×10^{-9} $GtCO_2$ ha^{-1} (= 2.45 – 3.78 tCO_2 ha^{-1}). We estimate that an average of 3,985 km^2 (= 398,500 ha) of deforestation was attributable to Bolsonaro in each of the first two years of his tenure (362,000 and 435,000 ha in 2019 and 2020, respectively). As noted above, this is calculated as the increase in deforestation above the 2009-2018 average rate. Consequently, the first two years of the Bolsonaro administration reduced the Amazon sequestration potential by an estimated 1.95 – 3.01 $MtCO_2$ per year due to deforestation. This estimate is based on an assumption that the average carbon sequestration rate of deforested land is equal to the mean sequestration rate of the Amazon and does not account for the carbon sequestration of ecosystems replacing the forest after deforestation (e.g., pasture), which is likely to be far lower than the sequestration of the pre-existing forest ecosystem. Nevertheless, this is a conservative estimate as it does not take into account reductions in carbon sequestration due to forest degradation. Over 2010-2019, forest degradation caused three times as much aboveground carbon loss as deforestation[23]. The resultant reduction in sequestration capacity is not estimated here.

If Amazon deforestation continued at current rates for the final two years of Bolsonaro's tenure, the overall reduced carbon sequestration potential of the Amazon attributable to Bolsonaro would equal 4.1 – 6.3 $MtCO_2$ per year in the 'low' deforestation scenario, rising to 8.1-12.5 $MtCO_2$ per year in the 'high' scenario (see Table 1 and Figure 5a, below). This represents a long-term, persistent, reduction in the capacity of the Amazon rainforest to take up carbon.

1.5.2 Emissions associated with burning deforested land

Brazil is home to the world's largest amount of live woody biomass, a total of 118 Gt, and nearly twice as much as the 2nd largest national woody biomass stock (Russia, 61.8 Gt)[56]. However, 18% of the Brazilian Amazon was deforested between 1970 and 2010[48], and the recent acceleration of deforestation in Brazil has continued this trend. Historically, fire was extremely rare or entirely absent in humid tropical forests, such as the Amazon, but has become increasingly common as deforestation increased since the 1980s[57]. As climate change has accelerated, due in part to deforestation, rising temperatures and more-frequent droughts have increased the probability of severe fires[58]. Fire is strongly associated with losses of aboveground biomass and forest area[23], and essentially all deforested land is burned to prepare it for conversion to agricultural uses[53]. The average carbon density of remaining unprotected forests was 231 tC ha^{-1} in the Brazilian Amazon in 2009[59], and there is evidence that deforestation was increasingly occurring on high-biomass regions of the Amazon[60]. Assuming all land that is deforested is burned and has a mean carbon density of 231 tC/ha, CO_2 emissions from burning of deforested land will be 847 $MtCO_2$ / million ha[§]. We estimate that emissions attributable to the Bolsonaro administration associated with clearing and burning of land deforested in 2019-2020 are 675 $MtCO_2$. This is equal to 1.7% of annual global emissions[61].

Over the remainder of Bolsonaro's presidency, deforestation-related emissions appear likely to remain at least at present levels and may rise considerably. Under our 'low' deforestation scenario, cumulative attributable emissions are 1.4 $GtCO_2$ for 2019-2022, rising to 2.8 $GtCO_2$ under the high deforestation scenario.

1.5.3 Emissions associated with land use change (e.g., agriculture)

The existing mean 'stocking rate' for cattle in Brazil is 0.97 cows per hectare[62]. In 2011, 1,294,100 ha of Brazilian deforestation was attributed to removing forest cover to expand pastureland for cattle farming. Clearing of land for cattle farming in Brazil was responsible for 542 $MtCO_2e$ yr^{-1} over 2010-2014. This does not include greenhouse gas emissions produced by the introduction of cows themselves. Consequently, Brazilian deforestation for the expansion of cattle farming accounts for 21% of global deforestation-related emissions[29].

By area, 72% of deforestation in Brazil has been attributed to cattle ranching[21] (supported by earlier analyses that attributed 71% of Brazilian deforestation to cattle ranching in 2011[48]), equivalent to 574,000 ha attributable to the Bolsonaro administration over 2019 and 2020. Based on the stocking density of 0.97 cows per hectare (the average figure for Brazil in 2014/15[62]), this is equivalent to 557,000 more cows added over the two-year period. Given an average of 100 kg of annual methane emissions per cow[63], this increase in cattle ranching is equivalent to a one-off release of 240 tCO_2e

[§] Burning 1 tonne of carbon produces 3.67 tonnes of carbon dioxide.

(see glossary), followed by annual emissions of 0.8 tCO_2e[64]. Consequently, the estimated increase in cattle farming over 2019-2020 results in a one-off emission of 134 $MtCO_2e$, followed by annual emissions of 0.4 $MtCO_2e$.

Under our 'low' deforestation scenario, cumulative attributable emissions are 279 $MtCO_2e$ for 2019-2022, in addition to annual emissions of a further 0.9 $MtCO_2e$ as long as cattle herds remain at the same size. These figures rise to 552 $MtCO_2$ under the high deforestation scenario for 2019-2022, and an additional 1.8 $MtCO_2e$ annually thereafter.

1.5.4 Summary of Bolsonaro-attributable emissions

Prior to the election of President Bolsonaro, Brazilian deforestation rates had stabilised at a substantially lower level than they had been in the early 2000s. Deforestation-related emissions would have been expected to have remained approximately stable, if not for the election of Jair Bolsonaro. Instead, deforestation rates have soared since 2019 and the associated greenhouse gas emissions are substantially greater than they would likely have been in the absence of the Bolsonaro administration.

Overall, under our low-deforestation scenario, Bolsonaro-attributable emissions over the duration of his tenure are estimated to be 1.7 $GtCO_2$, rising to 3.4 $GtCO_2$ in the high emissions scenario (Table 1, Figure 5). Further to these emissions, reduced sequestration and increased cattle numbers imply an estimated commitment of 6.1-12.1 $MtCO_2$ in annual emissions after 2022. In addition to the ongoing deforestation-related emissions due to deforestation and land-use change occurring during the Bolsonaro government, the legacy of the Bolsonaro government's impact on deforestation rates may continue beyond the end of his tenure. Deforestation and associated greenhouse gas emissions are likely to continue at high rates after 2022, due to policy changes made by the Bolsonaro administration, unless major policy changes are introduced to reverse the factors facilitating the present extremely high rates of forest destruction.

Emissions from burning deforested land make up a substantial proportion of the estimated emissions attributable to the Bolsonaro administration (307 $MtCO_2$ in 2019). We can evaluate how reasonable these estimates are through comparison with existing data on fire-related emissions in Amazonia. A recently published assessment[65] based on detailed measurements of carbon dioxide emissions over a nine-year period (2010-2018) calculated annual fire emissions at 0.41 GtC, equal to 1.50 $GtCO_2$ (1,500 $MtCO_2$). Given that deforestation rates increased by 34% between 2018 and 2019, the first year of the Bolsonaro administration, and approximately 60% of the Amazon is in Brazil, and assuming that fire-related emissions due to each deforested hectare are approximately equal across Amazonia, the data provided in ref. [65] indicate that Bolsonaro-attributable deforestation would produce approximately 300 $MtCO_2$ in emissions, in 2019. The proximity of this estimate to the value we calculate based on observed deforestation data provides strong evidence to support the robustness of our estimates.

	2019		2020		2021		2022		Total	
<u>Deforested area (Million ha)</u>										
L	1.013		1.085		1.085		1.085		4.268	
M	1.013		1.085		1.157		1.230		4.485	
H	1.013		1.085		1.628		2.170		5.896	
Pre-Bolsonaro baseline	*0.650*									
Anomalies										
L	0.362		0.435		0.435		0.435		1.666	
M	0.362		0.435		0.507		0.579		1.883	
H	0.362		0.435		0.977		1.520		3.294	
<u>Reduced sequestration ($MtCO_2$/yr)</u>										
Rate (tCO_2/ha/yr)	***2.5***	***3.8***	***2.5***	***3.8***	***2.5***	***3.8***	***2.5***	***3.8***	***2.5***	***3.8***
L	0.9	1.4	1.1	1.6	1.1	1.6	1.1	1.6	4.1	6.3
M	0.9	1.4	1.1	1.6	1.2	1.9	1.4	2.2	4.6	7.1
H	0.9	1.4	1.1	1.6	2.4	3.7	3.7	5.7	8.1	12.5
<u>Burning deforested land ($MtCO_2$)</u>										
Conversion factor (MtCO2/ million ha)	*847*									
L	306.978		368.132		368.132		368.132		1411.373	
M	306.978		368.132		429.285		490.438		1594.833	
H	306.978		368.132		827.671		1287.211		2789.993	
<u>Land use change for cattle farming ($MtCO_2e$/yr)</u>										
Stocking rate (cows / million ha)	*970000*		***One-off emissions per cow ($MtCO_2e$)***				*0.00024*			
Proportion deforested land for cattle	*0.72*		***Annual emissions per cow ($MtCO_2e$/yr)***				*0.0000008*			
	One-off	Annual	One-off	Annual	One-off	Annual	One-off	Annual	One-off	Annual
L	60.7	0.2	72.9	0.2	72.9	0.2	72.9	0.2	279.3	0.9
M	60.7	0.2	72.9	0.2	85.0	0.3	97.1	0.3	315.6	1.1
H	60.7	0.2	72.9	0.2	163.8	0.5	254.7	0.8	552.1	1.8
Overall attributable emissions										
	Cumulative to 2022 (MtCO2)			**Annual from 2022 (MtCO2/yr)**						
L	**1695.9**			**6.1**						
M	**1916.3**			**6.9**						
H	**3352.4**			**12.1**						

Table 1: Overview of observed and projected deforestation in the Legal Amazon in Brazil, and associated greenhouse gas emissions. 2019 and 2020 deforestation data from PRODES[33], 2021 and 2022 projected according to the low ('L', 2020 deforestation rate maintained), medium ('M', 2019-2020 increase in deforestation rate maintained for 2021 and 2022) and high ('H', doubling of deforestation rate by 2022 to levels last seen in 2004) scenarios described in section 1.5. Data used for calculating emissions associated with reduced sequestration, burning of deforested land, and land-use change are described in sections 1.5.1, 1.5.2, and 1.5.3, respectively.

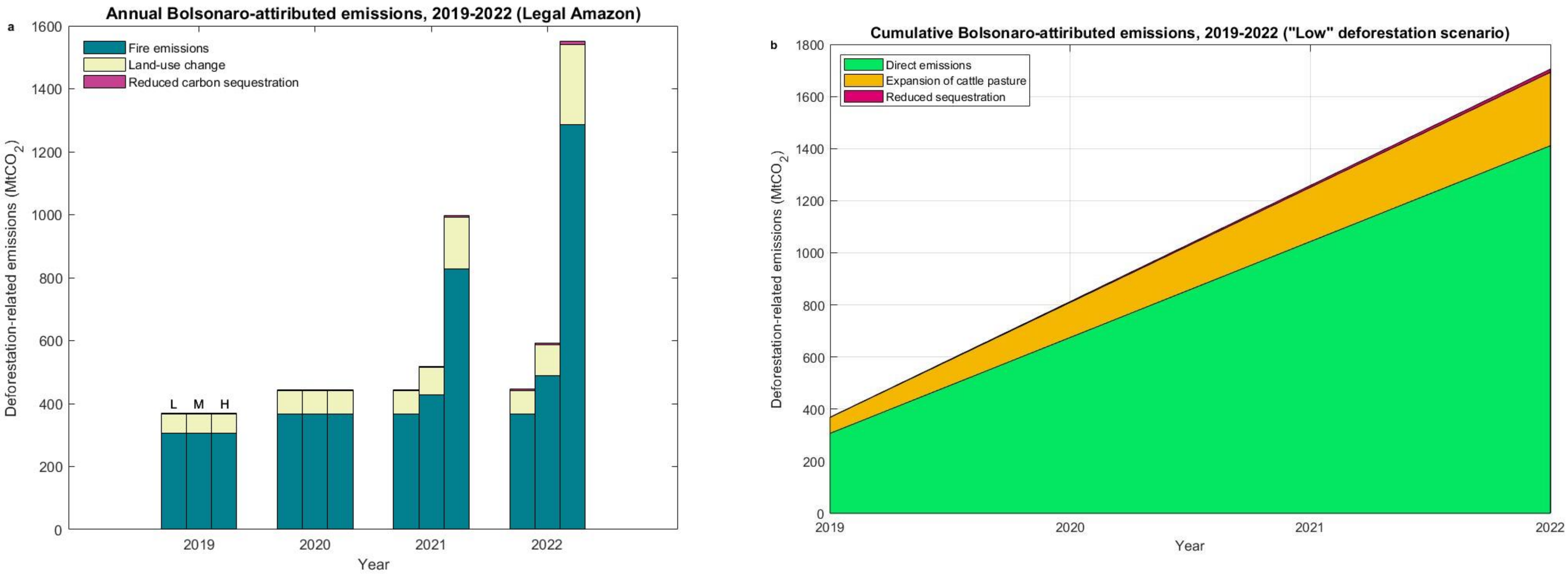

Figure 5: (a) Annual Bolsonaro-attributed emissions due to reduced sequestration, direct emissions from burning of deforested biomass, and expansion of cattle pasture, in the Legal Amazon (2019-2022) under the low, medium, and high deforestation scenarios described above. (b) Cumulative deforestation-related emissions from the Legal Amazon in 2019-2022, attributed to Bolsonaro under the low deforestation scenario, showing the contributions made by direct emissions from burning deforested biomass, the expansion of cattle pasture, and reduced carbon sequestration.

1.6 Contextualising deforestation associated with the Bolsonaro administration

In 2019 and 2020, deforestation-related emissions in the Amazon attributed to the Bolsonaro administration are estimated to account for approximately 1% of global greenhouse gas emissions. This is roughly the same contribution as that made by the total emissions of the UK. The greenhouse gas emissions associated with Amazonian deforestation contribute to climate change, and therefore substantial humanitarian consequences worldwide. These impacts, on a global scale, are discussed in detail in sections 2 and 3 of the report. Regional impacts of climate change affecting Brazil and the wider South American region are then explained in section 4.

A recently published estimate of the heat-related deaths projected to occur due to climate change found that under a high-emissions scenario in which rapid reductions in greenhouse gas emissions are not made, 226 excess deaths will occur over 2020-2100 for each $MtCO_2$ emitted in 2020. Deep cuts in greenhouse gas emissions that limit global warming to 2.4 °C above pre-industrial levels in 2100 imply that each $MtCO_2$ emitted today will cause 107 deaths by 2100[66]. The accelerated deforestation of the Amazon jeopardises efforts to limit global warming to lower levels in the 21st Century. Nevertheless, even if the lower-emissions scenario were to be achieved, the low-deforestation scenario presented above implies that greenhouse gas emissions attributable to the Bolsonaro administration will cause over 180,000 excess heat-related deaths globally over the next 80 years. This figure represents the shocking global humanitarian consequences of Bolsonaro's acceleration of deforestation in the Amazon. It is worth noting that this value is likely conservative as it accounts only for heat-related deaths due to climate change, whereas climate change also results in a far wider range of health impacts, including mortality due to other extreme weather events, such as storms and droughts, and sea-level rise.

1.7 The Bolsonaro-administration and efforts to limit warming to 1.5 °C and 2 °C

There is strong global consensus on the need to limit climate change to 1.5 °C, and certainly well below 2 °C, above pre-industrial levels to avoid the worst impacts of climate change. These targets are enshrined in Article 2 of the Paris Agreement, which defines global ambition on climate change mitigation. Pathways to meeting this goal require that net emissions of carbon dioxide are reduced to zero by around 2050 and involve steep cuts in forest-related emissions such that carbon uptake by forests and other land carbon sinks exceeds emissions associated with agriculture, forestry and other land use by around 2030[15].

At the beginning of 2021, the global emissions budget for limiting the increase in global-mean surface temperature to 1.5 °C above pre-industrial levels, with 67% probability, was 400 $GtCO_2$, falling to 300 $GtCO_2$ for a 83% likelihood of staying below 1.5 °C[2]. This budget was reduced by approximately 40 $GtCO_2$ in 2020[67], leaving a remaining budget of 360 $GtCO_2$ in 2021, equivalent to 9 years of emissions at current rates. Based on our assessment, the minimum expected contribution of the Bolsonaro administration to deforestation-related emissions (our 'low' scenario) is equal to 0.47% of the remaining carbon budget. This rises to 0.93% in the 'high' scenario. Total deforestation in the Legal Amazon of Brazil (including that attributable and not attributable to the Bolsonaro administration) is estimated to contribute 4.3 $GtCO_2$ over 2019-2022 in the 'low' scenario, over 1% of the remaining carbon budget for limiting warming to 1.5 °C. In the 'high' scenario, this rises to 1.35% of the remaining carbon budget. These calculations do not include deforestation in Brazil outside of the Amazon and represent a substantial contribution to the remaining allowable emissions if the world is to achieve the goals of the Paris Agreement. As described in section 1.3.2, deforestation-related emissions need to be eliminated most rapidly, and so increases in deforestation rates represent a significant obstacle for global efforts to achieve the goals of the Paris Agreement.

Despite the need for rapid and immediate cuts in deforestation-related emissions, under the Bolsonaro government, deforestation emissions have risen rapidly. Sustaining current high levels of deforestation compromises global efforts to limit warming to 1.5 °C. Any further increases in emissions will further jeopardise these targets.

2 The present-day impacts of climate change

In 2021, global warming due to human influence on the climate reached 1.2 °C above pre-industrial levels[16], and temperatures continue to rise. Virtually all observed global temperature change since the mid-nineteenth century has been attributed to human activities[68]. Due to human greenhouse gas emissions, increased global temperatures will remain for centuries to come.

The impacts of climate change that affect human societies arise not from changes in the global mean climate conditions, but through individual extreme weather events, and slow-onset changes such as sea-level rise. These impacts of climate change are growing in magnitude around the world and are projected to increase substantially over coming decades if greenhouse gas emissions continue unabated. Climate change violates human rights of communities around the world[69] through its manifestations in intensified and increasingly frequent extreme weather events, such as heatwaves, storms, and droughts, sea-level rise, and glacial retreat. These physical hazards result in direct or indirect impacts on human health, reduced agricultural productivity, damage to infrastructure, and threaten livelihoods.

Climate change impacts are already occurring around the world and are projected to increase substantially if greenhouse gas emissions continue unabated (section 3). In section 2 of this report, we summarise key findings from the field of attribution science which demonstrates the extent to which human influence on the climate has already affected the global burden of climate-related harms. It is not the case that all climate-related events are caused by climate change: storms, droughts, and heatwaves occurred in the past, and some would have occurred in the absence of climate change. However, the growing body of evidence produced by attribution science shows that climate change is causing substantial impacts for communities around the world. This report focuses on those impacts.

Attribution science describes a set of scientific methods for evaluating the role of climate change, or the emissions of individual entities, in causing climate-related impacts. Some studies encompass the full causal chain from emissions to the resultant damages experienced by human societies. In the context of the meteorological impacts of climate change, attribution studies seek to answer the question of how climate change has altered the *likelihood* or *intensity* of a defined event. For an individual event, attribution studies may find that an event of given magnitude was made *more likely*, and that an event of given probability was made *more intense* by climate change.

Some elements of natural systems affected by climate change, such as the extent of thick multi-year sea ice, glacier and ice sheet lengths, and sea levels respond gradually to climate change and filter out short-term variations. These 'slow-onset' trends have also been attributed to climate change, typically responding to climate change over protracted timescales. Climate change has been shown to be directly responsible for the mass loss of glaciers around the world[70], the retreat of individual glaciers[71,72], and anthropogenic greenhouse gas emissions are the dominant cause of observed global-mean sea-level rise, at least since 1970[73].

Attribution science substantiates the causal link between emissions of greenhouse gases and harms experienced by impacted communities around the world. The evidence provided by attribution science is aligned with the logic of legal causality[74,75] and provides a firm evidentiary basis for legal claims relating to climate change damages[75–78]. Attribution-science evidence has demonstrated the gravity of climate change impacts already occurring around the world.

The IPCC's recently-published 6th Assessment Report surveyed the evidence from attribution analyses conducted worldwide and found that climate change has already increased the incidence of extreme heat globally, has increased extreme precipitation events in most regions, and has increased the incidence of agricultural drought in Europe, Africa and parts of Asia and the Americas (Figure 6).

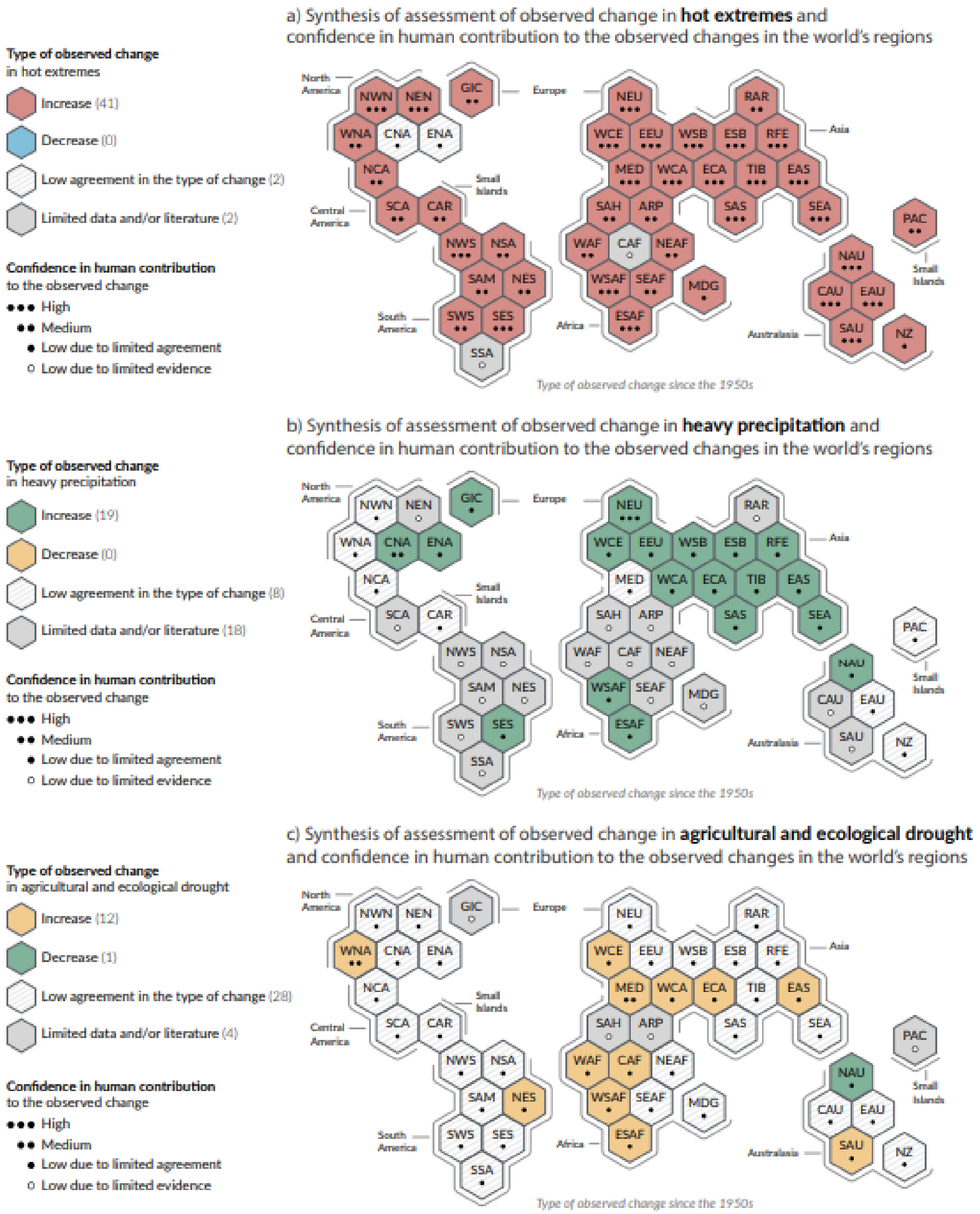

Figure 6: Observed and attributed regional changes in (a) extreme heat, (b) heavy precipitation and (c) agricultural and ecological drought across inhabited regions of the world. Regional acronyms represent: North America: NWN (North-Western North America, NEN (North-Eastern North America), WNA (Western North America), CNA (Central North America), ENA (Eastern North America), Central America: NCA (Northern Central America), SCA (Southern Central America), CAR (Caribbean), South America: NWS (North-Western South America), NSA (Northern South America), NES (North-Eastern South America), SAM (South American Monsoon), SWS (South-Western South America), SES (South-Eastern South America), SSA (Southern South America), Europe: GIC (Greenland/Iceland), NEU (Northern Europe), WCE (Western and Central Europe), EEU (Eastern Europe), MED (Mediterranean), Africa: MED (Mediterranean), SAH (Sahara), WAF (Western Africa), CAF (Central Africa), NEAF (North Eastern Africa), SEAF (South Eastern Africa), WSAF (West Southern Africa), ESAF (East Southern Africa), MDG (Madagascar), Asia: RAR (Russian Arctic), WSB (West Siberia), ESB (East Siberia), RFE (Russian Far East), WCA (West Central Asia), ECA (East Central Asia), TIB (Tibetan Plateau), EAS (East Asia), ARP (Arabian Peninsula), SAS (South Asia), SEA (South East Asia), Australasia: NAU (Northern Australia), CAU (Central Australia), EAU

(Eastern Australia), SAU (Southern Australia), NZ (New Zealand), Small Islands: CAR (Caribbean), PAC (Pacific Small Islands). Figure from IPCC AR6[2].

