Chapter 9: Africa

Coordinating Lead Authors: Christopher H. Trisos (South Africa), Ibidun O. Adelekan (Nigeria), Edmond Totin (Benin).

Lead Authors: Ayansina Ayanlade (Nigeria), Jackson Efitre (Uganda), Adugna Gemeda (Ethiopia), Kanungwe Kalaba (Zambia), Christopher Lennard (South Africa), Catherine Masao (Tanzania), Yunus Mgaya (Tanzania), Grace Ngaruiya (Kenya), Daniel Olago (Kenya), Nicholas P. Simpson (Zimbabwe/South Africa), Sumaya Zakieldeen (Sudan).

Contributing Authors: Philip Antwi-Agyei (Ghana), Aaron Atteridge (Sweden/Australia), Rachel Bezner Kerr (Canada/USA), Max Callaghan (United Kingdom/Germany), Tamma Carleton (USA), Colin Carlson (USA), Hayley Clements (South Africa), Declan Conway (United Kingdom), Sean Cooke (South Africa), Matthew Chersich (South Africa), David Chiawo (Kenya), Joanne Clarke (Australian/United Kingdom), Marlies Craig (South Africa), Olivier Crespo (South Africa), James Cullis (South Africa), Jampel Dell'Angelo (Italy/USA), Luleka Dlamini (South Africa) Hussen Seid Endris (Kenya), Christien Engelbreht (South Africa), Aidan Farrell (Trinidad and Tobago/Ireland), James Franke (USA), Thian Yew Gan (Malaysia/Canada), Christopher Golden (USA), Kerry Grey (South Africa), Toshihiro Hasegawa (Japan), Ryan Hogarth (Canada/United Kingdom), Nadia, Hassan O. Kaya (South Africa), Khalaf (United Kingdom), Mercy Kinyua (Kenya), Scott Kulp (USA), William F. Lamb (United Kingdom/Germany), Charne Lavery (South Africa), Johan Maritz (South Africa), Guy Midgley (South Africa), Danielle Millar (South Africa), Jan Minx (Germany), Glenn Moncrieff (South Africa), Rachid Moussadek (Morocco), Mzime Ndebele-Murisa (Zimbabwe), Emily Nicklin (South Africa), Michelle North (South Africa), Mary Nyasimi (Kenya), Elizabeth Nyboer (Canada), Romaric Odoulami (Benin/South Africa), Andrew Okem (South Africa/Nigeria), Gladys Okemwa (Kenya), Kulthoum Omari (Botswana/South Africa), Esther Onyango (Kenya/Australia), Birgitt Ouweneel (Netherlands/South Africa), Indra Øverland (Norway), Lorena, Pasquini (South Africa), Belynda Petrie (South Africa), Alex Pigot (United Kingdom), Wilfried Pokam (Cameroon), Bronwen Powell (Canada/USA), Jeff Price (United Kingdom), Heather Randell (USA), Maren Radeny (Kenya), Jonathan Rawlins (South Africa), Kanta Kumari Rigaud (Malaysia/USA), Carla Roncoli (USA), Olivia Rumble (South Africa), Elisa Sainz de Murieta (Spain), Georgia Savvidou (Sweden/Cyprus), Lucia Schlemmer (South Africa), Laura Schmitt Olabisi (USA), Chandni Singh (India), Thomas Smucker (USA), Nicola Stevens (South Africa), Anna Steynor (South Africa), Bamba Sylla (Rwanda/Senegal), Arame Tall (Senegal/USA), Richard Taylor (Canada/United Kingdom), Meryem Tenarhte (Morocco/Germany), Mia Thom (South Africa), Jessica Thorn (Namibia/South Africa), Katharina Waha (Germany/Australia), Hitomi Wakatsuki (Japan), Edna Wangui (Kenya/USA), Portia Adade Williams (Ghana), Kevin Winter (South Africa), Caradee Wright (South Africa), Luckson Zvobgo (Zimbabwe/South Africa).

Review Editors: Stuart Mark Howden (Australia), Robert (Bob) J. Scholes (South Africa), Pius Yanda (Tanzania).

Chapter Scientists: Michelle North (South Africa), Luckson Zvobgo (Zimbabwe/South Africa).

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Executive Summary

Overall Key Messages

Africa has contributed among the least to greenhouse gas emissions, yet key development sectors have already experienced widespread loss and damage attributable to anthropogenic climate change, including biodiversity loss, water shortages, reduced food production, loss of lives and reduced economic growth (*high confidence*[1]). {9.1.1, 9.2, 9.6.1, 9.8.2, 9.10.2, 9.11.1; Box 9.4}

Between 1.5°C and 2°C global warming—assuming localised and incremental adaptation—impacts are projected to become widespread and severe for reduced food production, reduced economic growth, increased inequality and poverty, biodiversity loss, increased human morbidity and mortality (*high confidence*)**. Limiting global warming to 1.5°C is expected to substantially reduce damages to African economies and ecosystems** (*high confidence*). {9.2, 9.6.2, 9.8.2, 9.8.5, 9.10.2, 9.11.2}