2.1 Extreme Weather

Here, we present a high-level synthesis of the current state of expert knowledge on changes in extreme weather hazards linked to climate change, on a global scale. As described in section 1, global climate change is caused, *inter alia*, by deforestation, and the loss of the Brazilian Amazon is a major contributor to this. We highlight the regions most affected by changes in each type of extreme weather hazard discussed, focusing on the most severe impacts. To do this, we summarise findings from the field of climate change attribution, which identifies already-occurring impacts of climate change. We note that only a tiny subset of the present-day impacts of climate change have been formally assessed using these methods. Consequently, the impacts of climate change extend well beyond the events discussed below, which merely give an indication of the gravity of the harm inflicted by climate change. The findings of attribution science have demonstrated that human influence on single weather events can cause more destruction in a few days than had been estimated for whole years in economic models of the impacts of climate change[79].

2.1.1 Heat

Summary: Heat extremes have increased in likelihood and intensity across the world due to climate change. The most significant changes have been in the likelihood of the hottest events, as detected in many recent individual heatwaves. In just two extreme heatwaves, discussed below, 125,000 deaths were directly linked to climate change. Thousands more deaths from other heatwaves occur annually, and 37% of heat-related deaths have been attributed to climate change[80]. Globally, heat-related mortality due to climate change is vastly underestimated due to the limited recording of impacts from extreme heat across the hottest and most densely populated regions. Even though cold extremes are less likely in all regions, the reduction in mortality is insignificant in comparison to the increases in heat-related deaths.

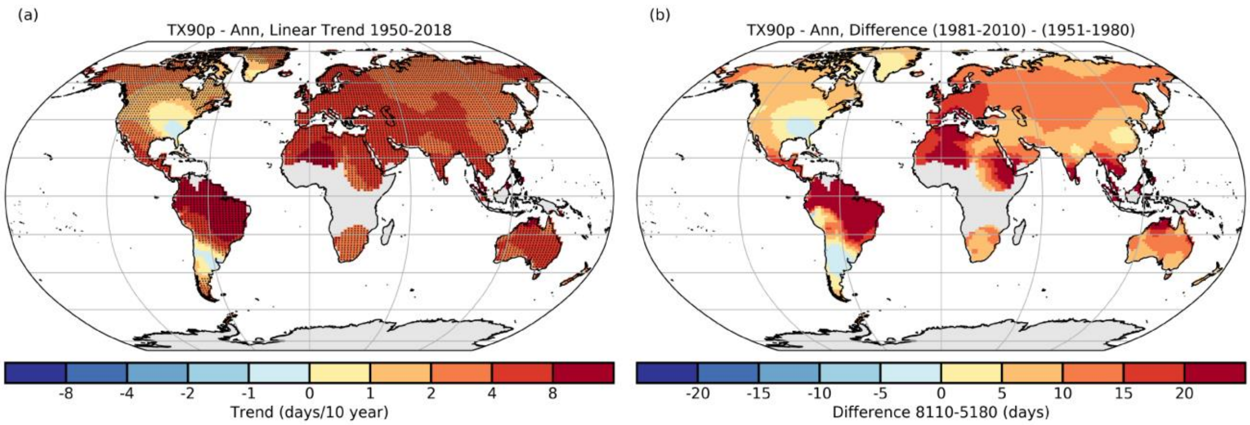

Figure 7: The number of days per year that exceed the 90th percentile of daily temperature, TX90p, is used to characterise changes in extreme heat. (a) shows the trend in this value between 1950-2018, and (b) shows the absolute difference in number of days per year that exceeded this value across two 30-year time periods – adapted from Dunn et al., 2020[81].

Changes in extremes: The most dramatic changes in extreme weather induced by climate change are in the rate and intensity of heat and cold extremes. Cold extremes are declining while heat extremes are increasing, with dire consequences for communities around the world. By 2015, the chance of the most extreme daily temperatures (above the 99.9th percentile) averaged over land had increased fivefold; equivalently, 75% of daily heat extremes were attributable to climate change[82]. Globally, as a direct result of climate change, previously very rare heat is now just unusual[81,83–85], while events now considered 'extreme' reach temperatures that were formerly all but impossible[86–88]. The increasing regularity of formerly rare events is particularly consequential: we don't tend to prepare for events that were historically so unlikely that they have never occurred[89]. Societies are especially vulnerable to the exceptionally extreme events that are now possible in a changing climate. Regional trends in heat extremes are attributed to climate change in Asia[90,91], Australia[92], Europe[93] and South America[94].

Why it matters: The impact of increased temperatures on mortality is widely established in the epidemiological literature. As climate change intensifies heatwaves around the world, heat-related deaths increase in number. The increase in the global burden of heat-related mortality due to climate change is large and growing, with 37% of heat-related deaths attributed to climate change worldwide[80], equivalent to tens of thousands of deaths per year. Increases in the number of hot days, and intensity of heatwaves results in a range of heat-related illnesses. Such illnesses include cardiovascular and respiratory complications, renal failure, electrolyte imbalance, and harm to foetal health[95]. Increasing temperatures and heatwaves have also increased the prevalence and range of temperature-sensitive pathogens, such as *Vibrio*, which can cause cholera and gastroentiritis[96].

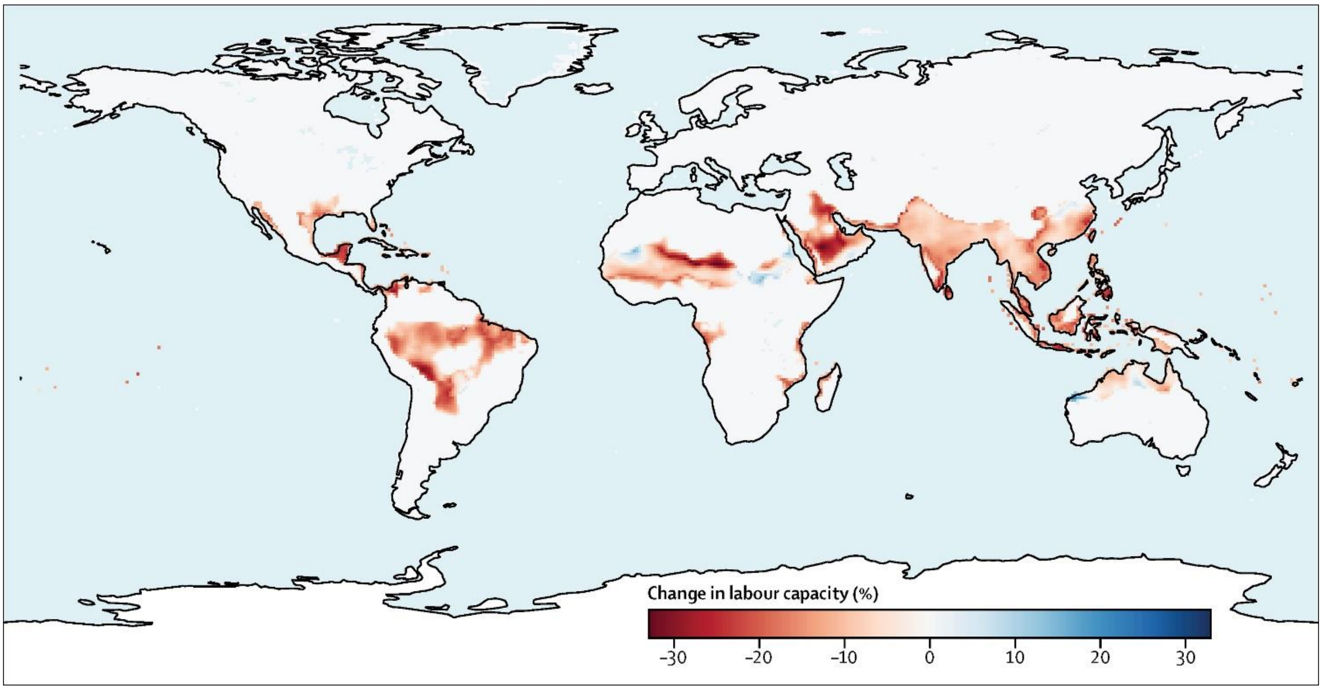

Figure 8: Change in labour capacity among rural populations by 2016 due to heat, compared to a reference period of 1986-2008[97].

Increases in the occurrence heat extremes result in substantial increases in mortality, and this effect is particularly pronounced at the hottest temperatures. Climate change increases the likelihood of reaching the hottest temperatures, at which point the human body may no longer be able to cool itself. The theoretical limit for human survival is a 'wet bulb' temperature of 35 °C, at which point even the healthiest human in shade and with water would die from severe heat stroke in a matter of hours[98]. Both mortality and morbidity rise significantly at far lower temperatures than this upper limit, affecting the elderly, very young and those with pre-existing medical conditions, such as respiratory and cardiovascular illness[97,99–101]. Heatwaves are also strongly associated with rises in harmful pollutants such as ozone, particulate matter, sulphur dioxide, carbon monoxide and nitrogen dioxide, which further contribute to respiratory health impacts[102–105].

While there have been very few observations of wet bulb temperatures over the critical 35 °C threshold, the occurrence of dangerous humid heat extremes has more than doubled since 1979[98]. By another measure, the average North Hemisphere area relevant to humans covered by extreme summer heat has more than doubled[106], and 40% of the total land surface has already entered an unusual climate in the warmest months[107]. Accounting for global population distributions, this is an even larger change in severe heat exposure due to climate change[97]. On top of that, between 2000-2016, the number of vulnerable people (over 65 years) exposed to extreme heat increased by 125 million, reaching 175 million in 2015[97]. Finally, the labour capacity of rural populations during summer months fell by 5.3% between 2000-2016 due to rising heat – in tropical regions capacity fell by up to 30% (Figure 8)[97]. Even in the US, this currently costs around USD 2 bn annually[108].

Hazard	Observed direct impacts			Attributable influence of climate change on hazard severity/likelihood (Confidence level)
	Deaths	Injured	Total Affected	
Heatwaves	157,000	193,000	320,000	Increase (High)
Cold waves and severe winter conditions	14,900	1.86 million	96.1 million	Decrease (High)
Floods	111,000	304,000	1.66 billion	Increase (Medium)
Droughts	21,300	N/A	1.44 billion	Increase (Medium)
Wildfires	1,570	7,260	3.38 million	Increase (Medium)
Storms	201,000	337,000	773 million	Rainfall Increase (High) Other impacts no change (Low)

Table 2: Direct physical health impacts of different types of disaster between 2000-2020, as recorded by EMDAT, and the attributable influence of climate change on each hazard.

Attributed impacts: Climate change amplifies the temperature of most heat extremes[109]. Attribution research has found that the most extreme heatwaves have become substantially more likely, or even only possible at all[88], due to climate change. A multitude of impactful heatwaves of the recent past have been explicitly shown to have increased in magnitude and/or likelihood as a result of climate change, including Europe 2003[110,111] and 2018[112], Russia 2010[87,113], the US[114], China[115] and across the world[116–123]. In some cases, events were effectively impossible in the absence of climate change[88,122–124], including the emerging possibility of simultaneous heat extremes across regions and continents[106].

Between the years 2000-2020, the disaster database EMDAT recorded approximately 157,000 deaths from heatwaves across the planet (Table 2)[125], although it is acknowledged that this is likely to be a substantial underestimate due to reporting limitations[126]. Around 125,000 of these deaths occurred during just two events, the European heatwave of 2003 and Russian heatwave of 2010, which resulted in 70,000 and 55,000 deaths, respectively. Both of these events were made substantially more likely by climate change, as noted above[87,110,113]. In the case of the 2003 heatwave, this was made at least twice as likely to occur, due to climate change, and has since become substantially more likely. The Russian heatwave, meanwhile, was found to have been made 5 times more likely to occur by the climate change observed since 1960[87], and the overall effect of human-induced climate change since pre-industrial times would Heatwaves as intense as that affecting Europe in 2003 have since become even more likely[111]. In the UK, estimates link around 1,500 excess deaths from three heatwaves directly to climate change[127]. And another study on the 2003 heatwave combined meteorological attribution with the effect of temperatures on mortality, to directly attribute deaths in Greater London and Central Paris; 64 additional Londoners (~20% of the total) and 506 Parisians (~70% of the total) lost their lives due to the influence of climate change[128].

CASE STUDY: Russia, 2010

In 2010, from early July until mid-August, an intense high-pressure system formed over Eastern Europe and Russia. During this time, temperatures soared above 30 °C throughout the region, breaking 40 °C in many major cities. The extremity of this event was overwhelmingly due to climate change[87,113].

This extreme heat led to widespread drought conditions that decimated 25% of the entire annual crop and triggered wildfires across more than 10 million hectares of dried-out forests, steppe and peat regions[537,538]. The destruction of grain crops led to rising food prices domestically and abroad; neighbouring Pakistan, for example, experienced a 16% rise in wheat price that caused a 1.6% rise in poverty[539]. The destruction of thousands of properties left over 3,500 people homeless. Harmful gases and aerosols from the fires became trapped in the stagnant high-pressure system, resulting in poor air quality in many major cities. This exacerbated the already-unprecedented public health crisis, particularly affecting those with severe asthma and heart problems. In the city of Moscow alone, around 5,000 more deaths were recorded than for the same period in the previous year, and across the whole country this was closer to 55,000 from a combination of heat and poor air quality[538]. The overall economic loss was approximately USD 15 bn.

Underestimation of impacts: These Europe-focused results are far from a complete tally of climate change-amplified heatwave impacts. This is largely due to data limitations. Both assessments of health associated with extreme heat[101] and weather observations, crucial for assessing the link to climate change[126], are concentrated within higher income countries. EMDAT lists 147 instances of impactful heat events from individual countries for the period 2000-2020, only an improbable 58 of which are from all of Asia, Africa, South and Central America and the Caribbean combined[125]. Of the 157,000 total deaths recorded, only 10,000 – or 6.3% – were recorded in these regions, which together constitute almost 85% of the world's population, over 60% of the land mass, and many of the hottest and most humid climates. Further, this dataset focuses only on heatwaves, periods of relatively extreme temperatures. Further, many heat-related deaths in fact occur outside of heatwaves, when temperatures are also increased by climate change, but are not captured within these data.

In the two most impactful European heatwaves recorded, the maximum recorded wet bulb temperature peaked at 28 °C; temperatures frequently exceed this in other regions of the world such as south Asia[98], with far more lethal heat events likely already occurring than are reported[129].

In addition to the attributable trends in exposure to extreme heat described in this section, we can elicit evidence from a few attribution studies that exist. For instance, in 2015 in the Indian city of Hyderabad, heat extremes over a 5-day period were made more than 30 times more likely by climate change. Including this event, three devastating heatwaves in India in 2010, 2013 and 2015 resulted in the deaths of at least 5,000 people[130,131]. Meanwhile in neighbouring Pakistan, also in 2015, the city of Karachi experienced an extreme heat event which by the same measure would have been effectively impossible without climate change[132].

The impacts from heatwaves in hotter climates may be somewhat mitigated by the natural acclimatisation of populations, among other factors such as age demographics[101,133], but this is more than likely offset by greater population density, higher frequency of more intense extremes, and greater vulnerability in many regions[134]. We are therefore extremely confident that the reported deaths from heatwaves and those linked to climate change in the 21st Century are a vast underestimate.

Is increased heat-related mortality offset by a reduction in cold extremes? Cold extremes display a decreasing trend in frequency and intensity across most of the world and at continental and subcontinental scales[81,85,93,135]. In the Arctic, the rise in heat extremes[136,137] and decrease in cold extremes[137] is especially pronounced, in line with its rapid warming[138]. Specific cold spells of recent years have displayed this decreased probability due to climate change, including in the UK[139], US[140], Europe[116,141] and China[142].

On average, mortality rates are higher in winter than summer months, especially in temperate regions[143]. However, the direct effect of cold on health remains obscured by the wide array of seasonal factors at play[144–146], including cardiovascular disease which is only weakly linked to cold temperatures[147]. For the effect of extremes specifically, there are two key factors to consider. First, temperature-mortality relationships are generally far steeper for extreme heat than extreme cold, with sharper impact thresholds[143]. Second, the most severe winter cold spells contribute little to overall winter mortality, and even in some temperature regions there is evidence that climate change will not decrease winter mortality[146]. Thus the reduction in frequency and intensity of cold extremes has likely not affected overall changes in mortality substantially, nor offset those from hot extremes[147] and the impact of increasing heat-related mortality are assessed to far exceed any reductions in cold-related mortality as a result of climate change[148–150].

2.1.2 Extreme rainfall and flooding

Summary: Heavy precipitation events are more likely and intense overall due to climate change, but with significant regional and seasonal variability. Around the world, floods cause ill health, mortality, and damage to homes, agriculture, and infrastructure. Several recent rainfall events that led to destructive flooding responsible for USD 50 bn in damages were found to be substantially strengthened by climate change. Heavy monsoon seasons and the most intense downpours are more likely due to climate change, resulting in more health impacts and damage due to flooding and drought.

Changes in rainfall extremes: By 2015, 18% of daily precipitation extremes averaged over all land were directly attributable to climate change[82]. A warmer atmosphere can hold more moisture at a given pressure: the Clausius-Clapeyron relation states that the increase in moisture held at a given pressure is 6-7% per °C. Extra water in the atmosphere combines with changes in weather patterns to affect rainfall extremes in a given region[151,152].

As a direct result of climate change, deluges are becoming more frequent and intense across many regions including North America, Asia and Europe[153–155]. In contrast to heat, these changes vary greatly across regions and seasons. For example, extreme rainfall is increasing in Northern Europe in winter but decreasing in the Southern part of the continent in summer.

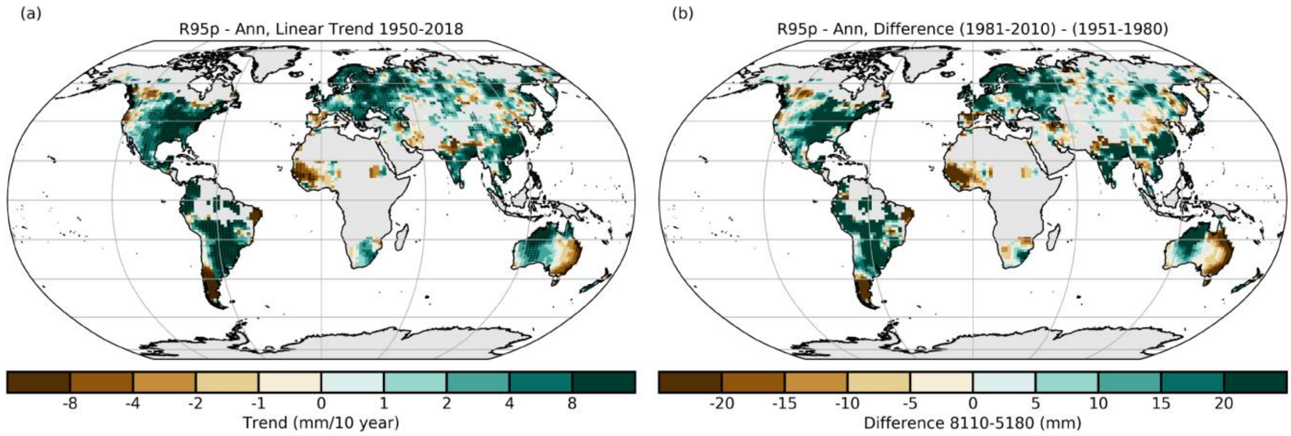

Figure 9: The amount of rainfall per year that comes from very wet days (exceeding the 95th percentile of daily rainfall), R95p, is used to characterise changes in extreme rainfall. (a) shows the trend in this value between 1950-2018, and (b) shows the absolute difference in mm from very wet days that exceeded this value across two 30-year time periods – adapted from Dunn et al., 2020[81].

Link with flooding: The impacts of rainfall extremes on human societies are primarily the result of flooding. In general, changes in the risk of flooding are due to the combination of heavy precipitation with other factors including the susceptibility of areas to flooding, land use change and river management[156]. As a result, there is high regional and sub-regional variation in trends in flooding[157,158], but many of the observed changes to river flow can only be explained by human influence on the climate[159]. Evidence from attribution-science literature shows that growing numbers of floods have been made more intense by the effect of climate change on precipitation[160–164].

Why it matters: Flooding damages property and infrastructure, as evidenced by disaster data for the years 2000-2020 in which floods globally caused USD 610 bn in damage (Table 2). It also places people in direct danger of injury and death. The flood events recorded in the EMDAT database led to 111,000 deaths and affected 1.66 bn people over the period 2000-2020 (Table 2). Indeed, flooding is the environmental hazard that affects the greatest number of people. One further study that considered only large floods found that 255-290 million people were directly affected by flooding between 2000-2018, and the number of people affected by flooding continues to increase due to population increases and climate change[165].

The health impacts of floods result directly from dangerous water flows and inundation, as well as 'cascading impacts', in which the destruction of infrastructure limits access to services and utilities including clean water and sanitation, resulting in ill health[166]. In turn, this enhances the spread of and vulnerability to water-borne disease, including leptospirosis, cholera and other diarrhoeal diseases such as giardiasis, salmonellosis, and cryptosporidiosis[166,167]. This occurrence of such outbreaks following floods is well-documented. This evidence includes an inventory of 87 extreme events between 1910-2010[168], known associations between flood events and gastrointestinal illness in the US[169,170] and India[171], and has been observed in the aftermath of floods in Pakistan[172], Mozambique[173], China[174], Ecuador[175], the Solomon Islands[176] and many others[177,178]. Crucially, this is especially impactful in areas of pre-existing high vulnerability[168,179].

In addition, vector-borne disease such as malaria, dengue and West Nile Fever spread further following flooding, as more widespread stagnating waters provide breeding grounds for the proliferation of mosquitoes[166,180]. Finally, many diseases are also enhanced by the effect of warmth (amplified by climate change) and high humidity, because this increases the longevity of many pathogens and mosquitoes[177,180,181]. The combination of climate change impacts on precipitation, and other factors that amplify the resulting impacts, such as temperature, create compound risks. These may be particularly pronounced in south Asia and south-eastern South America. Similar compound events also affect low-lying coastal areas where high coastal sea levels, due to storm surges and sea-level rise, combine with heavy rainfall combine to amplify resulting flood damages[182,183], or tropical cyclones result in blackouts, increasing vulnerability to high temperatures as air conditioning is disabled[184].

Hazard	Observed direct impacts		Attributable influence of climate change on hazard severity/likelihood (Confidence level)
	Insured Damages (USD)	Total Damages (USD)	
Heatwaves	10,000	13.4 bn	Increase (High)
Cold waves and Severe winter conditions	4.63 bn	31.3 bn	Decrease (High)
Floods	74.1 bn	610 bn	Increase (Medium)
Droughts	21 bn	119 bn	Increase (Medium)
Wildfires	51.3 bn	94.3 bn	Increase (Medium)
Storms	499 bn	1.30 trillion	Rainfall Increase (High) Other impacts no change (Low)

Table 3: Direct damages of different types of disaster between 2000-2020, as recorded by EMDAT, and the attributable influence of climate change on each hazard. Note that these values are likely to be substantial underestimates of the true magnitude of damages.

Attributable impacts: Annual monsoons are a critical source of rainfall for at least 60% of the world's population in areas including south and east Asia, Australia, and east and west Africa[185]. The south Asian monsoon is of particular societal importance, providing 80% of the water to the subcontinent, which contains nearly a fifth of the world's population and is heavily reliant upon agriculture[186]. In the 20th Century, a decline in the East Asian summer monsoon rains was observed, with the most intense rains becoming shorter but more intense, including flooding and droughts[187]. Since 2000, the strength of south Asian monsoon rains has increased, with the most pronounced increases occurring in the most intense events[186]. This pattern covers all monsoon regions, to varying degrees, and crucially an associated increase in both drought and flooding[187,188]. In response to future warming, and if aerosol emissions are reduced, substantial increases in monsoon rains are expected, resulting in growing flash flooding risks. However, as increased precipitation is expected to occur over fewer days of more intense rainfall, worsening of droughts also becomes more likely[187].

According to EMDAT, around 49,000 deaths due to flooding occurred in south Asia from 2000-2020, almost half of the global total flood mortality. The region has also suffered damages of around USD 104 bn, only around USD 4 bn of which is recorded as insured damages. Many of the deadliest and most destructive floods in this subset occurred during the monsoon season, including in 2000 (India and Bangladesh), 2007 (across south Asia), 2010 (Pakistan), 2017 (Bangladesh), and 2005, 2008, 2013, 2019 and 2020 (India). However, even outside of the monsoon season, rainfall extremes have been amplified by climate change[189].

Outside of south Asia, the most impactful flood events in terms of both mortality and numbers of people affected by flooding also occurred primarily in low- and middle-income countries in Africa, including Sudan, Ethiopia, and Nigeria; South America, including Peru, Colombia and Brazil; and the Caribbean, including Haiti and the Dominican Republic. While few attribution assessments on specific events are available in these regions, there is nonetheless evidence of links between these types of events and climate change (see above). Further, trends in increased flooding have been identified in regions including parts of Brazil[190] and Ethiopia[191], which combine with other factors to pose greater danger to people. For example, the Metropolitan Region of São Paulo has simultaneously undergone rapid urban expansion and an increase in the number of extremely heavy precipitation days. Such events were exceedingly rare in the 1950s, but by the 2010s, occurred 2-5 times per year. This has placed people at a rapidly rising risk of flash flooding.

Specific extreme rainfall events with a detected anthropogenic influence have occurred in Europe[192–195], the Mediterranean[196], US[118,162,197], New Zealand[198] and China[199–202]. Collectively, these events represent economic losses and destruction of property of more than USD 50 bn.

In certain areas, attribution studies on rainfall have directly estimated the fraction of damages incurred due to climate change. For example, in the UK between 2000-2020 approximately USD 9 bn in flood damages have been attributed to climate change[127], and in New Zealand between 2007-2017 we can attribute USD 140 million in insured-only damages (likely a significant underestimate of overall costs)[79]. While changing weather patterns can be complex in a given area, the general trend is increasingly extreme rainfall resulting in destructive flooding over a large portion of the world's surface.

2.1.3 Drought

Summary: Drought risk has increased in drought-prone and Mediterranean-like regions around the world, due to the influence of climate change on multiple causal factors. Several recent high-impact events have been shown to have been amplified by climate change, causing billions in economic losses and driving food insecurity, migration and conflict. In common with the assessments provided in other sections of this report, the events for which the role of climate change has been evaluated only represent a small subset of the total drought impacts inflicted by climate change globally. In some highly vulnerable regions such as East Africa, specific droughts cannot confidently be linked with climate change but are occurring more often, disrupting the livelihoods of millions of people.

Changes in extremes: Droughts are complex but extremely impactful events that affect billions of people worldwide (Table 2). There are many different types of drought with varying impacts. The main categories include meteorological, agricultural and hydrological drought. All are connected, and each simply refers to an anomalous moisture deficit in part of the hydrological system relative to some baseline, be it in precipitation directly, soil moisture, or groundwater reservoirs, respectively[203]. The fingerprint of climate change on increasing drought has been observed in several drought-prone regions of the world, including California, the Pacific Northwest, western North America, and the Mediterranean[203,204], as well as globally[205]. With the exception of the Mediterranean, which is already receiving markedly less precipitation, this is largely due to amplified temperatures driving evaporation and melting snowpack, reducing the meltwater contribution to riverflows[203]. Other smaller Mediterranean-like regions such as central Chile, the far southwest tip of southern Africa and southwest Australia have also dried due to climate change, and are now more prone to drought[206].

'Flash droughts' are a type of soil moisture, or agricultural, drought that occurs extremely rapidly, with little warning[207] and can have severe consequences for agricultural productivity. In recent years, there has been a notable rise in such events in the US, China and South Africa[203]. Meanwhile, some of the most catastrophic droughts in the world continue to occur in East Africa[208]. Though no single drought there has been linked directly to climate change, this is likely due in part to a relatively short observational record and high natural variability, especially for precipitation[209–211]. More generally, the drying of the major rainy season in the region, the 'long rains'[212], is likely connected to climate change[213,214].

Why it matters: Since 2014, the number of people in the world going hungry has increased year on year. In 2019, there were approximately 690 million undernourished people. The growth in food insecurity is linked to conflict, alongside climate-related shocks such as drought[215]. The least food secure regions of the world are the most vulnerable to drought, and thus any increase in drought severity due to climate change. In Brazil, an ongoing drought since 2019 has led to water scarcity, severe crop losses including corn and coffee, and amplified fire activity in the Amazon. In south Asia, the changing patterns of monsoon rainfall as well as rising temperatures and other types of extreme weather have already caused a decline in food security[216]. In East Africa, the major drought in 1984/85 led to a famine that caused the deaths of around 450,000 people. More recently, a drought in 2008-10 affected 13 million people, another in 2010-11 affected 12 million and caused the deaths of 250,000 people in Somalia alone. Since 2005, droughts have increased in frequency in East Africa and caused substantial livestock death, disruption of livelihoods and rising food prices[208,217]. In turn, this has contributed to internal migration and further socio-economic instabilities in the region[208]. From South Asia across the middle east and most of Africa, hunger is a growing challenge that climate-amplified drought is exacerbating. More broadly, extension of drought across water-scarce regions is exceptionally costly through its impact on ecosystems, agriculture and wider society[203].

Attributable impacts: Illustrating this, the fingerprint of climate change has manifested very clearly on many recent droughts. California provides an exemplary case. From 2011-2017, it suffered an extended drought, possibly the worst in a thousand years[218]. Even as this event unfolded, scientists demonstrated that various contributing factors were attributable to climate change, including reduced snowpack[219,220] and warm dry years[221,222]. This drought was then alleviated by incredibly intense seasonal rainfall that led to destructive flooding, with damages of at least USD 1 bn[223], in a compound event that has been linked to climate change[224]. Similar compound droughts and floods have occurred in the UK[225] and East Africa[208]. Not only that, new research shows that the California drought was a smaller part of a larger mega-drought stretching from 2000-2018, which itself was pushed from a moderate event to the worst in 1200 years by climate change[226]. From 2014-16, economic losses in the agriculture industry amounted to at least USD 5.5 bn, and the loss of 42,000 jobs[227–229]. Furthermore, during the first three years of the drought, hundreds of millions of trees perished due to water stress, wildfires and proliferating bark beetles; in parts of the Sierra Nevada almost half of all trees died[230].

There are several other cases of drought across the world that have been shown to have been intensified by climate change. This includes South Africa 2015-17[231,232], Europe 2016-17[233], Indonesia 2015[234], New Zealand[235] and Canada[236].

CASE STUDY: Indonesia, 2015

In July-October 2015, Indonesia experienced a combination of severe heat and extremely low precipitation that created drought conditions. This was due to the occurrence of a strong El Niño and the resulting sea surface temperatures were amplified significantly by climate change[234].

The impacts of this drought were myriad and severe. Farmland drought affected over 111,000 hectares of crops[540], which led to widespread loss of income, rises in food prices[541] and poverty[542]. It triggered the worst fire season since 1997, resulting in air pollution that detrimentally affected the health of millions and caused in the deaths of over 100,300 people across Indonesia, Malaysia and Singapore[543,544]. The impact on vegetation more widely disrupted local wildlife, causing thousands of long-tailed monkeys to attack and steal from villages in search of food[545].

The impacts of these droughts vary greatly in severity and form, being acutely related to vulnerability in the affected region. In Canada, drought conditions led to forest fires that created a serious public health risk (see section 2.1.4). In New Zealand, economic costs of the 2013 drought totalled at least USD 1.3 bn. In Europe, drought costs an average of €6.8 bn per year. Against this backdrop, the extreme 2016-17 event caused loss of many types of crops, including cereals, olives, tomatoes, wine grapes, and almonds, with losses of at least €2 bn in Italy alone. Episodic drought is becoming more common in Brazil, and though the number of fatalities has fallen drastically, the number of people affected is still increasing; since 1990, hundreds of droughts affected over a billion people[237]. In South Africa, economic losses totalled USD 400 million, cost tens of thousands of jobs and months of extreme water restrictions for citizens in late 2017[238]. Cape Town also narrowly avoided 'day zero', when there would have been no water remaining in city pipes. Attribution research has demonstrated that climate change amplified all of these impacts. Finally, in the Fertile Crescent from 2007-2010, the worst drought in the instrumental record led to widespread agricultural failure and livestock death. In Syria, this contributed to the large-scale migration of 1.5 million people from rural areas to cities, which has been held partially responsible for the outbreak of the still-ongoing conflict within the country.

2.1.4 Wildfire

Summary: Wildfire risk has substantially increased in several regions, with severe health impacts. Between a quarter and half a million deaths annually are attributable to landscape fires, as well as at least USD 100 bn annually in health impacts in the US and Canada alone. The signal of climate change has been detected in several recent fire events, suggesting direct causality to millions of killed or displaced animals, thousands of hectares of crops burned and thousands of deaths due to air pollution.

Changes in extremes: Wildfire risk is inextricably tied to dry and hot conditions, and is greatest during periods of 'Fire weather', classified using various metrics as some combination of high temperature, low humidity, lack of rain, fuel availability and high wind speed[239,240]. The risk of wildfire has already substantially increased in many regions, including the western US, Alaska and Canada[241–244], the Mediterranean[245–247], Amazonia[246–249], southeast Asia[247] and Australia[250–252].

Recent blazes across the world have proved to be violent manifestations of this. For instance, in British Columbia in 2017 and 2021 severe hot and dry summers led to unprecedented forest fires. In 2017, the burned area was made 7-11 times larger by climate change and, equivalently, the event was made 2-4 times more likely[253]. Similar results were found in an analysis of fire risk in Western Canada, where fires as large as those that burned almost 600,000 ha near Fort McMurray, Alberta, in 2016, were found to have become 1.5-6 times more likely to occur as a result of climate change[254]. In Sweden in 2018, extensive forest fires were made 10% more likely by climate change[255]. And using the same method, the record-breaking Australian bushfire season of 2019/20 was made at least 30% more likely by climate change[256].

Why it matters: Wildfires can cause direct mortality, although the total number of direct deaths are typically lower than for other extreme events (Table 2). However, wildfire smoke consists of fine particulate matter (known as $PM_{2.5}$ and PM_{10}) that reaches deep into the lungs when inhaled, can reach the bloodstream, and is likely more toxic than ambient particulates of the same scale[257]. The hazardous air pollutants that constitute the smoke aggravate existing respiratory health issues, trigger new conditions and may also have links to cardiovascular health impacts[258–260], as well as adverse effects on pregnancy outcomes[261]. In Canada, short term effects of wildfire smoke include 54-240 premature deaths and USD 0.41-1.8 bn annually, while long-term chronic issues are responsible for 570-2,500 premature deaths and costs of USD 4.3-19 bn annually[259]. A similar study for the US from 2008-2012 showed that short-term effects cost thousands of lives and additional hospital admissions for respiratory and cardiovascular illness annually, while long-term exposure cost tens of thousands of lives annually – the economic costs of these health burdens was estimated as USD 11-20 bn (2010$) per year for short-term, and USD 76-130 bn per year for long-term effects[262]. Finally, across the world total attributable deaths to landscape fire smoke are in the hundreds of thousands (262,000 in La Niña years, compared with 532,000 during El Niño), with the worst affected areas being sub-Saharan Africa and southeast Asia[263].

Attributable impacts: Severe impacts have also been recorded for attributed weather and fire events. For instance, during the anthropogenically amplified European heatwave of 2003, the central and Algarve regions of Portugal experienced the worst mega-fires in history[264]. The resultant smoke dispersed across Europe, increasing the concentrations of $PM_{2.5}$ by 20-200% in many places[265], where several hundred deaths were linked to air pollution in the UK and Netherlands alone[266]. As noted in section 2.1.3, fires across Indonesia in 2015 led to over 100,000 excess deaths. Similarly, in Russia in 2010 smoke from burning forests and peatlands became trapped over population centres, exacerbating the public health crisis and causing up to 2,000 excess deaths in Moscow alone[267]. And in the 2019/20 bushfires in Australia, levels of $PM_{2.5}$ exceeded the WHO guideline levels fourfold[268]. Smoke from the fires was responsible for "417 excess deaths, 1,124 hospitalisations for cardiovascular problems and 2,027 for respiratory problems, and 1,305 presentations to emergency departments with asthma"[269,270]. Finally, the 2016 Alberta wildfires displaced over 80,000 people and caused over CAD 3.5 bn in insured losses. As noted above, these fires were made substantially more likely due to climate change. Across Canada, wildfires burn 2.1 million ha per year, approximately the area of Wales[254].

CASE STUDY: Australia, 2019/20

In the summer of 2019/20, New South Wales experienced the worst fire season on record, since dubbed the 'Black Summer fires'. This event was made at least 30% more likely by climate change[256]. Not only that, the sheer scale of the fires went beyond anything simulated in models, leading to a call for urgent improvement of risk modelling for accurately informing society[546].

These fires burned a record 19 million hectares of forest and woodland[547], resulting in the direct destruction of 5900 buildings and tens of thousands of livestock being killed. An estimated 3 bn mammals, reptiles, birds and frogs were killed or displaced, making it "one of the worst wildlife disasters in modern history."[548], with fears of possible extinctions of endangered species[269,549].

Across the region, levels of $PM_{2.5}$ exceeded the WHO guideline levels fourfold[268]. Smoke from the fires was responsible for "417 excess deaths, 1,124 hospitalisations for cardiovascular problems and 2027 for respiratory problems, and 1305 presentations to emergency departments with asthma"[269,270].

2.1.5 Tropical Cyclones

Summary: Tropical cyclone rainfall increases across all basins are attributable to climate change, as is a global increase in rapid-intensification events. Basin-specific attributable changes include the poleward shift of storm tracks in the North Pacific and a slowdown of translation over the US. Further, several recent seasons of high cyclone activity and rainfall from many individual events were amplified by climate change. In the North Atlantic alone, this applies to events that caused half a trillion USD in damages.

Changes in extremes: Trends indicate no significant change in the frequency of tropical cyclones globally, but a greater fraction of those that do occur are the most intense Saffir-Simpson category 4 and 5 superstorms[271,272], which usually dominate the societal impacts[273]. Tropical cyclones are also shifting poleward in most regions, affecting the areas impacted[274]. Further, a slowing in tropical cyclone movement has been observed[275,276], accompanied by deposition of higher rainfall intensities[277], affecting the severity of impacts.

There is substantial variability between basins. Increasing trends in the number of storms are most significant in the central Pacific, Arabia Sea and North Atlantic, and decreases are observed in the Bay of Bengal, the southern Indian Ocean and western North Pacific. This spatial distribution change is too large to be explained by natural variability alone and is linked to climate change[278]. In the North Atlantic, an observed increase in intensification rate is likely too large for natural variability[279], likewise for the significant slowing of translation speed over the US[275], while the observed increase in overall activity is significant yet not attributable to climate change[280]. In the Bay of Bengal, despite the decreasing numbers, there is a clear increasing trend in the fraction of high intensity storms and overall cyclone energy[281]. Changes in overall activity are less certain in the west Pacific due to high variability, but northward shift in storm tracks since the 1980s is significant[274,282], as is a slowdown of translation speed[276].

There have also been several notable events amplified by climate change in recent years, including Hurricanes Irma, Maria, Katrina, Harvey, Florence, Sandy, Typhoon Haiyan and others. And notable recent seasons of high cyclone activity could not be explained without anthropogenic influence, including in the Arabian sea in 2015[283], in the western North Pacific in 2015[284–286], and in the North Atlantic in 2017[287].

Why it matters: Tropical cyclones often cause flooding, including due to storm surges affecting coastal areas, the impacts of which are encompassed in the losses described in section 2.1.2. In addition, storms generate high winds that fell trees, and destroy property and power lines, thus creating further disruption. For instance, in the wake of Hurricane Irma in 2017, services on Puerto Rico were hindered by blackouts after a partial collapse of the power system[288]. When Hurricane Maria struck just two weeks later it caused devastation exacerbated by this additional vulnerability. Further, it extended the spatial and temporal aspects of disruption to services and the power grid across the island and for months into the future[289,290]. The subsequent reliance on generators led to worsening air quality in San Juan[291]. The extreme rainfall also triggered over 40,000 landslides across the island, wiping out other power lines, roads and other structures[292]. The storm's passage also severely damaged vegetation across the island, which took months to fully recover[293]. There were also more long-term impacts. For example, in 2017 in Puerto Rico, in the context of an already-struggling economy, the severity of the 2017 hurricane season may have led between 129,000 – 477,000 Puerto Ricans to migrate away from the island[294].

Attributable impacts: Rainfall from both Hurricanes Maria and Irma was amplified by climate change[277]. As a result of these hurricanes, at least 1,000, and potentially as many as 4,645, people lost their lives[289,295]. Other high-mortality tropical cyclones include Typhoon Haiyan[296] and Cyclone Idai[173], which are estimated to have led to over 7,000 and 1300 deaths in southeast Asia and across south-eastern Africa, respectively. Typhoon Haiyan was shown to have been strengthened by climate change, increasing the height of the resulting storm surge by 20%[297]. During Cyclone Idai, flooding destroyed over 800,000 hectares of croplands belonging to half a million households[298]. In the Philippines, Haiyan severely impacted the livelihoods of 3.4 million coconut farmers and thus disrupted a major component of the nation's agriculture industry[299]. The deadliest cyclone in the global record in the 21st Century, representing nearly 70% of all recorded mortality for storms in the period, was Cyclone Nargis, which struck Myanmar in 2008 and caused over 138,000 fatalities[300]. This cyclone formed due to anomalously warm waters in the Bay of Bengal[301], where such storms are becoming less frequent but more intense due to climate change[281].

The extreme rainfall from Hurricanes Katrina, Irma, Maria, Harvey, and Florence were each individually amplified by climate change[277,302–305]. Furthermore, analysis of specific drivers of Hurricane Harvey showed that such an event was linked with anomalously high ocean temperatures (both in the Gulf of Mexico and globally), therefore suggesting direct causality to global warming[306]. Together, just these five storms caused almost half a trillion dollars in damage to property and infrastructure, wiping out homes, roads, utilities and businesses.

In the North Atlantic basin alone, it is likely that other hurricanes constituting damages in excess of USD 200 bn follow a similar pattern[125]. Furthermore, while Hurricane Sandy was not significantly intensified by climate change[307], the probability of storm surges as high have more than tripled due to sea level rise[308]. The added effect of climate change on this storm surge resulted in an extra USD 8 bn in damage and affected a further 71,000 people[309].

2.2 Sea-level rise

Summary: Sea levels are rising at increasing rates, primarily due to human influence on the climate[73]. Sea-level rise occurs due to rising global temperatures, leading to the thermal expansion of the oceans, and the melting of ice sheets and mountain glaciers. Global sea levels have risen by an average of 1.7 ± 0.3 mm per year since 1950, increasing to 3.3 ± 0.4 mm for the period 1993-2009, and the rate is anticipated to increase significantly in coming decades[310]. Sea-level rise leads to damage to property, infrastructure, agriculture and water resources through permanent inundation of land, increasing high-tide flooding, salinization of freshwater resources and coastal erosion. Further, sea-level rise can amplify the impacts of storm surges induced by tropical cyclones, increasing deaths and damage associated with tropical cyclones.

Sea-level rise impacts: Emissions of greenhouse gases and aerosols as a result of human activity are responsible for at least one third of observed global-mean sea-level change over the 20th Century[311]. A widely-cited estimate is that at least 49% of the observed 20th-Century sea-level rise is due to climate change[312] and the IPCC state that 'there is *high confidence* that anthropogenic forcing *very likely* is the dominant cause of observed [global-mean sea-level] rise since 1970'[73].

Sea-level rise causes direct impacts through inundating coastlines, salinizing water resources in freshwater lakes and groundwater[313], and increasing the area affected by high-tide flooding. Sea-level rise impacts also result from its combination with other phenomena, such as wind storms and coastal precipitation[183], to increase storm surge heights and coastal erosion. The impacts of sea-level rise affect coastal populations, infrastructure and ecosystems[73].

Why it matters: 640-700 million people lived in coastal areas below 10m above sea level in 2000, representing a huge proportion of the world's population exposed to sea-level rise impacts[73]. In Europe, the present-day expected annual economic impacts of extreme sea levels is estimated to be €1.25 bn, with 102,000 people exposed to coastal flooding[314]. In New York City, what was a 1-in-500-year flood is now expected to occur once every 25 years. Such flooding events are projected to occur as frequently as every 5 years by 2030-2045[315]. Although the impacts of sea-level rise attributed to human influence to date are limited[73], sea-level rise is projected to become a key driver of the impacts of climate change over coming decades (section 3.3).

Attributable impacts: Sea-level rise has been shown to have amplified cyclone impacts through increasing storm surge heights and therefore the area affected. For instance, USD 8.1 bn of the USD 60 bn in economic damages inflicted by Hurricane Sandy in 2012 in the area around coastal New York would have been avoided in the absence of human-induced sea-level rise. As a result of sea-level rise, the area flooded by Sandy's storm surge increased such that 71,000 additional people were affected[309]. In addition to storm surge impacts, attribution evidence on 'sunny-day' flooding has also found that the flooding affecting Southeast Florida in September 2015, while caused by a natural spring tide, was made 6 times more likely by the sea-level change observed between 1994-2015 alone[316]. The risk of coastal flooding is increasing globally due to sea-level rise. Projections of future sea-level rise (Section 3.3) indicate that these risks will grow substantially in future, especially in the absence of rapid greenhouse gas emission reductions.

2.2.1 Other marine impacts

In addition to the direct impacts of sea-level rise, the warming of the oceans can cause marine heatwaves, periods of extremely high sea temperatures, that can cause severe impacts on marine ecosystems. These impacts include mass death of marine organisms, including invertebrates, fish and seabirds, local extinction of mangrove and kelp forests, coral bleaching, changes in phytoplankton blooms, changing species composition and geographical distribution, and toxic algal blooms[317]. These effects can lead to reductions in fisheries' catches and threaten food availability for communities that are nutritionally dependent on the seas. The incidence of marine heatwaves has doubled since 1982. In 2016, around 25% of the ocean surface experienced its longest or most intense marine heatwave on record[318].

Globally, 84-90% of marine heatwaves occurring worldwide have been attributed to the global temperature increase since 1850-1900, which in turn is almost entirely attributable to human emissions of greenhouse gases and aerosols[68].

As ocean temperatures rise and marine heatwaves occur more frequently, a range of impacts on coastal and marine organisms will occur (Figure 10). Coral bleaching has become more prevalent[319]. Coupled with the impacts of ocean acidification, the fate of the world's coral reefs will have substantial implications for the 450 million people who live close to coral reefs and depend on these ecosystems for income and nutrition[320]. Tropical coral reefs also play a vital role in coastal protection against storms, with reefs dissipating approximately 97% of wave energy, reducing coastal erosion. Mangroves also provide important protection for coastal communities from storms, but these too are threatened by the impacts of climate change, due to being unable to keep up with sea-level rise and suffering other impacts such as reductions in sediment supply. Coastal areas that are currently protected by mangroves and coral reefs are therefore likely to become exposed to growing risks in future[321].