Exposure and vulnerability to climate change in Africa are multi-dimensional with socioeconomic, political and environmental factors intersecting (*very high confidence*). Africans are disproportionately employed in climate-exposed sectors: 55–62% of the sub-Saharan workforce employed is in agriculture and 95% of cropland rainfed. In rural Africa, poor and female-headed households face greater livelihood risks from climate hazards. In urban areas, growing informal settlements without basic services increases the vulnerability of large populations to climate hazards, especially women, children and the elderly. {9.8.2, 9.9.1, 9.9.3, 9.11.4; Box 9.1}

Adaptation in Africa has multiple benefits, and most assessed adaptation options have medium effectiveness at reducing risks for present-day global warming, but their efficacy at future warming levels is largely unknown (*high confidence*). {9.3, 9.6.4, 9.8.3, 9.11.4}

Enabling Climate-Resilient Development

Climate-related research in Africa faces severe data constraints, as well as inequities in funding and research leadership that reduce adaptive capacity (*very high confidence*)**.** Many countries lack regularly reporting weather stations, and data access is often limited. From 1990–2019 research on Africa received just 3.8% of climate-related research funding globally: 78% of this funding went to EU and North American institutions and only 14.5% to African institutions. The number of climate research publications with locally-based authors are among the lowest globally and research led by external researchers may focus less on local priorities. Increased funding for African partners, and direct control of research design and resources can provide more actionable insights on climate risks and adaptation options in Africa. {9.1, 9.4.5, 9.5.2}

Adaptation generally is cost effective, but annual finance flows targeting adaptation for Africa are billions of USD less than the lowest adaptation cost estimates for near-term climate change (*high confidence*). Finance has not targeted more vulnerable countries. From 2014–2018 more finance commitments were debt than grants and—excluding multilateral development banks—only 46% of commitments were disbursed (compared to 96% for other development projects). {9.4.1}

Adaptation costs will rise rapidly with global warming (*very high confidence*)**. Increasing public and private finance flows by billions of dollars per year, increasing direct access to multilateral funds, strengthening project pipeline development, and shifting finance from readiness activities to project implementation would help realise transformative adaptation in Africa** (*high confidence*). Concessional finance will be required for adaptation in low-income settings. Aligning sovereign debt relief with climate goals could increase finance by redirecting debt-servicing payments to climate resilience. {9.4.1}

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

Governance for climate resilient development includes: long-term planning, all-of-government approaches, transboundary cooperation and benefit-sharing, development pathways that increase adaptation and mitigation and reduce inequality, and NDC implementation (*high confidence*). {9.3.2, 9.4.2, 9.4.3}

Cross-sectoral 'nexus' approaches provide significant opportunities for large co-benefits and/or avoided damages (*very high confidence*). For example, climate change adaptation benefits pandemic preparedness; 'One Health' approaches benefit human and ecosystem health; and Ecosystem-based Adaptation can deliver adaptation and emissions mitigation (*high confidence*). {9.4.3, 9.6.4, 9.11.5; Box 9.6}

Without cross-sectoral, transboundary and long-term planning, response options in one sector can become response risks, exacerbating impacts in other sectors and causing maladaptation (*very high confidence*)**.** For example, maintaining indigenous forest benefits biodiversity and emissions mitigation, but afforestation—or wrongly targeting ancient grasslands and savannas for reforestation—harms water security and biodiversity, and can increase carbon loss to fire and drought. Planned hydropower projects may increase risk as rainfall changes impact water, energy and food security exacerbating trade-offs between users, including across countries. {9.4.3; Boxes 9.3, 9.5}

Robust legislative frameworks that develop or amend laws to mainstream climate change into their empowerment and planning provisions will facilitate effective design and implementation of climate change responses (*high confidence*). {9.4.4}

Climate information services that are demand-driven and context-specific (e.g., for agriculture or health) combined with climate change literacy can affect the difference between coping and informed, adaptation responses (*high confidence*). Across 33 African countries, 23–66% of people are aware of anthropogenic climate change—with larger variation at subnational scales (e.g., 5–71% among states in Nigeria). Climate change literacy increases with education level but is undermined by poverty, and rates average 12.8% lower for women than men. 71% of Africans aware of climate change agree it should be stopped. Production of salient climate information in Africa is hindered by limited availability of and access to weather and climate data. {9.4.5, 9.5.1, 9.8.4, 9.10.3}

Ecosystem-based adaptation can reduce climate risk while providing social, economic and environmental benefits (*high confidence*). Direct human dependence on ecosystem services in Africa is high. Ecosystem protection and restoration, conservation agriculture practices, sustainable land management, and integrated catchment management can support climate resilience. Ecosystem-based adaptation can cost less than grey infrastructure in human settlements (e.g., using wetlands and mangroves as coastal protection). {9.6.4, 9.7.3, 9.8.3, 9.9.5, 9.12.3; Box 9.7}