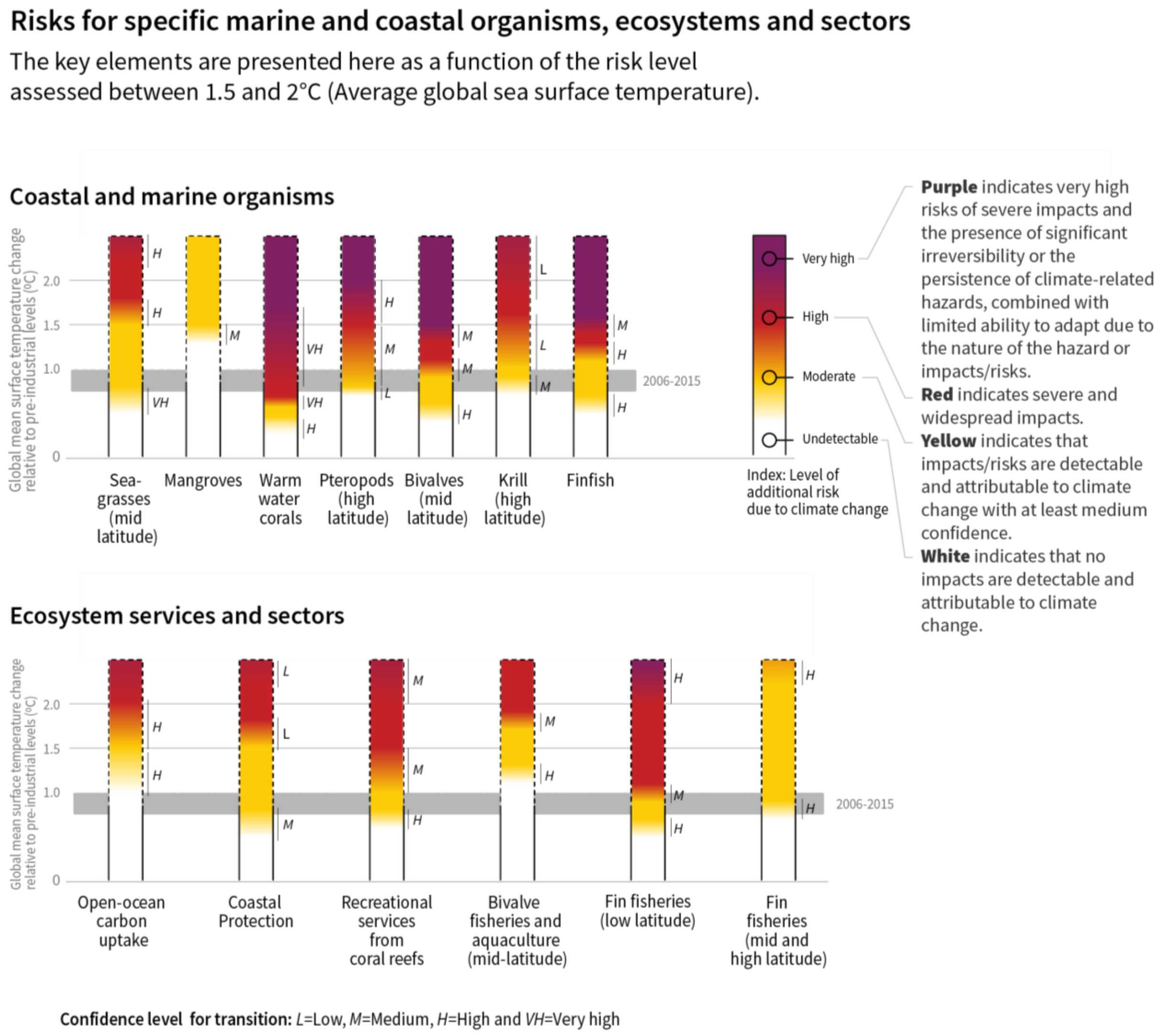

Figure 10: Risks due to ocean warming (amplified by other consequences of climate change including ocean acidification) for various ocean organisms, ecosystems and sectors at 1.0 °C, 1.5 °C and 2.0 °C of sea-surface temperature warming above pre-industrial levels. The grey bar shows the global-mean surface temperature over 2006-2015 and assessed changes in risk levels derived from expert judgement of IPCC authors and evidence in the peer-reviewed literature. Confidence levels for the location of points of transition between different risk levels are noted in the diagram (L = low, M = moderate, H = high, VH = very high). Figure from ref. [17].

2.3 Glacial retreat

Summary: Glaciers are retreating globally, threatening water resources in regions that are (seasonally) dependent on glacial meltwater and creating a range of hazards in mountain regions. Although the impacts of glacial retreat are not yet as substantial as extreme weather events on the global scale, the impacts of climate change on glaciers can have profound consequences for communities downstream of glaciers, especially if they overlap with the growing impacts of extreme weather events, and hazards attributed to the retreat of glaciers have caused thousands of deaths, directly attributed to human influence on the climate.

Impacts of glacial retreat: The worldwide retreat of mountain glaciers is one of the most prominent impacts of climate change in public discourse and an established consequence of anthropogenic climate change[71,72,322,323]. Glaciers are retreating in nearly all high-mountain regions[322]. In some cases, this may compromise vital water resources[324], and these impacts are likely to become much more pronounced in future[325].

Why it matters: Glacial meltwater plays an important role in maintaining streamflow in river systems fed by mountain glaciers. In regions with low seasonal or annual precipitation, meltwater from glaciers[326–329] and snowpack[330–332] may constitute a substantial portion of agriculturally-available water. Around 800 million people depend in part on meltwater from the 95,500 high-mountain glaciers of Asia, where glaciers are drought-resilient sources of water which mitigate the region's vulnerability to drought[333]. Drier river basins with higher interannual precipitation variability, such as the Indus, experience the greatest relative precipitation reductions during droughts, making extreme water shortages more likely and amplifying the importance of meltwater for communities[334]. For instance, in the Indus basin, the July mean meltwater fraction of streamflow is 53%, rising to 63% in a drought year. Glacial melt is consequently vital for hydropower, and water supplies for communities and agriculture. The annual net glacier melt volume of the Indus basin is equivalent to the needs of 87 +/-19 million people at the threshold of absolute water scarcity[334]. Past analyses have shown that mass loss from high-mountain Asia is among the highest of the regions evaluated in the IPCC's Special Report on the Ocean and Cryosphere in a Changing Climate[323]. The retreat of glaciers in the Upper Indus basin has negatively affected glacier-supported irrigation systems[335].

Attributable impacts: As a result of the human-induced retreat of mountain glaciers, proglacial lakes are expanding[336], threatening downstream communities with glacial lake outburst floods[337,338]. Attribution research has found that early human-induced climate change increased the risk and impacts of a deadly glacial lake outburst flood that killed at least 1,800 people in the Peruvian city of Huaraz, in 1948. The ongoing risk of a glacial lake outburst flood from the same lake that produced the 1948 event, Lake Palcacocha, now threatens a city of 120,000 people and has been directly linked to climate change[72]. Other disasters in mountain regions may be affected by climate change, although formal attribution assessments have not yet been possible. For instance, the catastrophic mass flow that left over 200 people dead or missing in February 2021, in Chamoli, India, occurred due to a huge rock and ice avalanche. Even though that specific event has not been attributed to climate change, warming is known to decrease the stability of slopes in mountain regions, including due to the degradation of permafrost and glacier ice[339]. Finally, human-induced retreat of mountain glaciers has led to the re-routing of rivers, affecting downstream communities that rely on stable water supplies[340].

2.4 Mental health impacts of disasters

Summary: We can confidently attribute an increase in mental health challenges in affected communities alongside a rise in many types of severely impactful extreme weather. In particular these mental health impacts disproportionately affect more vulnerable and marginalised communities.

Links between climate and mental health: Mental health risks and impacts are growing due to climate change, as evidenced by a limited but rapidly expanding literature[97,341,342]. Climate change affects many aspects of mental health, not only triggering mental illness and exacerbating pre-existing problems but also impacting overall states of resilience and well-being[341]. It does this in several ways: disasters trigger post-traumatic stress disorder (PTSD), anxiety, depression and suicidal thoughts, among other conditions[343]; incremental changes such as rising temperatures, sea levels and episodic drought lead to increased financial and relationship stress and increased instances of violence, especially towards women[343]; the global scale of climate change leads to hopelessness, guilt and despair[341,342].

For extreme weather events, quantitative attribution of mental health impacts to climate change remains challenging. This is due to the diverse nature of such impacts, and because attribution studies typically consider one aspect of the causal chain (climate-meteorological event or meteorological event-mental health impacts), not both[341]. Nonetheless, the severe mental health impacts of different types of disaster including heat and humidity extremes[344–346], floods[347–353], storms[354–357], wildfires [358,359] and drought[360–363] are very well documented. These impacts persist long after individual events themselves occur, they affect disaster first responders severely and local first responders most of all[364,365], and are more likely to occur in those with pre-existing mental health conditions[341,343]. In addition the mortality and morbidity toll of climate change will cause substantial mental ill health for relatives of those worst affected.

Attributable impacts: A few cases now exist in which mental health impacts are attributed to an event and the event itself is attributed to climate change. For instance, Hurricanes Katrina and Maria had rainfall amplified by climate change[277] and resulted in widespread anxiety-mood disorders[354,366–368] especially prevalent among the most marginalised groups[369] and the young[370]. The Black Saturday bushfires in Victoria, Australia were made more likely by climate change[371], and resulted in PTSD in a significant minority of the most affected groups[358]. The 2013/14 UK floods were made more likely by climate change[192,372,373] and caused increased psychological morbidity among those both flooded and disrupted[348].

3 Future impacts of climate change

3.1 Introduction

Continued emissions of greenhouse gases will result in increasingly severe climate change impacts in future. Since the magnitude of climate change impacts increases with greater levels of global warming, future greenhouse gas emissions will determine the extent of future impacts. In section 3, below, we provide an overview of the future impacts projected to occur under a range of scenarios. These scenarios include those in which greenhouse gas emissions are cut rapidly and future warming is limited, and higher-emissions scenarios in which global temperatures continue to rise, causing more extreme impacts.

The future impacts of climate change are assessed using climate model simulations. These simulations can project changes in the climate system, and therefore the incidence and intensity of extreme weather events, sea levels, glaciers, and other components of the earth system that are affected by climatic changes. Here, we overview the projected changes in these impacts under a range of greenhouse gas emissions scenarios. This assessment is not comprehensive but indicates some of the impacts that are likely to arise as a result of greenhouse gas emissions, including those occurring due to the Bolsonaro administration's acceleration of Amazon deforestation.

3.2 Extreme Weather

3.2.1 Heat

Summary: Extreme and dangerous heat will occur more frequently across the world (Figure 11, Figure 12), especially Africa, South Asia and South America. The impacts include substantial losses in summer labour productivity, up to 20% in some regions, and rapidly rising mortality in vulnerable populations. These will be most severe in tropical nations, poorer nations, and those most heavily reliant upon primary industries. Limiting warming to 1.5 °C rather than 2 °C approximately halves most impacts.

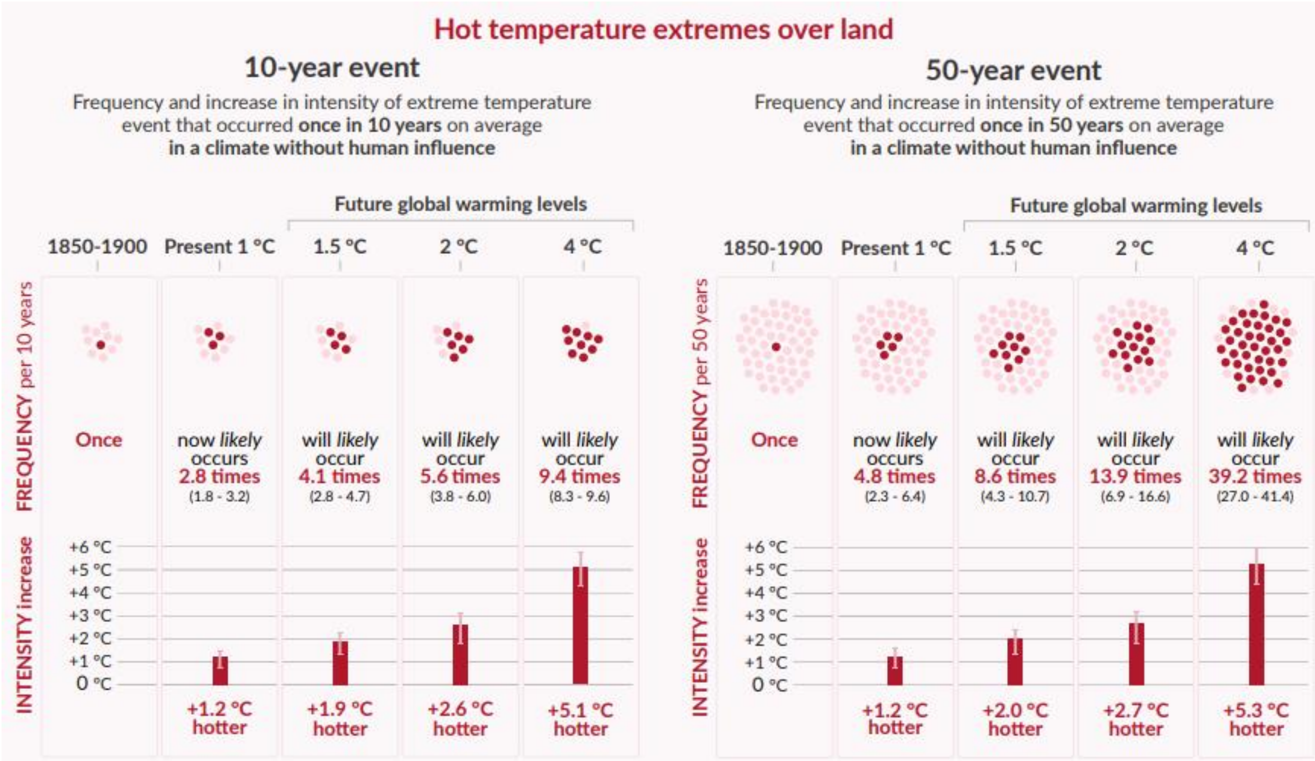

Figure 11: Projected changes in the intensity and frequency of extreme heat events, relative to the intensity / frequency of such events in the pre-industrial climate (1850-1900). Extreme heatwave conditions have already become hotter and more frequent due to observed climate change. Future warming will substantially increase the regularity and impacts of these heat extremes, but the extent to which the incidence / intensity of extreme heat will increase is determined by the magnitude of future warming – and therefore future greenhouse gas emissions. Figure from IPCC AR6[2].

Changes in extremes: In a warming world, heat extremes will occur more often and with greater intensity, causing growing heat stress across the world[374]. Currently, around 30% of the population are exposed to hot humid conditions that cause mortality for more than 20 days per year. If climate change continues unabated, this will rise to 74% by 2100[129]. As populations are still increasing, this means that the absolute number of people exposed to deadly heat conditions will grow even more rapidly. By another measure, global exposure of people to extreme heatwave events will increase 30-fold by 2100[375]. This global view shrouds the even more intense regional impacts of future extreme heat; while the average exposure in Europe to severe heat will increase by 4 times, African nations will experience 118 times more[375] and south Asia and south America will also experience more rapid increases[376].

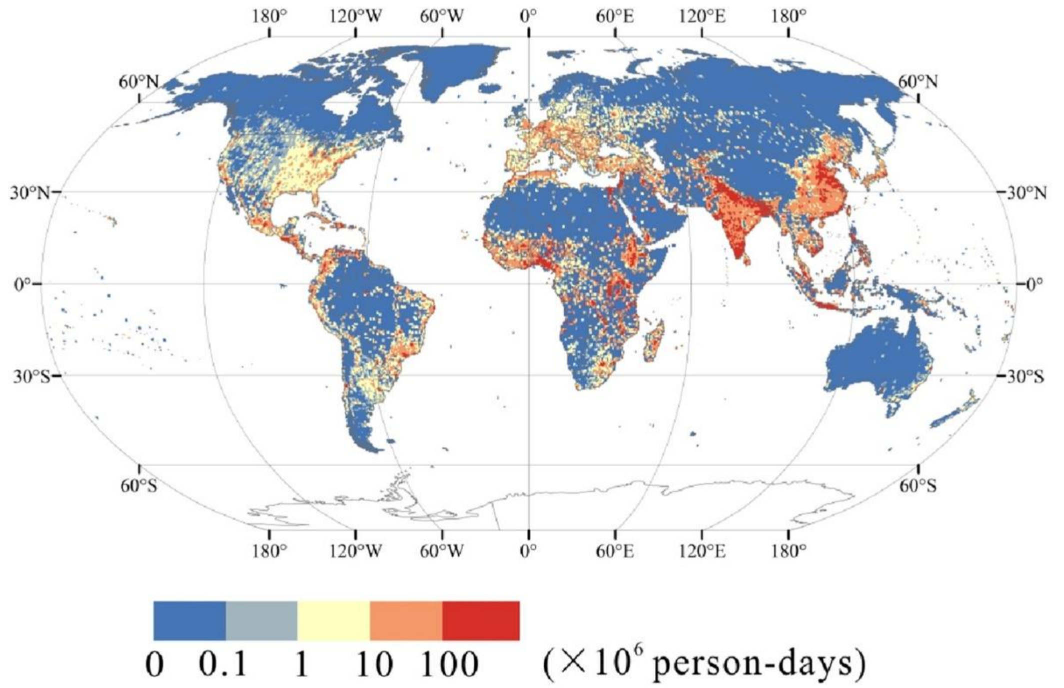

Figure 12: Projected population exposure to extreme heat under high-emission scenario climate change and projected population growth (scenario RCP8.5-SSP3) for 2046-2065 – adapted from Chen et al., 2019[377].

In west and north Africa and the Middle East, the overwhelming majority of people will begin to experience days of dangerous heat stress due to climate change[378,379]. Similarly, across south Asia and east Africa, overall exposure to severe heat will increase nearly 16-fold for 2 °C of warming, and more when the expected population increases are accounted for[380]. And in India specifically, exposure to severe heat will rise by roughly 15 times by mid-century and 92 times by end-century[381]. These regions are all densely populated, still rapidly growing and acutely vulnerable to extreme heat due to limited cooling infrastructure and adaptive capacity, especially west Africa and south Asia[374]. Moreover, the most extreme temperatures are increasing at the fastest rate. The most extreme wet bulb temperatures of today will occur over 150-750 million more person-days by 2080, depending on the global warming rate, which in turn depends, *inter alia*, on deforestation practices. Furthermore, from being effectively impossible in the modern day, events that exceed the upper limit for human survivability may occur by mid-century and cover a million person-days annually by 2080, especially in south Asia[374,382].

Growing megacities will bear the brunt of impacts. Even with relatively low warming, south Asian cities such as Kolkata and Karachi will experience heat as severe as the 2015 event every year, while 350 million people in megacities across the world (such as Shanghai, China and Lagos, Nigeria) will begin to experience such conditions[383]. This is a conservative estimate that doesn't incorporate the amplifying effects of urban heat environments, which can make heat stress twice as bad as the surrounding areas[384]. Heat stress will also increase across the entire US[385], most European cities[386] and all of China[387].

Projected impacts: Given the present-day impacts of extreme heat described in section 2, the projections of rapidly increasing exposure indicate significant growing risks from climate change. This is also in light of the modern-day underestimation of heat impacts across the world. These changes therefore pose dire implications for ecosystems, economies and human health on a global scale[383].

A wet bulb temperature of 32 °C is considered the absolute upper limit for labour productivity[388], while heat stress at work (or the essential measures needed to prevent serious health impacts) causes a loss in productivity[389,390]. The occurrence of more extremes over the productivity threshold will directly impact industries, especially those reliant upon manual and outdoor workers, from steel workers in India to construction workers in Saudi Arabia[391–393]. In the US, unmitigated climate change will lead to USD 51-119 bn worth of labour losses annually, which could be reduced by USD 20-71 bn with moderate emissions reductions[108]. In China in the summer, for a scenario of high emissions, this could mean a slump in labour capacity of 5% in the near future (2020-2050) and up to 20% in the latter half of the century, with some of the most developed areas losing up to 40%[387]. In Pacific Island nations, which are heavily reliant on primary industries, labour loss may rise from 2-3% up to 9-18% by the end of the century [394]. In Brazil, over 20 million people work in agriculture and construction, and wet bulb temperatures are projected to increase in frequency, intensity and spatial coverage across the nation, indicating clear economic vulnerability[395]. Overall, heat extremes will cause many tropical regions to experience labour losses of 6% annually (from 2% now) at just 1.5 °C, with this doubling for higher emissions[396]. Across the world by 2050, hot months could mean a 20% loss in labour capacity[389], representing repeated catastrophic blows to the global economy.

In the absence of adaption measures, or even in spite of them, many construction, agriculture and other outdoor workers experience will also experience growing health impacts from heat stress[392,393,397]. Poorer nations with a larger fraction of outdoor and manual workers and greater vulnerability will experience greater impacts from extreme heat[398], with India and Brazil ranked highest for 'integrated heat-stress exposure'[399], but the overall negative effect on public health will be globally ubiquitous. For example, the mortality risk to vulnerable people (over 65 years) in the Middle East and north Africa will grow by 8-20 times, but less (3-7 times) if global temperature rise is limited to 2 °C[379]. Across urban areas in China, heat-related mortality will increase by between 25,000 and 40,000 annually by mid-century and up to 60,000 by 2070, depending on the magnitude of future emissions[400]. In the UK, from 1974 heat-related deaths per year in the 2000s, studies project 7,040 deaths per year (a 257% increase) in the 2050s and 12,538 deaths (a 535% increase) in the 2080s[401]. In southwest Germany, the 2015 heatwave that caused approximately 1,400 excess deaths will become around 6 times more likely by 2080[402]. And the extreme European 2003 heatwave, which resulted in 70,000 deaths, would cause 20% higher mortality in Paris and London in a 2 °C world and become several times more likely[403]. The mortality risk will increase most drastically in tropical and subtropical regions, and while data is limited in many of these regions, estimates suggest that the rate of heatwave mortality could increase by as much as 500-2,000% by mid-century in nations including Colombia, Brazil and the Philippines[404].

1.5 vs 2 °C: The difference between 1.5 and 2 °C of peak warming is substantial. Globally, it directly translates into 420 million fewer people frequently exposed to extreme heatwaves and 65 million fewer to exceptional heatwaves[376]. This 0.5 °C difference provides benefits over a range of societally relevant impacts, including 38% less health-related heat exposure, 50% less exposure to wildfires and 35-50% crop heat stress[399]. The significance of this difference will also manifest at regional scales. Over south Asia and east Africa, the exposure to extreme heat will increase by 4 times at 1.5 °C, but around 16 times at 2 °C, before accounting for population changes[380]. In south Asia specifically, at 2 °C of warming compared with the present day, the exposure of a given person to upper labour threshold of 32 °C will increase by 2.2 times, and to the lethal 35 °C threshold by 2.7 times. At 1.5 °C, these risks are halved[381,388].

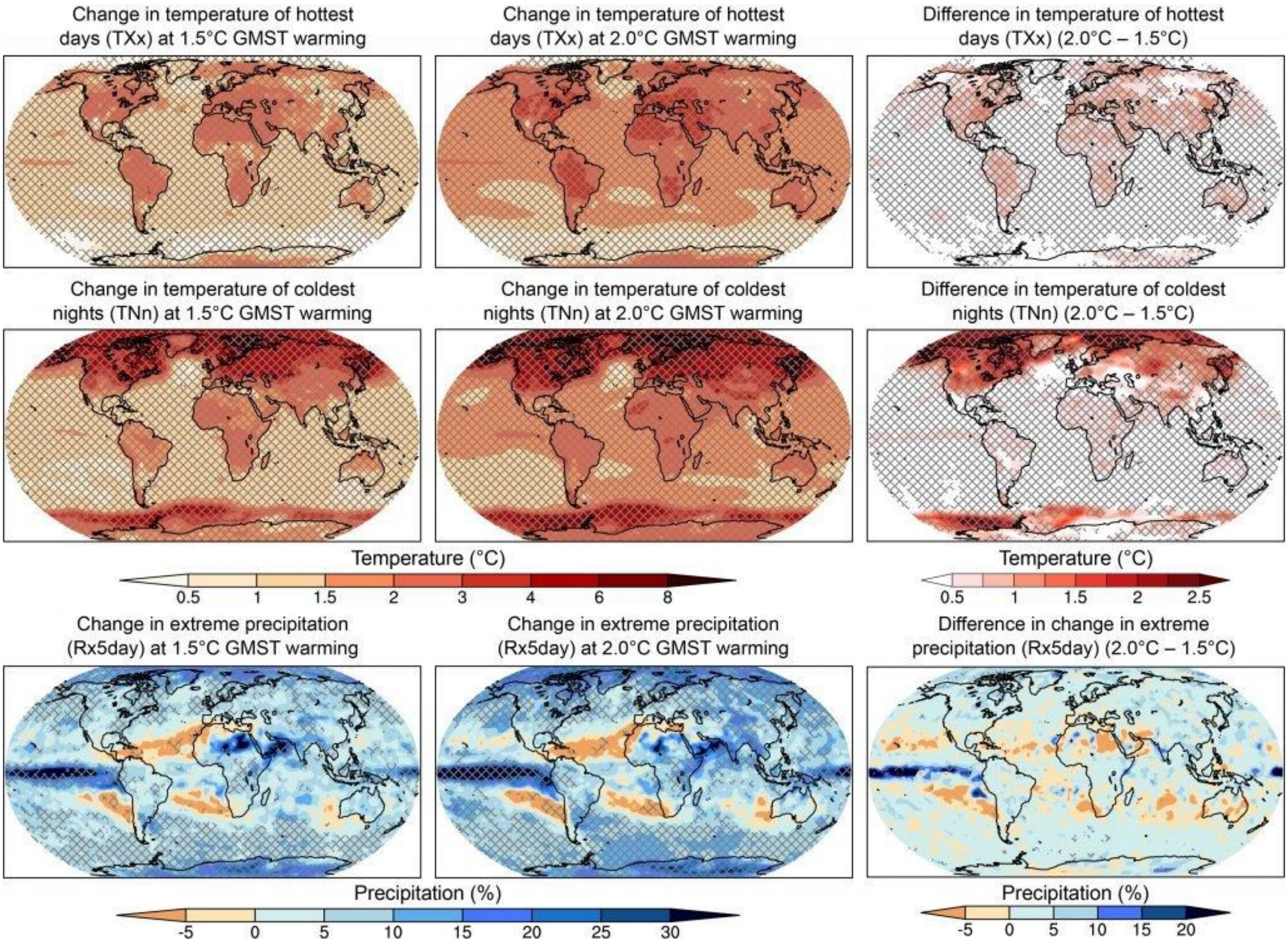

Figure 13: Projected changes in extremes at 1.5°C (left) and 2°C (middle) of global warming compared to the pre-industrial period (1861–1880), and the difference between 1.5°C and 2°C of global warming (right). Cross-hatching highlights areas where at least two-thirds of the models agree on the sign of change as a measure of robustness. Figure 3.4 of IPCC Special Report on Global Warming of 1.5°C[321].

3.2.2 Extreme rainfall and flooding

Summary: Extreme rainfall will occur more frequently across the world, but especially in the tropics. The impacts include rapidly increasing damages to property and destruction of crops, resulting in food insecurity and loss of livelihoods. The impacts vary by region, with property especially at risk in Europe and the US and humanitarian impacts more severe in Asia, Latin America and Africa.

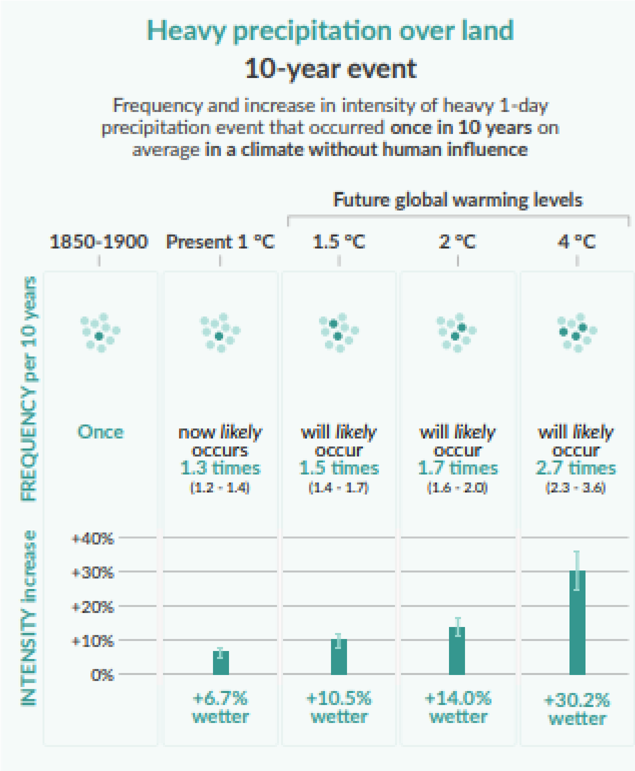

Figure 14: Projected changes in the intensity and frequency of extreme precipitation events, relative to the intensity / frequency of such events in the pre-industrial climate (1850-1900). Extreme precipitation events have already become more frequent and intense due to observed climate change. Future warming will substantially increase the regularity and impacts of these events, but the extent to which the incidence / intensity of extreme heat will increase is determined by the magnitude of future warming – and therefore future greenhouse gas emissions. Figure from IPCC AR6[2].

Changes in extremes: In general, sudden heavy downpours will become more intense and common as the climate changes, because a warmer atmosphere holds more moisture[405]. So far this holds true for multi-day and single-day rainfall events, while sudden hourly bursts will increase even faster than the linear climate change rate[406,407]. The more extreme the event, the more rapidly the chance is increasing[408]. The amplified temperature effect of cities will also cause even more intense rainfall over urban areas, amplifying the chance of flash flooding[409]. These extremes will increase across nearly all land regions, especially in the tropics and parts of the mid-latitudes[405,410,411], though there is some diversity by season and subregion[412,413].

Globally, intensifying rainfall will bring more flooding from sudden flash floods[414,415] and overflowing rivers[416,417], though the latter is highly regionally dependent. In Europe, especially cities in the northwest such as in the British Isles, river flooding will rapidly increase[386] as will destructive compound flooding from high sea levels and heavy rainfall[183]. Brazil is especially vulnerable to increased rates of flash flooding with climate change[418] as well as swollen levels of the western Amazon draining from the Andes[419]. More widespread rainfall extremes will likely cause more flooding in the US[420]. Meanwhile, more intense rainfall before, during and after monsoons will especially trigger more flooding in west and central Africa[421–423] as well as south Asia[424]. East Africa will see more wet extremes from wet areas getting wetter, even in the midst of drying trends in other places[425,426].

Projected impacts: If climate change continues unabated, at 4 degrees of warming losses from river flooding will increase by 500% in the majority of nations, hitting hardest in the US, Latin America, Europe and Asia (Figure 15)[416]. However, the differences in extreme rainfall even between 1.5 °C and 2 °C are significant (Figure 15) and will translate into substantial differences in flooding. At just 1.5 °C warming, flood mortality rises 75% and damages by 200%, and at 2 °C the mortality ramps up another 50% and damages are doubled again[427]. For context, flood damages over the period 2000-2020 totalled USD 610 bn (Table 2). In southeast Asian cities, the combination of rapid urbanisation and climate change will cause flood damages to more than double in the near future[428]. Globally, the number of people exposed to a 1-in-100 year flood will increase by 50 million due to climate change alone, between 2010 and 2030[165].

Many destructive recent flooding events have already been attributed to climate change (Section 2.1.2), all of which will likely get more likely and intense going forwards. Other events that have not yet been attributed to climate change are projected to strengthen in response to future climate change. For example, in Bangladesh, rainfall-driven flooding in 2017 destroyed 650,000 ha of cropland, affecting food security and livelihoods across the region – such an event will become 1.7 times more likely in a 2°C world[429]. And in Pakistan in 2010, catastrophic flooding inundated over a million homes, affected 20 million people and caused over 1500 deaths[430]. By 2090, the rainfall from such an event will be 50-100% more intense, inevitably leading to further destruction and suffering[431].

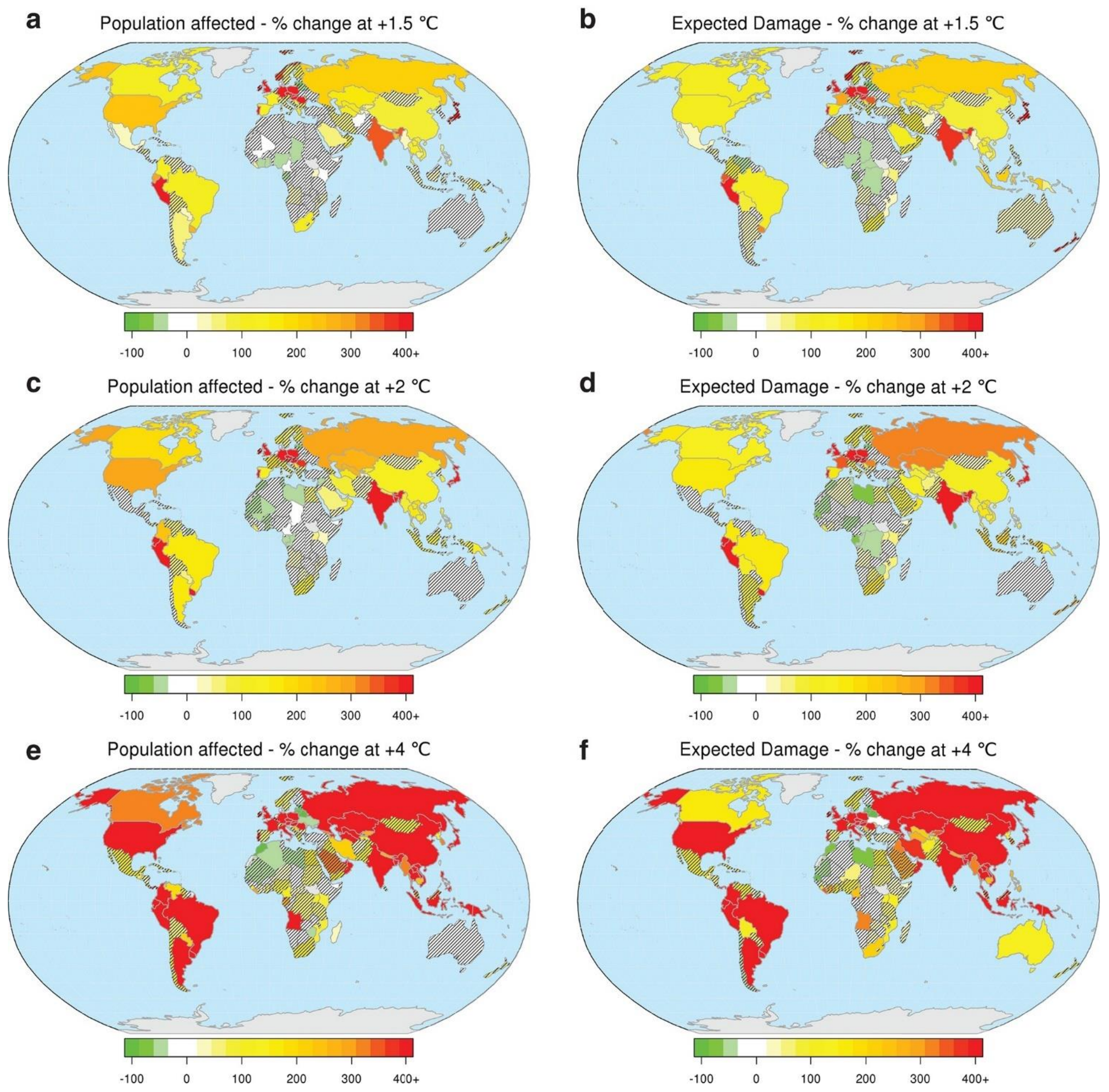

Figure 15: Average change in population affected (a, c, e) and expected damage (b, d, f) per country at specific warming levels. Hatching indicates countries where the confidence level of the average change is less than 90%[416]**.**

3.2.3 Drought

Summary: Drought will occur more frequently across large parts of the world, becoming more intense, and covering twice the land area. Presently, droughts cause billions in economic damages and threaten millions of livelihoods annually. Without adaption, this will increase several times over because of climate change even in wealthier regions such as Europe. It will also drive 100s of millions more into water and food scarcity and form a growing contribution to violent conflict in agriculture-reliant nations.

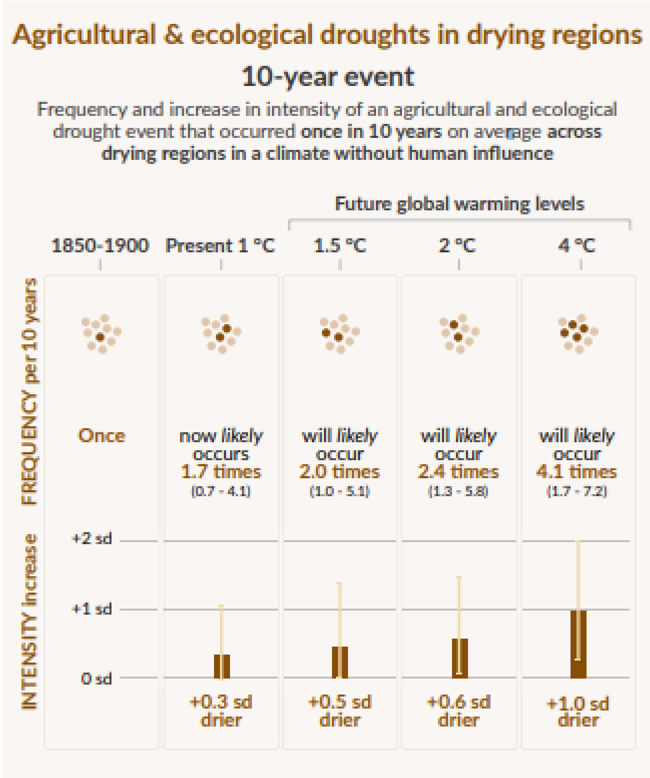

Figure 16: Projected changes in the intensity and frequency of agricultural and ecological droughts, for drying regions only (western and central North America, north and south Central America, Caribbean, northern, north-eastern, south-western and southern South America, west and central Europe, Mediterranean, western and eastern Southern Africa, Madagascar, eastern and southern Australia) relative to the intensity / frequency of such events in the pre-industrial climate (1850-1900). Intensity changes are given in (fractions of) standard deviations of annual soil moisture change. Droughts have already become more frequent and intense due to observed climate change. Future warming will substantially increase the regularity and impacts of these events, but the extent to which the incidence / intensity of extreme heat will increase is determined by the magnitude of future warming – and therefore future greenhouse gas emissions. Figure from IPCC AR6[2].

Changes in extremes: Over the coming century, drought will occur more often and with greater intensity because of lower average rainfall and warmer temperatures, especially in the subtropics and mid-latitudes[203]. By the end of the century, unmitigated climate change will cause a quadrupling of drought conditions[432], and combined with population changes will expose an additional 386 million people to extreme drought on a monthly basis, a nearly 500% increase from today[433]. Climate change will be directly responsible for 60% of this increase in people exposed to extreme drought: approximately 230 million people. Further, climate change will indirectly increase drought exposure for a further 100 million. The most extreme droughts are projected occur 200-300% more often in some regions[434] and affect over twice the land area as today[435].

Hotspots of increasing drought include regions such as West, Central, Southern and East Africa, Central America, South Asia, and subregions such as Amazonia, southern South America, China, most of Australia, western North America and central Europe[436–439], in many of which droughts will occur 5 to 10 times more often[440]. In South Asia, drought exposure will rise by 50% within the near-term (2021-2040) and double by mid-century[441]. Across the North American Southwest and Central plains, in line with the modern day megadrought, conditions will continue to dry to unprecedented levels[442]. Drought will increase across the entire African continent, but especially severely in central African nations including Niger and Chad, and East Africa -- these changes will combine with rapid population rise to affect more people, more severely[426,443].

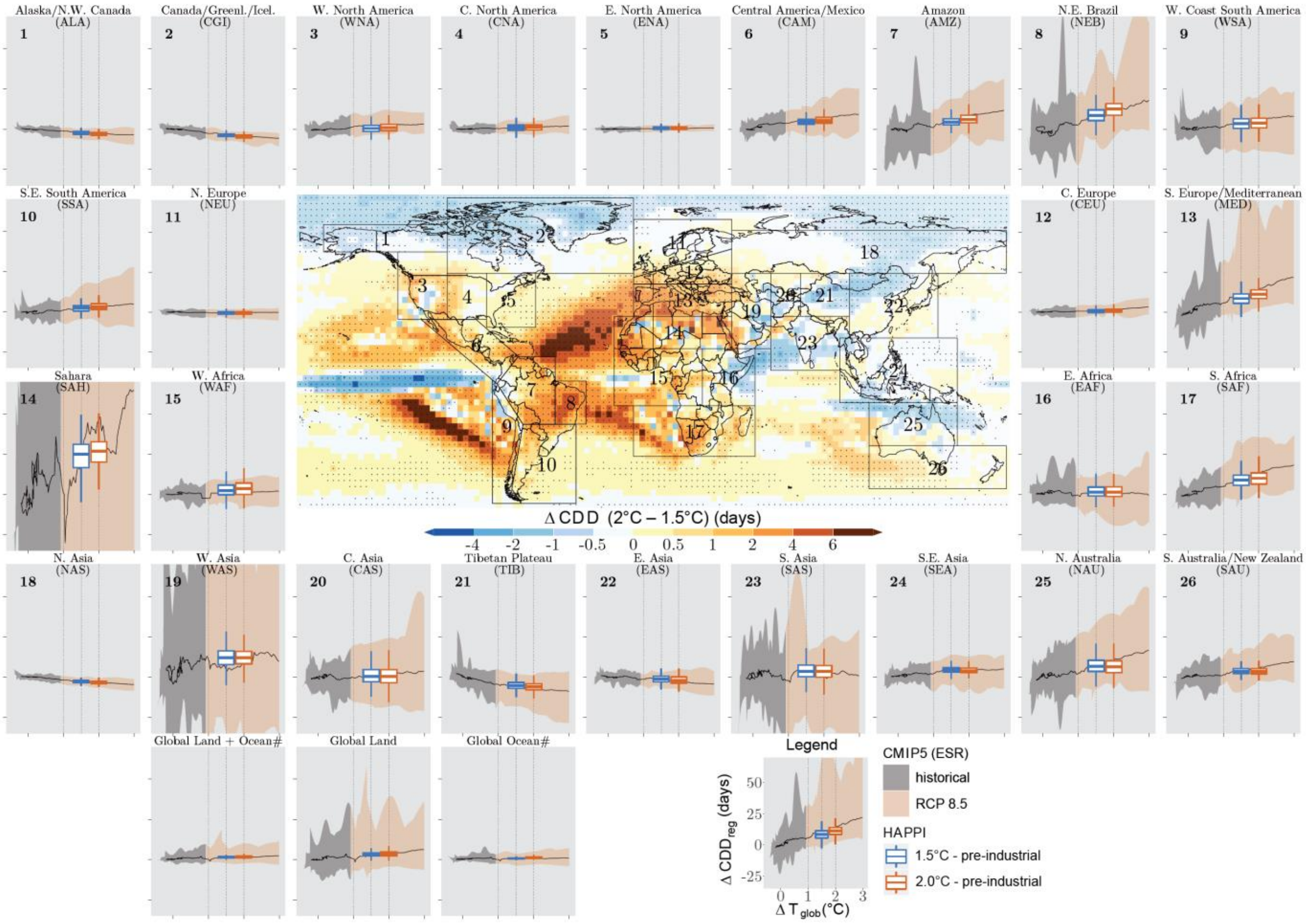

Figure 17: Projected changes in consecutive dry days (CDD) as a function of global warming. The difference in CDD between 1.5 and 2 degrees by location is in the centre, and the effect of global warming on CDD for each regional average is presented in the individual trend lines. Figure 3.13 of IPCC Special Report on Global Warming of 1.5°C[321].

Projected impacts: Few studies project the future impacts of drought. Nonetheless, the present impacts of drought (described in section 2.1.3) provide context to the projected increasing rate of droughts described above. This is especially problematic in parts of Africa where vulnerability to drought is likely to increase[444]. And across the continent, even expected decreases in vulnerability will not offset increases in the drought hazard and exposed populations, suggesting unilaterally rising impacts[443].

Resources such as food and water will become scarcer. Over the world by 2050, anywhere between 0.5 and 3.1 bn more people will experience water scarcity as a result of climate change[445]. Also by 2050, around 11% of global croplands will lose productivity to this water scarcity, the direct fallout from which would be 178 million people 'no longer fed', especially in Africa and the Middle East[446]. In the UK and EU, annual drought losses will increase from €9 bn per year currently to around €25 bn annually by 2100[447]. In China, increased drought rates even at 1.5 °C will cause losses 10 times that of the 1990s[448]. In East Africa, a variety of crops will be impacted by climate change, with growing zones for tea and coffee shrinking by 40%, yields of wheat falling by 72% and other grain crops by 45% by the 2080s[449]. A similar picture is seen in Latin America, where the coffee sector employs millions of people and is highly vulnerable to climate variability. Furthermore, drought during the growing season in nations heavily reliant upon agriculture can make violent conflict more likely[450–452], suggesting a small but increasing effect of climate change on armed conflict in the future[5].

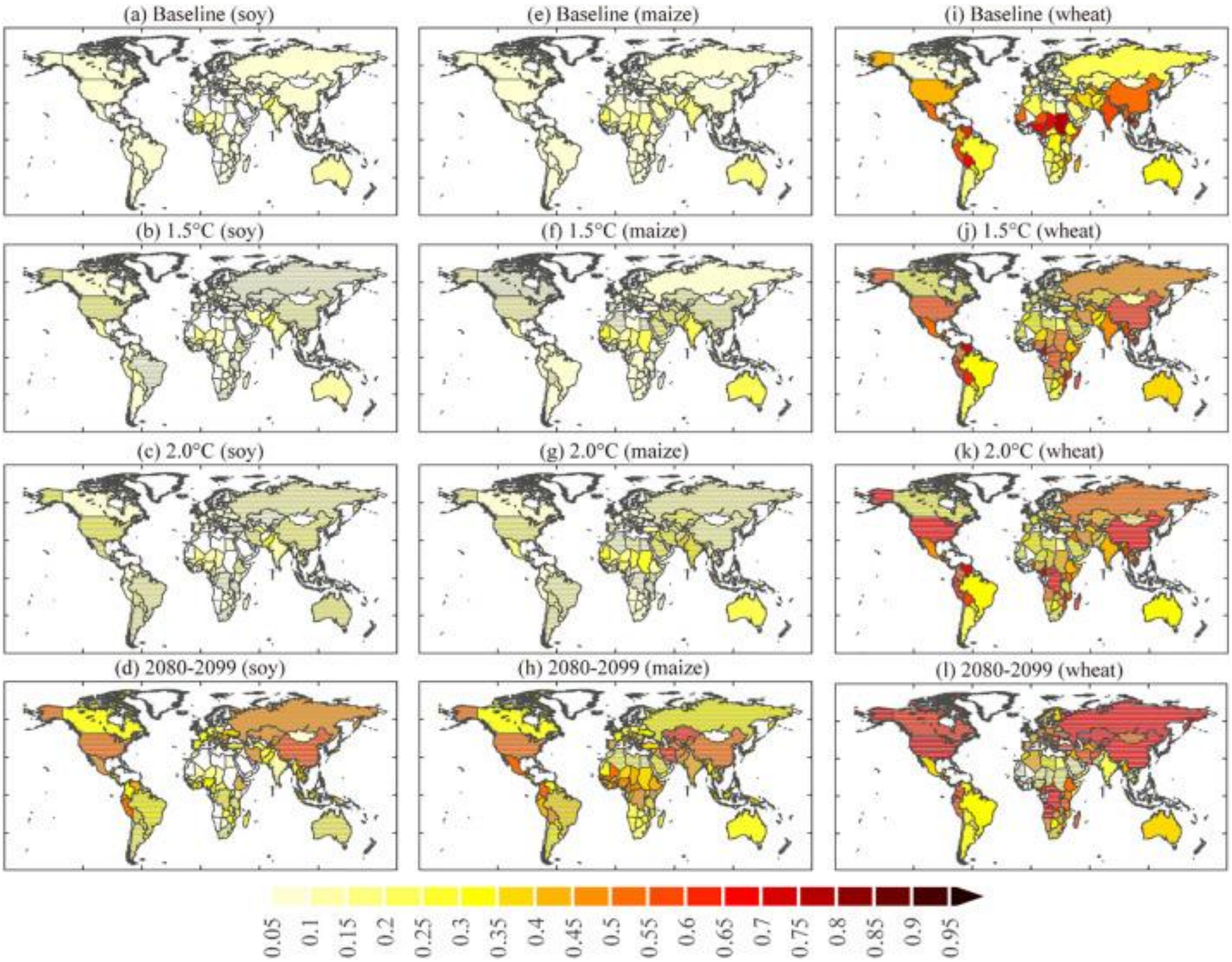

Figure 18: Normalized agricultural production damage index during different global warming levels. Country-level normalized agricultural production damage index for (a) soybean, (e) maize, and (i) wheat during the baseline period (1981–2000); (b) soybean, (f) maize, and (j) wheat for the 1.5 °C global warming target; (c) soybean, (g) maize, and (k) wheat for the 2.0 °C global warming target; and (d) soybean, (h) maize, and (l) wheat for the 2080–2099 (RCP 8.5) period. Stippling in (b–d, f–h, j–l) indicates locations where the degree of change during different global warming periods, relative to the baseline period (a, e, i), was statistically significant at the 95% confidence level[399].

We can also consider past drought events in a warmer world. In the 1930s, the US experienced devastating 'dustbowl' conditions, with a brutal drought in 1936 that ruined roughly 40% of maize crop yields. In a world 4 °C warmer, 80% of crops would be lost in such an event. Equivalently, by mid-century, the typical yearly yields will be similar to the 1936 drought[453]. Another event occurred in 1948-1957: the US experienced a historic drought that caused the loss of crops worth billions, widespread ecosystem disruption and cost hundreds of thousands of jobs across the southern states. A similar event in the mid-21st century, in the presence of climate change, would result in significantly lower soil moisture levels across all affected regions, thus causing far more severe impacts to agriculture and nature[454]. Modern day analogues of these events include the Texas and California droughts, which together wiped out over 400 million trees[455]. Worse, the largest trees are the most vulnerable to drought stress[456], and these store a substantial fraction of forest carbon and provide valuable ecosystem services[457].

1.5 vs 2 °C: Globally, the difference between 1.5 and 2 °C is roughly 60 million less people exposed to severe drought conditions[436]. This means nearly 40% less people exposed, and 30% less cropland[458]. The average drought will be 2 months longer at 2 °C than 1.5. Further, the magnitude of droughts will double in intensity across 38% of Earth's land surface at 2 °C, and 30% at 1.5 °C[440]. The future impacts of increased drought, and therefore the drought-related benefits of limiting global warming, are regional. In particular, they are heavily focused in the Mediterranean, central Europe, northeast South America, East and West Africa, South Asia and China[438,448,459]. For instance, in China the drought-related losses are halved by limiting at 1.5 rather than 2 °C, a difference worth tens of billions of dollars per year[448]. In Europe, the difference is worth around 2-3 bn dollars per year[447]. And in East Africa, where drought is already a strong driver of socio-economic instability, droughts will become more severe at 2 °C than 1.5 °C, and at each 0.5 °C increment thereafter, with implications for a wide range of impacts[426,438].

3.2.4 Wildfire

Summary: Wildfires will occur more frequently across large parts of the world, especially in the Amazon and other parts of Latin America. Presently, wildfires cause hundreds of thousands of deaths annually, decimate ecosystems, release CO_2 and create a global public health burden worth several tens of billions USD. Without mitigation of global emissions and urgent halting of deforestation, these problems will continue to increase.

Changes in extremes: If climate change is not mitigated, such as by curbing deforestation practices like those in Brazil, fire weather conditions will continue to increase in several regions in Africa, Australia, several regions of South America, the Mediterranean, Europe, parts of China, India and Russia, and North America. Fire frequency could increase over 37.8% of the global land area during 2010–2039, corresponding to a global warming level of approximately 1.2°C, compared with over 61.9% of the global land area in 2070–2099, corresponding to a warming of approximately 3.5°C[460], rising to 74% of global land with uncontrolled warming[399]. The Amazon is one of the region with the greatest projected increases in fire weather[399]. In the southern Amazon specifically, fire will intensify in both low and high emissions scenarios, but to varying degrees. The area burned will double by mid-century without mitigation of climate change, up to 16% of the entire forested area, which in turn will release millions of tonnes of CO_2. However, halting current deforestation practices could offset around half of the emissions and prevent around 30% of the burned area, reducing the spread into protected and indigenous lands and the loss of ecosystems[461].

Projected Impacts: Annual deaths attributable to landscape fires already range from quarter to half a million people per year. This is most likely an underestimate[462]. As populations grow and climate drives increases in fire weather, this number, and the vast number of people affected by smoke-related morbidity, will increase proportionally. In the US, even with moderate emissions reductions, wildfire smoke exposure will rise 55%, and for business-as-usual emissions by as much as 190% by 2100, causing a doubling in premature deaths related to fires[463]. The vast health costs already caused by wildfires, detailed in section 2.1.4, will therefore rise substantially.

1.5 vs 2 °C: Limiting warming to 1.5°C will reduce global biome exposure to wildfires by 50% (Figure 19). In Europe, the fire season would be 3.3 days shorter and far fewer countries would see an increase in risk[399]. Given the catastrophic impacts of wildfire on ecosystems and human health, remaining at 1.5 °C represents a major mitigation of damage. Individual fire events in the modern day have been responsible for the deaths of billions of creatures and hundreds of thousands of people across several nations; thus, limiting climate change and deforestation practices (which affects both climate change and directly impacts burned area) could save the lives of countless plants and animals, and millions of people.

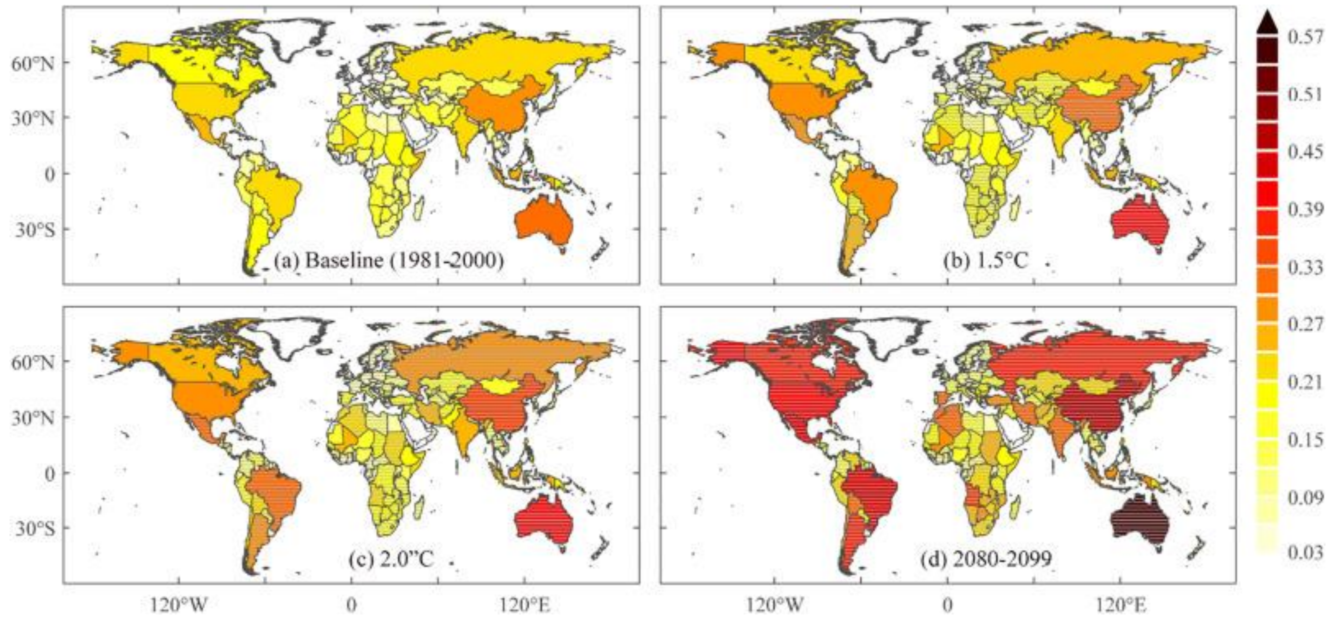

Figure 19: Integrated exposure to wildfire during different global warming periods. Country-level wildfire exposure index for (a) the baseline period 1981–2000, (b) the 1.5 °C warming target, (c) the 2.0 °C warming target, and (d) the 2080–2099 RCP 8.5 period. Stippling in (b, c, d) indicates locations where the degree of change during different global warming periods, relative to the baseline period (a), was statistically significant at the 95% confidence level[399].

3.2.5 Tropical Cyclones

Summary: The high winds and intense rains of tropical cyclones will become even more intense. Though the number of cyclones that occur will decrease or remain unchanged, the fraction of the most intense and destructive storms will increase. As a result, they will cause far more damage to property, lives and livelihoods. Flooding from rainfall and wind-blown storm surges will also increase, affecting thousands more people and costing tens of billions USD without further adaptation.

Change in extremes: A few important changes will occur as the world warms. Tropical cyclones overall will occur at about the same rate, or slightly less. However, the most intense storms happen more frequently – around 13%, taking 2°C as the illustrative case. The maximum wind speed will increase by about 5%. The already-intense rainfall will intensify further, by about 14%. The rise in sea levels as well as wind speeds means that inundation will occur more often, more destructively and reach further inland. In the northwest Pacific, cyclones will occur further northwards, affecting different regions. Finally, cyclones will move more slowly, such that the regions underneath experience impacts sustained over a longer period[464].

Projected Impacts: There is little formal evidence in the form of projections of future impacts of tropical cyclones. However, from the projected changes in meteorology, it is clear that tropical cyclones will become more destructive. In particular, we will see more record-breaking extreme cyclones like Hurricanes Maria, Katrina and Harvey, Typhoon Haiyan and Cyclone Nargis. These rare but powerful events cause the bulk of all damages from cyclones, with impacts often exceeding hundreds of billions USD and affecting millions of people.

1.5 vs 2 °C: The main difference between these warming levels manifests in the extreme rainfall from cyclones. At 2 °C, the heavy rainfall that leads to flooding and landslides would be around 3-4% more intense than at 1.5°C. Storm surges would be lower at 1.5°C due to less sea level rise. Given the significant attributed effects of climate change on tropical cyclones in the present day, these seemingly minor changes could also cost billions in additional damages to property and businesses and each affect tens of thousands additional people. The amount of climate change is therefore crucial and depends, *inter alia*, upon deforestation practices such as those occurring in Brazil.

3.3 Sea-level rise

Summary: Sea-level rise is a consequence of climate change and affects coastal communities through the permanent submergence of low-lying areas, more frequent or intense coastal flooding at high tide or due to the combination of high sea levels and storm surges, increased coastal erosion, loss or change to coastal ecosystems, salination of soils, groundwater and surface water, compromising agriculture and drinking water, and impeded drainage[73,465]. The Intergovernmental Panel on Climate Change's recent Special Report on the Ocean and Cryosphere in a Changing Climate concludes that there is 'very high confidence that as the sea level continues to rise, the frequency, severity and duration of hazards and related impacts increases'. The gradual response of sea levels to changing global temperatures means that the most substantial impacts will be experienced in the future[73]. The greenhouse gas emissions of today therefore create a legacy of sea-level rise impacts that will impact future generations the most. The emissions of today mean that urgent investment in adaptation measures is required or as many as one-in-25 people globally will be flooded every year by 2100. The damages due to this flooding could causes losses of 0.3-9.3% of global GDP annually[73].

Sea-level rise projections: Existing greenhouse gas emissions are sufficient for sea levels to continue to rise for centuries and continued global warming will further increase the rate of sea-level rise, causing greater impacts for coastal areas around the world[466]. This is the result of the timescale of the global sea-level response to climate change which occurs gradually over centuries. Even under the most stringent reductions in greenhouse gas emissions that limit warming to 1.5 °C, sea levels will rise by 0.28-0.55 m by 2100 and as much as 0.86 m in 2100, while continued high emissions could lead to sea-level rise of 1 m by 2100 and 1.88 m in 2150[2]. In previous periods when global temperatures were warmer than those of the mid-19th Century, sea levels were considerably higher than those of today[73]. The legacy of the greenhouse gas emissions of today is that over future centuries, sea levels will continue to rise. If warming is limited to 1.5 °C, sea levels will rise by 2-3 m over the next 2000 years, by 2-6 m for warming of 2 °C, and by 19-22 m if warming reaches 5 °C above pre-industrial levels. While unlikely, the IPCC has warned that sea-level rise of 15 m by 2300 cannot be ruled out if emissions continue unabated[2].

Previous research has shown that it is possible to demonstrate the contribution made by individual countries' emissions to future sea-level rise. For instance, China's emissions over 1991-2030 (based on their commitments made under the Paris Agreement) will result in 12.3cm of sea-level rise in 2100, and 26.2cm by 2300[8].

Continued greenhouse gas emissions create a long-term commitment to sea-level rise, and delayed emission reductions substantially increase the rate and total amount of sea-level rise. Indeed, a delay in the peak of global CO_2 emissions by just 5 years is projected to increase sea-level rise in the year 2300 by a further 20cm, although high-end estimates indicate that this increase could be as large as 1m[465].

Projected impacts: As sea levels rise over the 21st Century, the number of people exposed to sea-level rise impacts increases substantially. As such, the burden of the impacts of sea-level rise will fall greatest on the young people of today, and on future generations, representing a major intergenerational iniquity. Even without taking into account future population growth, a sea-level rise of 70-90 cm will cause an additional 1.5 million people in Latin America and the Caribbean to live in regions exposed to a 10-in-100-year extreme sea-level event[73]. Including expected population growth, just 21 cm of sea-level rise by 2060 would mean that the number of people living below the hundred-year extreme sea level globally will increase from 189 million to 316-411 million. The largest increases in the number of people exposed to coastal flooding will take place in regions of the Global South where financial capacity to adapt to these increasing risks is often limited, including South and Southeast Asia, and Western and Eastern sub-Saharan Africa[73,467]. In the USA, 13.1 million people will live in areas that will become inundated due to sea-level rise by 2100, if sea levels rise by 1.8 m. Limiting sea-level rise to 0.9 m reduces the number of people affected by inundation to 4.2 million[468]. In the absence of substantial adaptation measures will be required or annual damages from coastal flooding will grow to 100-1000 times great than they are today, by 2100[73].

Various studies have sought to quantify the impacts of projected changes in sea levels. Global estimates indicate that losses due to sea-level rise could reach USD 1 trillion by 2050 in the absence of major investments in adaptation measures[469].

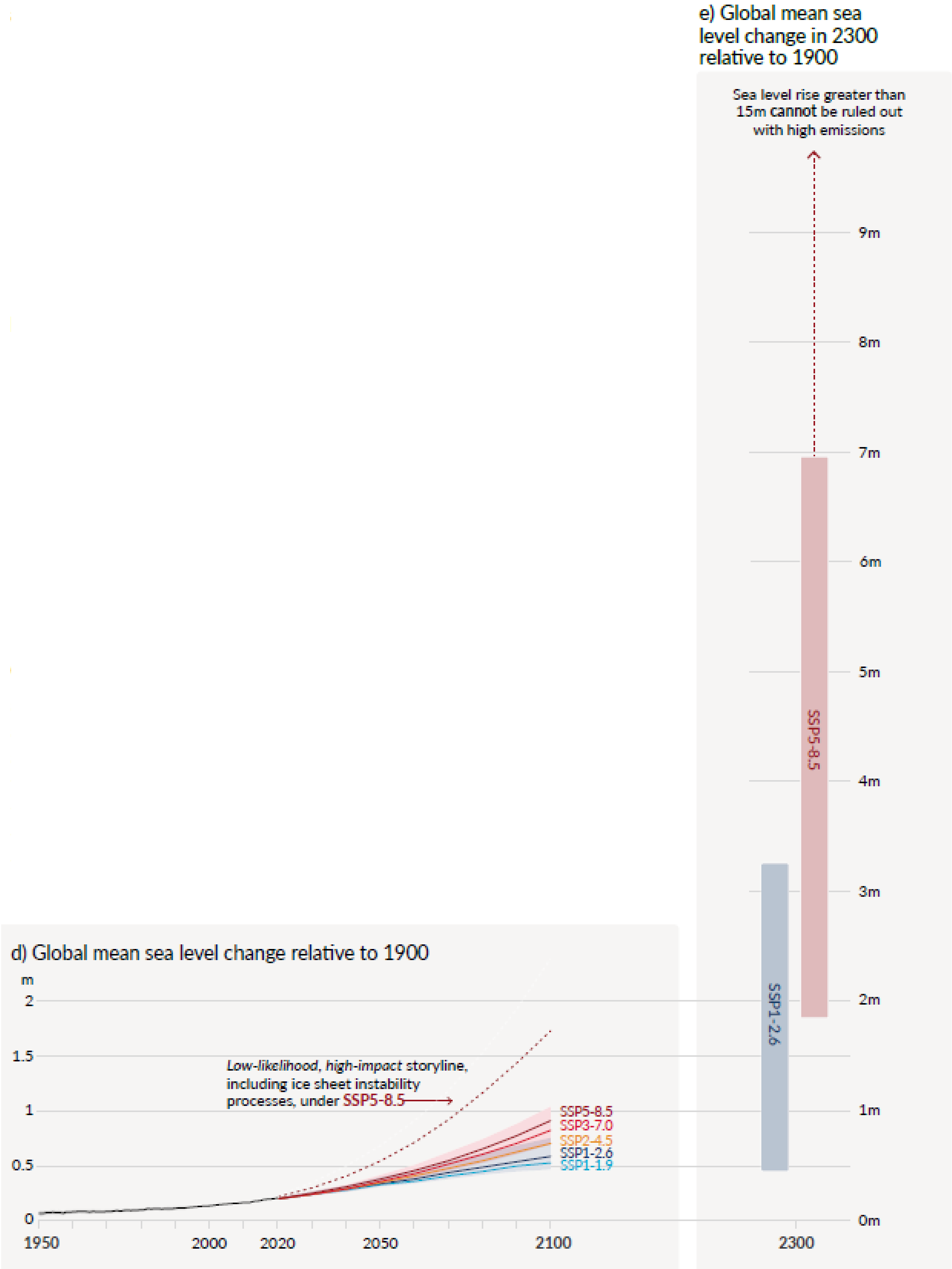

Figure 20: Left panel: projected sea-level rise until 2100, relative to 1900. Future changes in sea levels are projected for low (SSP1-1.9), intermediate, and high (SSP5-8.5) emissions scenarios. The red dashed curve indicates the risk of more rapid sea-level rise if high impact ice sheet processes occur. Right panel: global mean sea-level change in 2300, relative to 1900 under a scenario that leads to 1.8 °C of global warming in 2100 (SSP1-2.6, blue) and a high-emissions scenario, in which warming reaches 4.4 °C by 2100 (SSP5-8.5). While there is a possibility of extreme sea-level rise of 15 m, the likelihood of sea-level rise reaching these levels in coming centuries remains very low. Figure from the IPCC's Sixth Assessment Report[2].

3.3.1 Other marine impacts

In section 2.2.1 we noted the various ecological and societal impacts resulting from the increasing occurrence and intensity of marine heatwaves. While the number of marine heatwave days have doubled globally between 1982 and 2016, these events are projected to increase in frequency substantially in future. At 1.5 °C of warming, marine heatwaves will occur 16 times more frequently, rising to 23 times as frequently for a global temperature rise of 2 °C above pre-industrial levels[470]. While 87% of marine heatwave days are presently attributable to human influence on the climate, this percentage rises to nearly 100% at beyond 2 °C of warming. The intensification and increasing regularity of marine heatwaves may take marine organisms and ecosystems beyond their survival limits[470]. The consequences of these changes will not be limited to the ecosystems themselves, but also all communities dependent on the health of marine ecosystems for income and sustenance.

Global analyses have found that coral reefs are likely to begin disappearing globally and irreversibly within the coming decades[320]. The Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5 °C found that warm-water coral reefs will decline by 70-90% if global warming reaches 1.5 °C above pre-industrial levels, and by greater than 99% at +2 °C, and that these losses will largely be irreversible. These coral reefs provide habitats for over one million species[15].

3.4 Glacial impacts

High-mountain glaciers serve as 'water towers', maintaining the flow of water into river systems, even in dry seasons when rainfall is limited. In regions with low seasonal or annual precipitation, meltwater from glaciers[326–329] and snowpack[330–332] may constitute a substantial portion of agriculturally-available river flow. A global assessment of water towers found that the Indus watershed is the world's most important water tower, and highly vulnerable to climate change. Communities living in the Indus basin depend on its water and already experience high levels of water stress, complicated by water-related tensions between the countries receiving water from the Himalaya: Pakistan, India, China, and Afghanistan. The population living in the Indus basin, 235 million in 2016, is projected to increase by 50% by 2050, and water supplies from the Indus water tower will become increasingly compromised by human-induced glacial retreat[325].

Over recent decades, warming temperatures have raised summer meltwater releases from mountain glaciers. While glacial melt rates initially increase as temperatures rise, as glaciers retreat towards mountaintops melt rates will then decline substantially. 'Peak water', the maximum melt rates occurring in response to initial warming, is expected to be reached around 2050 in the river basins of the Himalaya and Karakoram mountains, after which summer flows will decline, even as summer temperatures continue to increase[471]. In the Cordillera Blanca mountains of the Peruvian Andes, peak water is expected to be reached by 2030-2060[472] Ultimately the ice reserve of the 'Asian water tower' will be lost[473].

4 Local and regional climate change impacts

4.1 Local impacts in Brazil

In addition to global climatic changes, intense deforestation also results in changes to the local hydrological cycle, causing decreasing rainfall for surrounding regions (Figure 21). Studies have found that for the western Amazon and La Plata basins, projected 21st-Century deforestation can reduce dry-season rainfall by as much as 20%[474], which may in turn increase the risk of forest dieback, destabilising parts of the Amazon forest and acting as a powerful feedback, amplifying the impacts of deforestation[475]. If the rates of deforestation prior to 2004 had been maintained, an 8.1% reduction in annual rainfall in the Amazon basin was projected to occur by 2050[476].

Large-scale deforestation is projected to have such severe impacts on local rainfall that overall reductions in agricultural productivity may outdo local increases achieved by expanding agricultural areas through deforestation[31]. In areas where greater than 60% of land has been deforested, substantial reductions in rainfall are expected: each 10% of additional forest loss reduces annual rainfall by around 50 mm. Amazon deforestation therefore not only leads to the loss of globally-important biodiversity and carbon dioxide emissions, but may also cost the Brazilian agricultural sector as much as USD 1 bn per year in losses due to reduced rainfall[31]. Large-scale forest destruction, such as that caused by commodity agriculture has greater impacts on rainfall reductions and causes larger local temperature increases than smaller-scale deforestation[477].

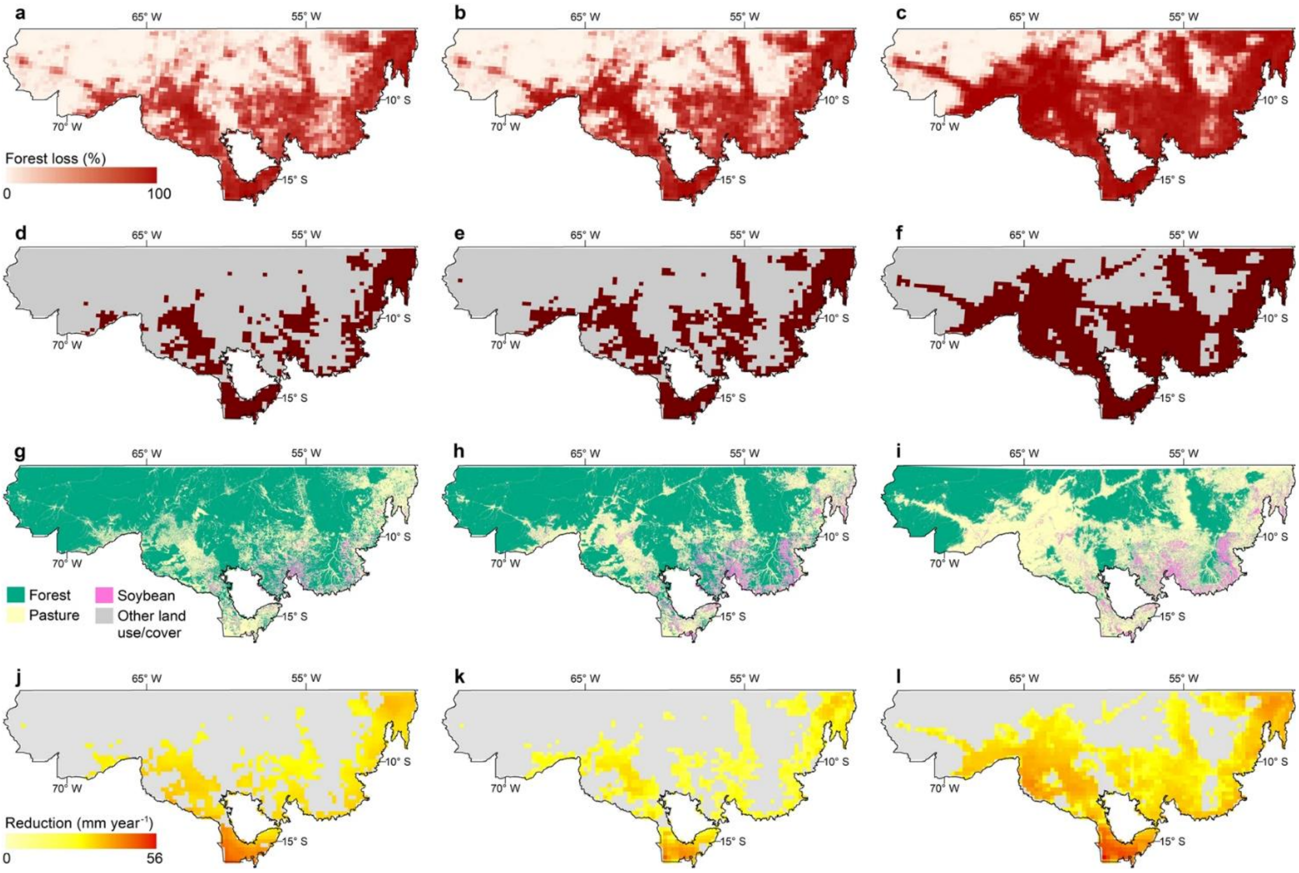

Figure 21: Impacts of forest loss in the Brazilian Amazon on rainfall. (a) Percentage of forest loss in 2019; (b,c) as (a) but simulated for 2050 under strong governance and weak governance scenarios, respectively. (d-f) The 28 x 28 km grid cells that exceed the critical forest loss threshold beyond which precipitation reductions are projected, for 2019, and 2050 under the strong and weak governance

scenarios, respectively. (g-i) Land use / cover under the conditions in a-c. (j-l) Rainfall reductions under the three conditions in a-c. Figure from ref. [31]**.**

Reductions in rainfall will also reduce electricity output from hydropower stations. One study of the projected hydropower output from stations in the Grande River Basin found that precipitation reductions over the 21st Century would reduce annual energy production by 6.1 – 58.6%, with the largest reductions occurring in the absence of greenhouse gas emission reductions[478]. Large-scale deforestation also results in amplified local warming, increasing deforested regions' exposure to the impacts of more extreme heat[479]. Forests mediate local temperatures by reducing variability and daily maximum temperatures. Deforestation therefore amplifies temperatures throughout the year, and the impacts on communities are most pronounced in tropical regions, due to their high temperatures, with substantial deforestation[480].

In addition to rainfall reductions, the Amazon is projected to warm at among the fastest rates of any region. The IPCC's 6th Assessment Report found that under high-emissions scenarios, parts of the Amazon could warm by as much as 6 °C[481]. As global warming increases in magnitude, drier and hotter conditions in South America create more favourable conditions for fire, and the area burned and carbon dioxide emissions from fire are both projected to increase[482]. In the absence of substantial reductions in greenhouse gas emissions, global temperatures could rise to 4 °C above pre-industrial levels, which could result in a 30% loss of the Amazon's carbon store due to burning in fires. By contrast, rapid near-term cuts in emissions that limit warming to 1.5 °C would reduce the carbon loss due to fire to 7% of the current carbon stock[482] These positive feedback effects offer support for the idea of a tipping point in the Amazon rainforest, with today's greenhouse gas emissions amplifying future fire-related emissions, and therefore causing increased warming (section 4.3).

Fires in Amazonia, as well as amplifying the impacts of climate change, cause substantial health impacts in surrounding regions. Peaking in the dry season of July – October, severe air pollution due to the fires result in a range of health impacts, especially for vulnerable people, especially children, older people, and those with pre-existing lung or heat diseases[483]. In 2019, fires in the Amazon resulted in 2,195 respiratory-illness hospitalisations, although limitations in access to health facilities in some communities implies that the impacts of the fires affected a substantially larger number of people[483]. The reduced Brazilian deforestation between 2001-2012 resulted in a 30% reduction in dry-season particulate matter concentrations in Brazil and Bolivia. This reduction in pollution has been estimated to have prevented 400-1,700 premature deaths per year in South America[53]. However, the recent growth in deforestation rates, and resulting fire incidence[44,49], is likely to increase local pollution-related deaths, adding to the global burden of climate-related harm induced by deforestation.

Further, human encroachment into biodiverse areas may lead to exposure to zoonotic infectious diseases. The world's largest pool of zoonotic viruses is located in the Amazon region and deforestation may increase exposure to these diseases, risking future pandemics, threatening public health and global security[484].

4.2 Climate change impacts in Latin America

Summary statement: Extreme heat and rainfall are increasing in frequency and intensity across Latin America, affecting property, health and livelihoods. Changing rainfall patterns and the retreat of Andean glaciers are causing growing water stress, especially for large cities, and challenges for the supply of crucial hydropower energy. As noted in section 4.1, reduced precipitation could reduce hydropower electricity output by as much as 60% in some river basins. The incredible biodiversity of Latin America is threatened by land-use change and deforestation, which in turn amplify climate change-driven species extinction. Coupled with the loss of mangroves and coral reefs around the coastline, ecosystem services –

the benefits to humans provided by the natural environment – worth billions annually are projected to disappear. Climate change is partially responsible for maintaining the severe inequality prevalent across Central and South America, which amplifies its impacts further. Food security in the region is decreasing due to drought, especially in northeast South America, while climate variability poses a threat to vulnerable region-wide agricultural sectors such as coffee, which employs millions of people. Finally, climate-related drivers are associated with increasing respiratory and cardiovascular diseases, outbreaks of vector- and water-borne diseases, chronic kidney diseases, and psychological trauma, among other growing health impacts.

In the remainder of Section 4, below, we summarise the IPCC's 5th Assessment Report's findings on the present and future impacts of climate change in Latin America. Unless otherwise referenced, the information in this section is drawn from the 5th Assessment Report of the IPCC [485].

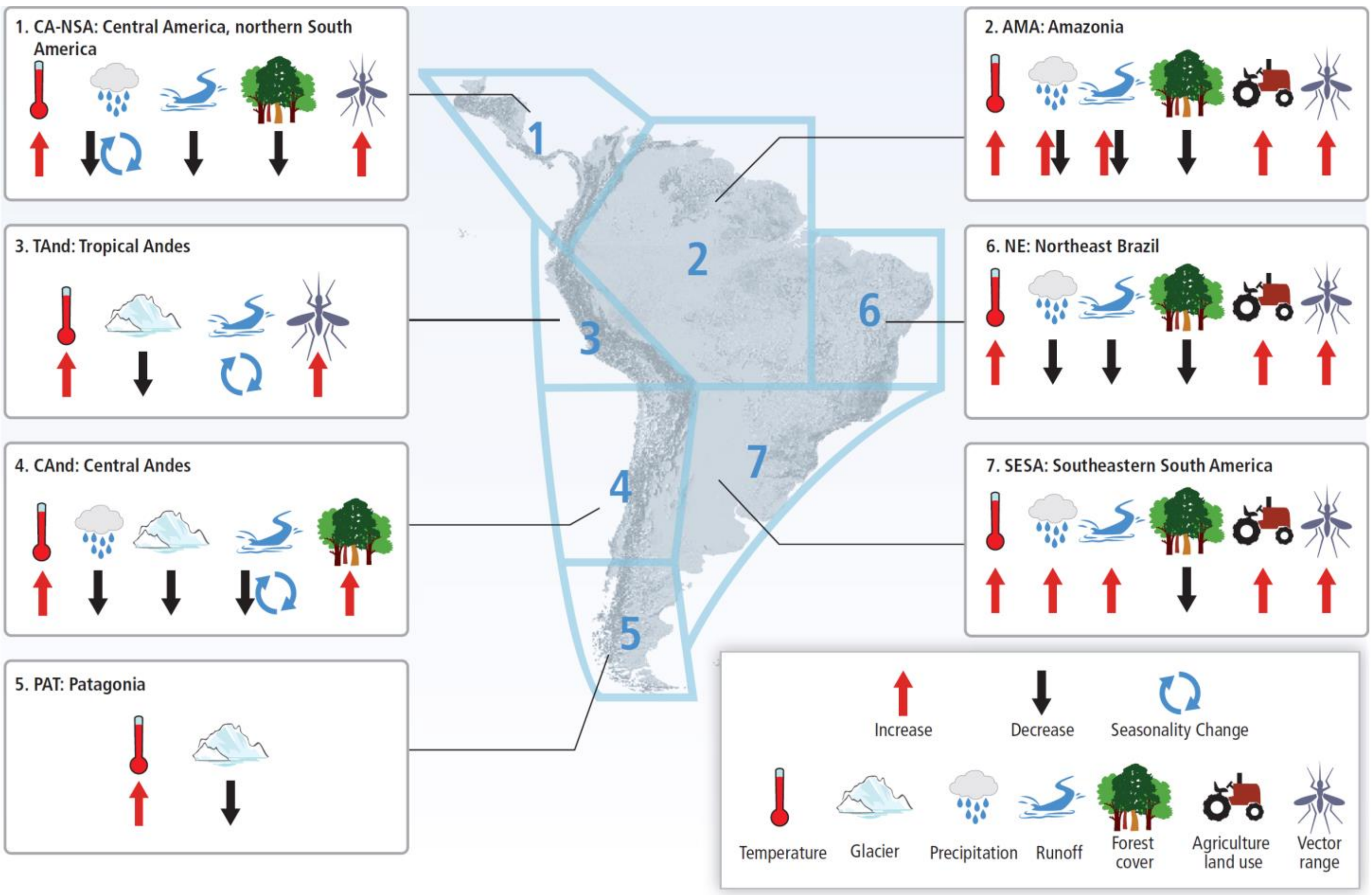

Figure 22: Summary of observed changes in climate and other environmental factors in representative regions of Central and South America. The boundaries of the regions in the map are conceptual (neither geographic nor political precision). Figure 27-7 in IPCC AR5 report[485].

4.2.1 Extreme heat and rainfall

To date, temperatures have risen faster than the global average across almost the entirety of Latin America. This is entirely due to human climate change, caused inter alia by deforestation practices such as those occurring in Brazil. Consequently, hot extremes are already more common across both regions, but especially in northern and southwest South America and the Caribbean. With further global warming, both regions will continue to get hotter and hot extremes will continue to become more intense and frequent. Compared to modern day, heat extremes will become at least 0.5, 1 and 2.5 °C hotter at 1.5, 2 and 4 degrees of global warming, respectively[405], and some of the hottest and most humid conditions in the record, causing dangerous heat stress, have been recorded along the northern coast of South America[98]. Dangerous heat stress will become far more common, experienced 200 more days per year with business-as-usual climate policy, reduced to 50-100 extra days with strong mitigation of future emissions[413,486]. This may be especially impactful in Latin America, given that a very large portion of the population resides in cities where urban heat island effects amplify temperatures further. This therefore represents a growing threat to human health, as well as labour productivity and economies[97].

Annual rainfall is falling across Central America and parts of Chile, while increasing in southeast South America. The frequency of rainfall extremes increased significantly since the 1950s across Latin America, causing more destructive landslides and flash floods[485,487]. Overall rainfall will decrease in northeast South America, where dry spells will become longer and more common, and increase in the southeast. Heavy rainfall extremes will continue to become more intense depending on the rate of global warming. Heavy rainfall intensity will increase by 0-1% at 1.5 degrees, 4% at 2 degrees, and 10-25% at 4 degrees[405,487], with even greater intensities expected for tropical storms in the Caribbean and coastal parts of Ecuador, Peru and Colombia[487]. The already-high risks of inland flooding and landslides are therefore growing across Latin America and the Caribbean[487,488], representing major risks to property, agriculture and life.

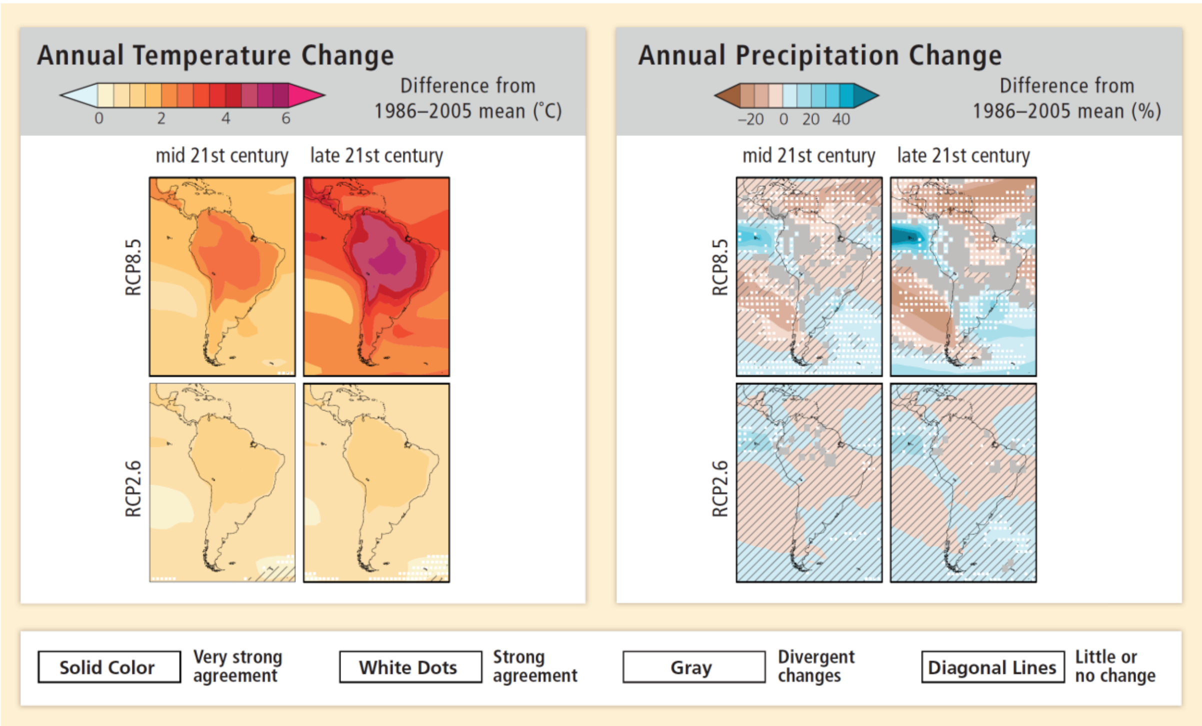

Figure 23: Projected changes in annual average temperature and precipitation under different levels of climate change. CMIP5 multi-model mean projections of annual average temperature changes (left panel) and average percent changes in annual mean precipitation (right panel) for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Figure 27-2 in IPCC AR5[485].

4.2.2 Freshwater resources

The availability of freshwater and rates of river flow have already been affected by climate change across Central and South America. First, glaciers throughout the Andes are retreating, and at rates among the fastest of the world's glaciers[323,489]. In the tropical Andes, glaciers have already lost around 20-50% of their area; in a 3 °C world they will lose 66%, and almost disappear entirely at 4 °C. In the southern Andes, glaciers are projected to shrink by at least 21 % in a 2 °C world up to 72 % in a 4 °C world[487]. This affects the seasonal supply of freshwater, which is crucial for agriculture in the region due to unreliable rainfall and in dry seasons. As explained in section 3.4, as temperatures rise, meltwater flowing from glaciers initially increases in volume. However, as glaciers retreat towards the mountaintops, melt amounts decline as the volume of water held in glacier ice falls[471]. In the Andes, peak glacial discharge is expected to occur within the next 40 years[487]. This critical threshold at which rivers begin to dry indefinitely has already been seen in the majority of rivers in the Cordillera Blanca of Peru[490]. Furthermore, the retreat of mountain glaciers leads to the development or enlargement of lakes at the bottom of glaciers, increasing the risk of outburst flooding, presenting a severe risk for Andean cities[491,492]. In 1941, an outburst flood from Lake Palcacocha in the Cordillera Blanca, Peru, destroyed a third of the city of Huaraz and caused at least 1800 fatalities. This event was caused by the retreat of the Palcaraju glacier attributable to the early rise in global temperatures due to human industrial activities[72]. Lake Palcacocha now poses a substantial threat once again to Huaraz[492,493] and this risk has also been attributed to climate change[72]. Glacial retreat also leads to an array of other challenges such as extreme low and high river flows, volcanic collapse and debris flows, and even water pollution from exposed contaminants.

Lower snowfall accumulation due to climate change also threatens freshwater supplies. In the Central Andes, low snowfall rates between 2010 and 2015 led to an extended hydrological drought, with severe impacts on agriculture, hydropower generation and international tourism[494]. Changes in rainfall rates have caused corresponding changes in water availability in river basins; increasing in the La Plata basin and decreasing in the central Andes, with no change for the Amazon. In some already-dry areas, there is an increasing risk of water shortages due to lower rainfall and higher evaporation. In both Central Chile and northeast Brazil, severe droughts occurred in 2010, affecting tens of millions of people and causing severe agricultural losses[494]. During the latter event, drought-driven dieback of the Amazon rainforest turned the vegetation into a net source of CO_2[495]. Projections for the Sao Paulo Metropolitan Region, with a population of 23 million people, suggest increases in both flooding and drought episodes because of moderate climate change. By mid-century, critical levels of seasonal water scarcity will become frequent and the dry season will extend by over a month[496].

The weight of scientific literature on the impact of climate change in Latin America demonstrates that human influence on the climate – substantially driven by deforestation and land-use change – is impacting the water supply of large cities, hydropower that is central to the region's power supply, and agriculture that is crucial to the world's food supply. The impact of climate change on the Peruvian electricity sector alone could cost as much as USD 1.5 bn if current trends continue. All of these impacts are projected to continue into the future, with the greatest impact on communities in sub-regions with the greatest vulnerability to these impacts, such as Andean mountain communities.

4.2.3 Ecosystems

Central and South America have the greatest biodiversity in the world. These regions are also acutely vulnerable to climatic changes. The combination of land-use changes and climate change has created several hotspots in which this biodiversity is threatened. Deforestation causes ecosystem loss, increase the vulnerability of species to climate variability and drive further global warming. Climate change compounds these issues by accelerating species extinction and furthers the loss of forests due to drought, wildfires and pest and disease outbreaks. In the absence of greenhouse gas emission reductions, 21 of 26 distinct biogeographic regions across South America will experience severe ecosystem changes in at least a third of their area[497].

Plant species extinction of 5-9% is projected across these regions by 2050, even before accounting for climate change impacts. Central and South America have the highest proportion of rapidly declining amphibian species, while Brazil is among the countries with most threatened bird and mammal species. High Andean ecosystems are expected to face the most severe changes due to warming, posing a growing threat to invaluable ecosystem services such as storage of carbon in soils, and further affecting the water supply for major cities. On average, 10% of vertebrate species across the Americas are expected to be eliminated or replaced over the course of this century, in parts of Central America and the Andes it is around 90%. Freshwater fisheries are projected to face negative impacts due to climate change, affecting both food security and economic development. The rate and severity of climate change, driven in part by deforestation, directly affects biological consequences such as species decline. This in turn affects the ecosystem services relied upon by millions of people.

4.2.4 Coastal Impacts

The rise, warming and acidification of the ocean is causing numerous impacts throughout Latin America, worsened further by human activities. First, there is more frequent episodic bleaching of the Mesoamerican coral reef, off the coast of Central America. Coupled with mangroves, this reef provides a whole range of ecosystem services, including marine-tourism, fisheries and coastal protection. In Belize alone, these services are valued at around half a billion dollars annually. It is projected that this reef could collapse entirely by 2050, depending on the global warming level, of which deforestation is a key driver. Similarly, eastern Brazilian reefs are under increasing strain. A 90% loss of coral reef cover would lead to direct economic losses of USD 8.7 bn (2008 value), and becomes rapidly more likely if global warming were to exceed 1.5 °C[487]. Additionally, Central American mangroves are some of the most threatened in the world, with 40% of species in danger of extinction. Mangroves are also threatened more widely across all of coastal Latin America due to deforestation and land conversion, agriculture, and shrimp ponds.

Sea-level rise is already causing more frequent flooding along almost all coastlines, amplified further by the loss of barrier reefs and mangroves. Extreme coastal flooding in eastern South America is likely to increase rapidly going forwards, especially in urban areas such as Buenos Aires. By 2050, across the 22 largest coastal cities of Latin America, coastal flooding could cost an average of USD 940 million annually with 20 cm of sea-level rise, or USD 1.2 bn if sea-level rise reached 40 cm. In the Caribbean, a 4 °C rather than 2 °C world would result in higher storm surges from tropical storms, causing USD 22 bn and USD 46 bn more in damage and loss of tourism by 2050 and 2100, respectively[487]. The Caribbean is especially vulnerable because half of all people live along the coast and 70% in coastal cities[487].

Finally, Colombia and Peru are two of the most vulnerable countries in the world to the decline of fisheries, which is accelerating due to a combination of ocean changes, the loss of habitats such as mangroves and reefs, invasive species, and other factors[498]. With 2 °C warming in 2050, projected fish stocks may double in the far south coast of South America, but will decrease by 15–50 % along the Caribbean coasts, by 5–50 % in parts of the Atlantic coast of Central America, by more than 50% off the Amazonas estuary and the Rio de la Plata and by up to 30% along the northern coasts of Peru and Chile[487]. This is without accounting for ocean acidification, which could cause a further 20-30% reduction in yields, and human overfishing.

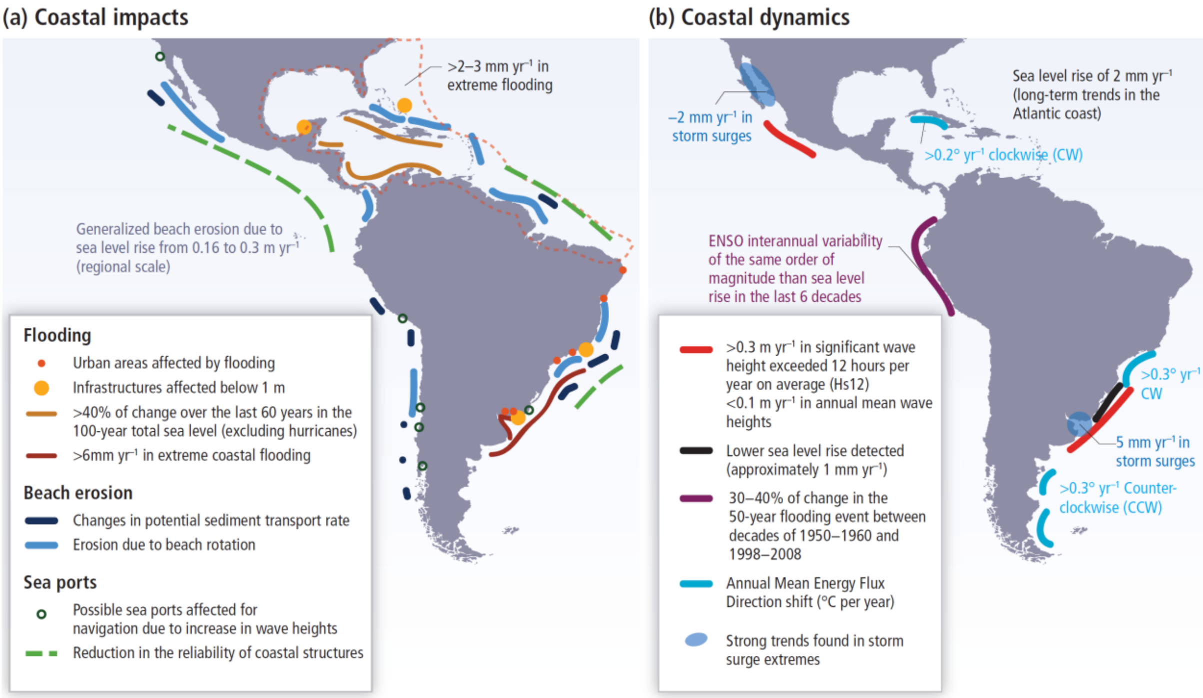

Figure 24: Current and predicted coastal impacts (a) and coastal dynamics (b) in response to climate change. (a) Coastal impacts: Based on trends observed and projections, the figure shows how potential impacts may be distributed in the region. (b) Coastal dynamics: Information based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information, and satellite information. Figure 27-6 in IPCC AR5 report[485].

4.2.5 Food security

In south-eastern South America, where rainfall totals are increasing, agricultural productivity will likely be sustained until mid-century at least. However, in Central America, northeast South America, the Caribbean and parts of the Andes, the combination of increasing temperatures and less rain is causing longer dry spells. This affects livelihoods across the region, disrupts the economy and compromises the food security of the poorest in society.

Central America is already acutely vulnerable to climate-related agricultural challenges, including both weather conditions and diseases. For example, during the coffee rust outbreak of 2012–2013, nearly 600,000 ha (55% of the total growing area) was affected. This reduced employment by around 30 to 40% for the harvest. Millions are dependent upon the coffee sector, which is generally susceptible to climate variations. Both coffee and soybean rust are expected to move further southwards, while in grain pests in Chile will increase 10–14 % in a 3 °C world and 12–22 % in a 4 °C world[487]. Later in the century, wider parts of South and Central America, representing one of the world's primary food-producing regions, will face more intense dry spells and plant diseases and pests as climate change and deforestation continue.

4.2.6 Human health

Extreme heat is impacting more people across the regions, causing morbidity and mortality, including dehydration leading to chronic kidney disease. This is especially problematic in nations with large sectors of outdoors workers, notable examples including construction, sugarcane and cotton workers in Central America and agricultural workers across wider Latin America. Summer labour capacity across tropical Latin America has already fallen dramatically since the turn of the century[97]. In urban areas, the combination of extreme heat and worsening air quality has led to higher rates chronic respiratory and cardiovascular diseases, morbidity from asthma and rhinitis, negative pregnancy-related outcomes, cancer, cognitive deficit, and diabetes. Other extreme events linked with climate change are also creating health risks. For example, severe floods in Colombia in 2010-2012 resulted in hundreds of deaths and the displacement of thousands more. In northeast South America, the rise in episodic droughts in the 21st century caused widespread shortages in water for drinking, irrigation and hydroelectric energy generation, as well as mental health issues and rates of stress-related violence.

Outbreaks of disease are also becoming more common and spreading further, often associated with extreme weather events and changing climates. For instance, hurricanes made stronger by climate change lead to flooding that in turn causes outbreaks of both vector- and water-borne diseases. Malaria rates are increasing with temperatures and spreading to new locations, with a notable rise in Colombia and Amazonia, as well as detection at higher altitudes than ever before in Bolivia and Venezuela. Incidence of dengue fever has also increased in recent decades, associated with temperature rises, causing losses of over USD 2 bn per year and spreading to non-endemic regions such as Central America and southern South America. Business-as-usual climate change is projected lead to an upsurge in dengue incidence in Mexico of 18% by 2030, 31% by 2050 and 40% by 2080[499]. Another study projected that the relative risk of diarrheal disease in all of South America will increase by 5–13% and 14–36% for the period 2010–2039 and 2070–2099 with 1.3 and 3.1 °C warming, respectively[500].

Across the region, climate-related drivers are associated with respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), hantaviruses and rotaviruses, chronic kidney diseases, and psychological trauma. The knock-on effects include severe economic losses, heightened rates of violence, and higher mortality.

4.2.7 Vulnerability

A crucial determinant of the severity of climate impacts is people's vulnerability to them. The rates of poverty and inequality in Central and South America remain relatively high despite continued economic growth. Climate change has contributed to maintaining such inequalities. The IPCC's Special Report on Global Warming of 1.5 °C states the following: "Climate change is projected to be a poverty multiplier, which means that its impacts are expected to make the poor poorer and the total number of people living in poverty greater." As a result, the regions will suffer disproportionately from greater climate variability and change, with a lower capacity to adapt to such changes and severe implications for development and human well-being.

4.3 The Amazon tipping point

Unabated climate change may trigger abrupt, nonlinear changes in the Amazon rainforest. This 'tipping point' could result in large areas of the Amazon rainforest being converted to savanna or seasonally dry forest[501], and greater evidence supporting the existence of such a tipping point has been developed in the last decade[502]. The continued deforestation of the Amazon increases the possibility of triggering this tipping point. This self-reinforcing feedback would induce an amplification of global warming of 0.05 °C by 2100[503]. Modelling experiments indicate that deforestation is expected to lengthen dry seasons and 20-25% deforestation in eastern, southern and central Amazonia may be sufficient to shift ecosystems to savanna[504]. Other studies have found that 21st-Century climate change is more likely to convert eastern Amazonia's rainforest to seasonal forest or fire-dominated, low-biomass forests[505]. This would also release portions of the Amazon carbon sink into the atmosphere and reduce its carbon uptake potential. There is substantial evidence that limiting deforestation reduces the likelihood of the conversion of the Amazon beyond a tipping point at which point maintaining the extensive rainforest that still exists becomes unsustainable[505]. The IPCC's 6th Assessment Report, published in 2021, warns that continued deforestation of the Amazon, in combination with global warming, increases the risk of crossing a tipping point and transitioning the Amazon to a dry state. While relatively unlikely, this could occur in the 21st Century[481].

Large amounts of moisture cycles through the Amazon rainforest, creating wetter conditions than would occur if the rainforest weren't there. In particular, regions such as the La Plata basin receive substantially more winter rainfall than would be expected without the Amazon, providing important support for agricultural systems. Climate change and the local climatic impacts of deforestation are projected to reduce rainfall and cause more severe drought in the eastern Amazon, although there is evidence that climate change alone is unlikely to cause major forest loss before 2100[506]. Nevertheless, the Intergovernmental Panel on Climate Change found that the combination of climate change-induced severe droughts, deforestation, and fires are likely to lead to large-scale shifts in the Amazon to low-biomass fire-adapted forests, instead of the rainforests that exist today. While most virgin forest in the Amazon Basin has low fire susceptibility, even during dry seasons, logging, severe drought and previous fires, all of which are amplified or caused by deforestation, increase the susceptibility of the Amazon to burning. Earlier research found that over half of Amazonia's forests will be lost or exposed to drought between 2008-2030 if deforestation patterns observed through 2005 were continued[507], although the slowdown in deforestation rates prior to 2019 had meant that this extent of deforestation was less likely.

Overall, despite conflicting evidence on the point at which the Amazon tipping point would be reached, the accelerated deforestation of the Amazon substantially amplifies the risk of breaching the Amazon tipping point. The consequences of doing so would include a substantial shift in regional climate to much drier conditions, the loss of one of the world's most valuable biodiversity hotspots[508], and increasing the global impacts of climate change.

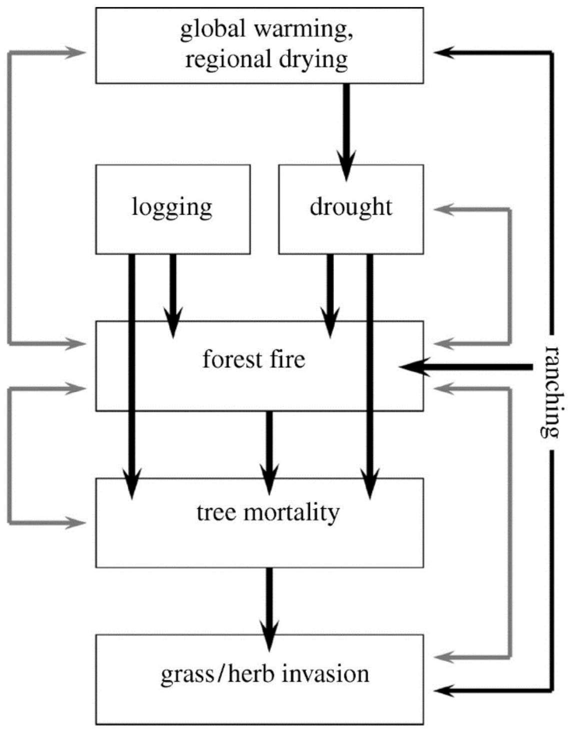

Figure 25: The processes and interactions that could lead to the dieback of the Amazon Forest over the near term. Figure reproduced from ref. [507].

5 Climate change as a stress multiplier

In sections 2-4 we summarised a range of direct impacts that have been causally linked to climate change, and therefore to greenhouse gas emissions resulting from deforestation and land-use change. These impacts, including the direct consequences of extreme weather events and slow-onset changes on health, property and infrastructure, are substantial and affect communities around the world. For instance, climate change is causing growing numbers of deaths from extreme heat and other weather events[80,509]. Indeed, one recent estimate is that every 4,434 tonnes of carbon dioxide emitted in 2020 would cause one excess death in 2020-2100[66].

Alongside the direct and traceable impacts of anthropogenic climate change – such as ocean acidification, ice-mass loss, sea-level rise and increases in the frequency of extreme heat, flooding, wildfires, drought other extreme weather hazards – the increased intensity, occurrence and persistence of climate-related extreme events, in particular water stress, raises the risk of a range of wider impacts. Such impacts include, but are not limited to, food insecurity, conflict and forced displacement. Climate change, through its manifestations in extreme weather events and slow-onset impacts, is a socially disruptive force that foments conditions that increase the risk of population displacement, violent conflict and other harmful events[510,511]. The risk of these complex socio-political impacts is increased by climate change impacts that induce political instability, financial and nutritional insecurity, and resource scarcity[512]. For instance, past studies have found that the risk of armed conflict increases immediately after climate-related disasters that provide opportunities for armed groups to escalate violence in ongoing conflicts. This is part of a vicious cycle in which armed conflict increases populations' vulnerability to climate-related disasters, that in turn create the conditions for more violent conflict[511].

While it is clear that climate change creates or amplifies social disruption, there are still a range of factors that contribute to individual complex socio-political events, such as the outbreak of conflict. It may therefore be difficult to directly attribute specific conflicts or other crises to climate change alone: it is one increasingly influential element in a web of causal factors. Consequently, there is limited evidence quantifying the role of climate change in increasing the likelihood of any specific instance of food insecurity, armed conflict or population displacement[513,514]. In any given instance, there exists a multitude of risk factors that interact with one another are not directly climate-induced – for example, the quality of local governance and other socio-economic factors[515] – which are crucial determinants of the onset of these adverse social impacts[511]. However, climate change may affect these risk factors, for instance by limiting socioeconomic development, entrenching inequality, inducing economic shocks, and compromising natural resources, agricultural and water systems[5]. It is therefore increasingly clear that climate change amplifies the risk of a wide range events that carry substantial humanitarian consequences, including amplifying the risk of conflict[516].

Synthesis assessments by the United States Department of Defense[3], The World Bank[4] and other researchers[5] have concluded that climate change will contribute to increases in the risk of food insecurity, armed conflict and higher rates of internal displacement over the twenty-first century.

5.1 Water stress as a driver of social impacts

Water insecurity represents the main climate-related driver of societal unrest. For example, the months of June and July 2021 have seen widespread civil unrest and protests over water shortages in Algeria, Iraq, Iran, Sudan and Yemen[517] (Figure 26) while extreme water shortages have also resulted in protests in Latin America, including in Peru and Chile[518]. Widespread drought and subsequent food insecurity[519] was also thought to be a contributing factor to the civil unrest which marked the beginning of the 2011 Syrian war[520]. Similar concerns relating to land degradation, persistent drought and high levels of food insecurity also exist in the Sahel[521], a region described by the UNHCR as facing one of the "fastest growing displacement crises in the world[522]".

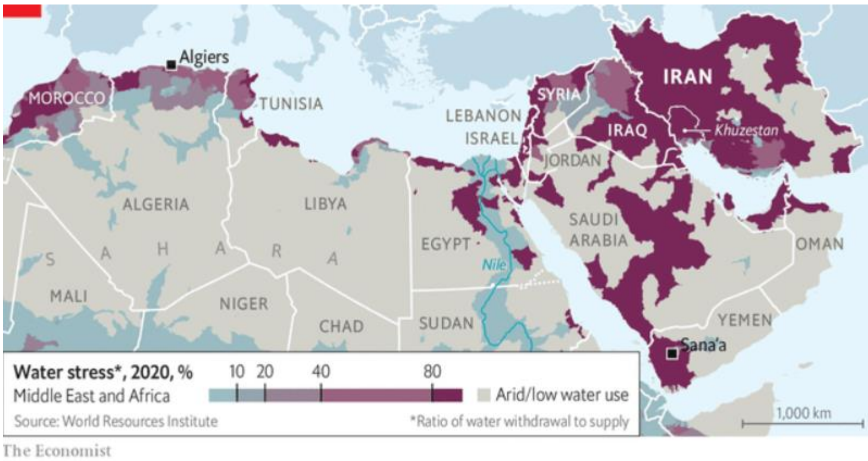

Figure 26: Water stress in North Africa and the Middle East. Source: The Economist[517].

5.2 Projected changes in water availability under climate change

There is strong scientific agreement that the driest regions of the world – those that are characterised as hyper-arid, arid and semi-arid – are expected to become even drier[523–525]. Further, the rate of temperature change varies between regions. Although there are uncertainties in these projections[526], many already hot and dry regions are expected to experience some of the fastest rates of temperature rise under climate change[527].

In some regions downstream of montane 'water towers', large, glaciated areas that store and supply water, such as the Himalayas, glacial meltwater plays an essential role in maintaining water security. This is especially the case for regions that experience limited rainfall, either year-round or in dry seasons. As noted in previous sections, the retreat of mountain glaciers will compromise water availability in dependent downstream regions. For instance, in Asia, observational records shows accelerating rates of ice loss in the Himalayas[528], where some 130 million farmers are reliant on snow and glacier melt to support their livelihoods[326]. Although, meltwater-related river runoff is projected to increase in these regions up to 2050[529], water security prospects thereafter are uncertain[530]. Reduced water supply from glaciers could lead to negative impacts for some 1.9 billion people[325].

6 Summary: deforestation and its global humanitarian consequences

6.1 Impacts of global deforestation-related emissions

The impacts of climate change result from the combined effect of all greenhouse gas emissions produced globally. However, it is also possible to assess the impacts that can be traced to individual contributions to climate change, such as the emissions produced by the Bolsonaro administration. In section 6.2 we overview the recent literature that has linked the emissions of individual companies and countries to the impacts of climate change. These studies are able to demonstrate the consequences of individual entities' greenhouse gas emissions for a range of weather events, sea-level rise, ocean acidification, and global temperature rise.

We then illustrate the magnitude of global climate change impacts that can be linked to emissions from land-use changes, such as deforestation. As set out in section 1, land-use change is responsible for approximately 19% of global greenhouse gas emissions[25]. In section 0, we indicate the contribution that land-use change would make to global climate change impacts, were global warming to reach 2 °C above pre-industrial levels. We then supplement this with an example of the extent to which mortality in a specific heatwave can be amplified by contributions to climate change that approximately reflect the contribution made by land-use change (section 6.4).

6.2 Impacts of 'small' emissions contributions

Every increment of greenhouse gas emissions and their resultant contribution to global warming amplifies the impacts of climate change around the world. Recent research found that every 4,434 tonnes of CO_2 emitted in 2020 causes one additional climate-related death globally between 2020-2100[66]. The humanitarian impacts of the greenhouse gas emissions attributed to the Bolsonaro administration in section 1 are therefore substantial. Even in the lowest emissions scenario of the three we present in section 1, an additional 180,000 excess heat-related deaths globally over the next 80 years are expected to be caused by the greenhouse gas emissions traceable to the Bolsonaro administration (section 1.6). This estimate is based on the world making substantial emissions cuts, and efforts to achieve this are being jeopardised by the Bolsonaro administration's pursuit of increasing rates of deforestation. In economic terms, even using the highly conservative[303] value of USD 31 / tCO_2 for the 'social cost of carbon', the global economic cost caused by emitting one tonne of carbon dioxide emissions[531], the emissions attributable to the Bolsonaro administration due to Amazon deforestation will cause global damage of over USD 52 bn (in 2010 USD), in the low deforestation scenario presented in section 1.

Peer-reviewed research has shown that it is possible to link climate change impacts, including heatwaves, ocean acidification, sea-level rise and global temperature change, to individual emitters of greenhouse gases[7–10]. It is possible to quantify contributions to global-mean temperature change at the level of individual countries: for instance Brazil contributed 4% of global temperature change due to CO_2 emissions from fossil-fuel combustion and land-use change between 1850-2010[6]. Other studies have shown that individual emitters' contributions to global-mean temperature change can be linearly transferred to their contribution to heatwaves[10].

The impacts of emissions of individual countries over a number of years are calculable. For instance, one assessment found that over 1991-2030, the emissions produced by China, assuming they meet their pledged climate targets for 2030 would produce 10cm of sea-level rise by 2300[8]. Even though Bolsonaro's contribution to deforestation-related emissions is smaller, and effective for fewer years, than 40 years of China's emissions, the principle that contributions to greenhouse gas emissions can be causally linked to climate change impacts holds.

6.3 Climate change impacts at 1.5 and 2 °C: a proxy for estimating the impacts of global deforestation-related emissions

Global emissions due to land-use change make up roughly one fifth of the human contribution to warming. If global warming were to reach 2 °C above pre-industrial levels, these deforestation emissions will be responsible for a substantial portion of the difference between a 2°C world and a 1.5°C world, assuming an approximately linear relationship between emissions and warming (a reasonable approximation at these temperatures[2,532]). Consequently, the difference in climate change impacts projected to occur between these two warming levels is indicative of approximately 25% more than the contribution of land-use and agriculture-related emissions would have made, were global warming to reach 2 °C above pre-industrial levels. In summarising the difference between climate change impacts at 1.5 and 2 °C of warming, and thereby indicating the approximate contribution of land-use change to climate change impacts at that level of warming, we focus on the findings described in the IPCC's 2018 Special Report on Global Warming of 1.5 °C[15].

Moreover, if global warming is to be limited to 1.5 °C, then all deforestation must stop by 2030. Continued deforestation, and especially any acceleration in deforestation rates compromises natural carbon sinks and puts the world on track for warming of at least 2 °C by mid-century.

Globally, the impacts of climate change are projected to be substantially greater at a global warming of 2 °C above pre-industrial levels than at 1.5 °C warming (Figure 27). Based on the findings of the IPCC, such differences will include the likelihood and intensity of hot extremes globally, and both heavy rainfall events and droughts in some regions. Heatwaves are becoming even hotter at a faster rate than the global-mean temperature: in temperate regions, hot days are projected to be 3 °C warmer than pre-industrial conditions at 1.5 °C of global warming, rising to 4 °C warmer at 2 °C of global warming. The largest increases in hot days will occur in the tropics, which are already heavily exposed to the risks of extreme heat[15].

The IPCC also found that allowing global temperatures to reach 2 °C above pre-industrial levels will result in increased risks, including of flooding, due to heavy precipitation events in eastern Asia and eastern North America, and in regions affected by tropical cyclones. Limiting warming to 1.5 °C would also reduce sea-level rise in 2100 by 10cm, compared to the projected 2100 rise given 2 °C of warming, exposing an additional 10 million people to the risks of rising sea levels. Further, the increased rate of sea-level rise compromises the ability of coastal communities to adapt to changing risks[15]. As noted in section 3, above, warm-water coral reefs will decline by 70-90% if global warming reaches 1.5 °C above pre-industrial levels, but all-but disappear at +2 °C[15].

The health impacts of climate change also increase substantially between 1.5-2 °C, including heat-related mortality and morbidity[15], and risks from ozone-related mortality, malaria, Dengue, and Lyme disease[533]. For agriculture, 2 °C of warming will result in greater yield reductions for staple crops such as maize, rice, and wheat, especially in sub-Saharan Africa, Southeast Asia, and Central and South America, jeopardising food security. Food availability is also projected to fall further at 2 °C warming than 1.5 °C in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon[15].

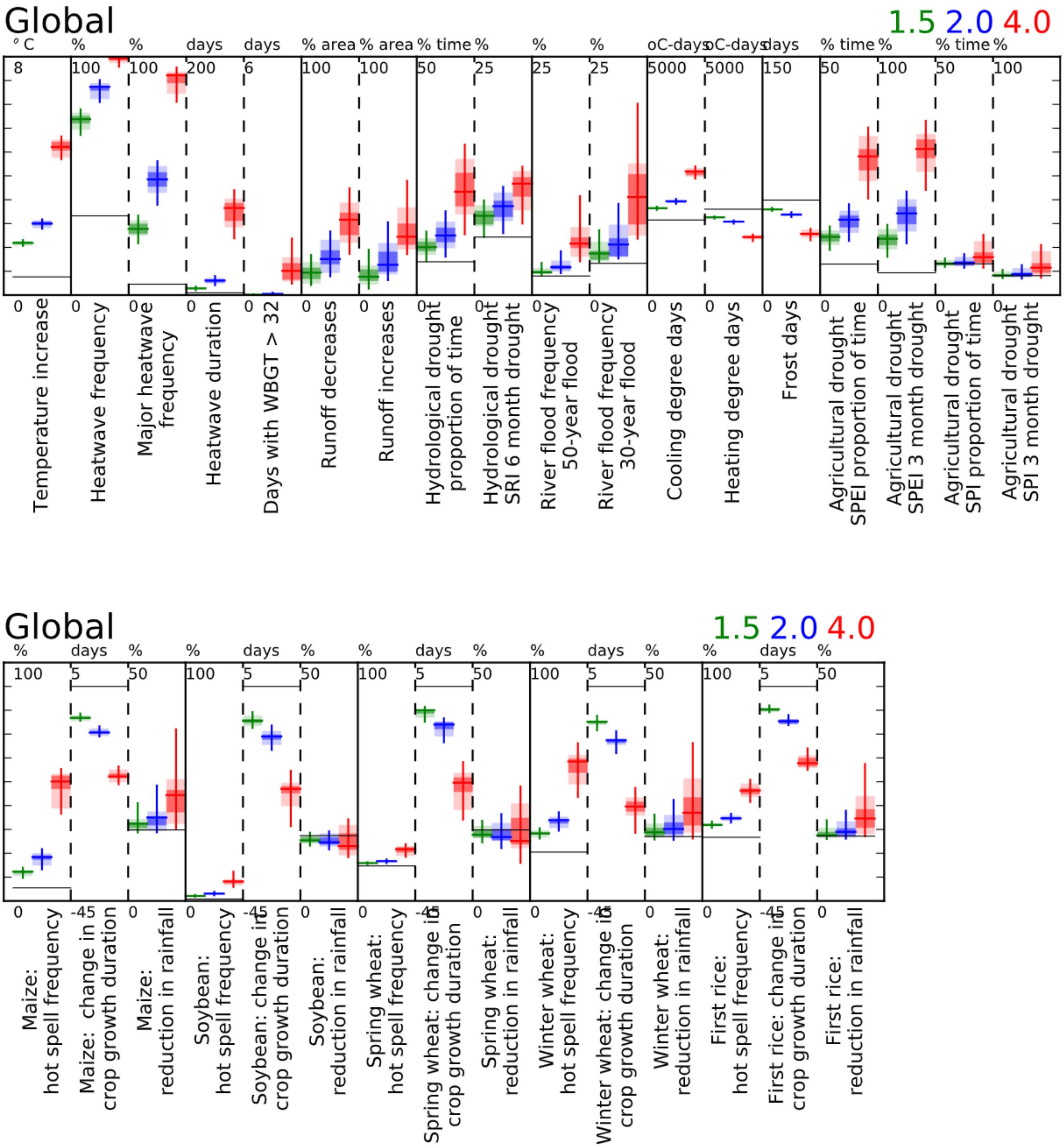

Figure 27: Summary of the global-scale impacts across many indicators, at 1.5, 2 and 4 °C above pre-industrial levels. The horizontal, coloured lines show the median impact, the dark shading shows the inter-quartile range and the light shading shows the 10th to 90th percentile range of likely changes. The vertical lines show the range between lowest and highest impact[432].

Further research has focused specifically on the impact of 0.5°C of warming on changes in extreme temperatures and precipitation. This warming has been shown to intensify extreme hot conditions by over 1 °C. Crucially, this warming has resulted in over half of the world's land area experiencing substantial increases in the occurrence of high temperatures that exceed the range of natural temperature variability that could be expected to occur in the absence of climate change[534]. The increasing occurrence of events that were unprecedented in affected regions has especially pronounced impacts as communities are generally less likely to be well prepared for such events that would not have occurred under past climate conditions. The recently published Sixth Assessment Report of the IPCC found that even at 1.5 °C of warming, there will be substantial increases in the occurrence of unprecedented extreme events[2], but will become even more prevalent if warming reaches 2 °C or more[535].

6.4 Case study: mortality from a heatwave

The European summer heatwave of 2003 resulted in 70,000 excess deaths[125]. At the time, atmospheric CO_2 levels stood at approximately 376 ppm, 96 ppm above the pre-industrial level[536]. In 2015, atmospheric CO_2 levels were at 401 ppm, or 120 ppm above pre-industrial. As such, 20% of anthropogenic greenhouse gas emissions produced prior to 2015, were emitted between 2003-2015. We can therefore estimate the implications of deforestation-related emissions by considering the likelihood of the 2003 event occurring in the climates of 2003 and 2015. We compare the probability of an event like that of 2003, in the climates of 2003 and 2015, to indicate how the portion of emissions attributable to land-use change affects the impacts.

In 2003, an attribution study indicated that the heatwave event was approximately doubled in likelihood by climate change, using a very conservative estimate[110]. Based on an approach used in past attribution studies on heatwave mortality attributed to climate change[127,128], around 35,000 deaths were attributable to climate change. In 2015, a new study estimated the likelihood of the same event in the modern day and the extent to which climate change had changed that likelihood. In the 12 years since the event occurred, using the same conservative definition, it became 10 times more likely again[111] (Table 4). In other words, an event that extreme had become at least 20 times more likely because of climate change. This means that if the same event occurred at this higher emissions level, 95% or 66,500 deaths would be attributable to climate change. Based on this approach, as a result of the increase in global warming between 2003 and 2015, around 31,500 extra deaths would be attributable to these emissions.

Event Date	Total mortality	Fraction of risk attributable to climate change	Climate change-related mortality
2003	70000	50%	35000
2015 (hypothetical)	70000	95%	66500

Table 4: Mortality attributable to climate change from the European summer heatwave, at the date of its occurrence in 2003, and a hypothetical version of the same event had it occurred in 2015. These data demonstrate how much more likely extreme events like these have become as a result of human influence on the climate. Data for the attribution of the 2003 event from ref. [110], and for the hypothetical 2015 event from ref. [111].

To summarise, at any given level of warming, had the emissions related to global deforestation never occurred, the impacts of extreme weather upon humans and society would be substantially lower. For a single deadly heatwave, this could represent tens of thousands of deaths.

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