Observed Impacts and Projected Risks

Climate

Increasing mean and extreme temperature trends across Africa are attributable to human-induced climate change (*high confidence*). {9.5.1, 9.5.2}

Climate change has increased heat waves (*high confidence*) **and drought** (*medium confidence*) **on land, and doubled the probability of marine heatwaves around most of Africa** (*high confidence*). Multi-year droughts have become more frequent in West Africa, and the 2015–2017 Cape Town drought was three times more *likely*[2] due to human-induced climate change. {9.5.3–7, 9.5.10}

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

Above 2°C global warming, meteorological drought frequency will increase and duration will double from 2 to 4 months over North Africa, the western Sahel and southern Africa (*medium confidence*). {9.5.2, 9.5.3, 9.5.6.}

Frequency and intensity of heavy rainfall events will increase at all levels of global warming (except in North and southwestern Africa), increasing exposure to pluvial and riverine flooding (*high confidence).* {9.5.3–7, 9.7}

Glaciers on the Rwenzoris and Mt. Kenya are projected to disappear by 2030, and by 2040 on Kilimanjaro *(medium confidence*). {9.5.8}

In East and southern Africa, tropical cyclones making landfall are projected to become less frequent but have more intense rainfall and higher wind speeds at increasing global warming (*medium confidence*). {9.5.7}

Heat waves on land, in lakes, and in the ocean will increase considerably in magnitude and duration with increasing global warming (*very high confidence*). Under a 1.5°C-compatible scenario, children born in Africa in 2020 are *likely* to be exposed to 4–8 times more heat waves compared to people born in 1960, increasing to 5–10 times for 2.4°C global warming. The annual number of days above potentially lethal heat thresholds reaches 50–150 in west Africa at 1.6°C global warming, 100–150 in Central Africa at 2.5°C, and 200–300 over tropical Africa for >4°C. {9.5.2, 9.5.3, 9.5.4, 9.5.5, 9.5.6, 9.7.2.1}

Most African countries will enter unprecedented high temperature climates earlier in this century than generally wealthier, higher latitude countries, emphasising the urgency of adaptation measures in Africa (*high confidence*). {9.5.1}

Compound risks

Multiple African countries are projected to face compounding risks from: reduced food production across crops, livestock and fisheries; increasing heat-related mortality; heat-related loss of labour productivity; and flooding from sea level rise, especially in West Africa (*high confidence*). {9.8.2, 9.8.5, 9.9.4, 9.10.2, 9.11.2}

Water

Recent extreme variability in rainfall and river discharge (c. -50% to +50% relative to long-term historical means) across Africa have had largely negative and multi-sector impacts across water-dependent sectors (*high confidence*) {9.7.2, 9.10.2}. Hydrological variability and water scarcity have induced cascading impacts from water-supply provision and/or hydro-electric power production to health, economies, tourism, food, disaster risk response capacity and increased inequality of water access. {Box 9.4}

Extreme hydrological variability is projected to progressively amplify under all climate scenarios relative to the current baseline, depending on region (*high confidence*). Projections of numbers of people exposed to water stress by the 2050s vary widely—decreases/increases by hundreds of millions, with higher numbers for increases—with disagreement among global climate models the major factor driving these large ranges. Populations in drylands are projected to more than double. Projected changes present heightened cross-cutting risks to water-dependent sectors, and require planning under deep uncertainty for the wide range of extremes expected in future. {9.7.1, 9.7.2}

Economy and Livelihoods

Climate change has reduced economic growth across Africa, increasing income inequality between African countries and those in temperate, Northern Hemisphere climates (*high confidence*)**.** One estimate suggests GDP per capita for 1991–2010 in Africa was on average 13.6% lower compared to if climate change had not occurred. Impacts manifest largely through losses in agriculture, as well as tourism, manufacturing, and infrastructure. {9.6.3, 9.11.1}

Climate variability and change undermine educational attainment (*high agreement, medium evidence*). High temperatures, low rainfall, and flooding, especially in the growing season, may mean children are removed from school to assist income generation. Early life undernutrition associated with low harvests can impair cognitive development. {9.11.1.2}

Limiting global warming to 1.5°C is *very likely* to positively impact GDP per capita across Africa. Increasing economic damage forecasts under high-emissions diverge from low-emissions pathways by 2030. Inequalities between African countries are projected to widen with increased warming. Across nearly all African countries, GDP per capita is projected to be at least 5% higher by 2050 and 10–20% higher by 2100 if global warming is held to 1.5°C versus 2°C. {9.11.2}

Food systems

In Africa, climate change is reducing crop yields and productivity (*medium confidence*). Agricultural productivity growth has been reduced by 34% since 1961 due to climate change, more than any other region. Maize and wheat yields decreased on average 5.8% and 2.3%, respectively in sub-Saharan Africa due to climate change in the period 1974–2008. Farmers and pastoralists perceive the climate to have changed and over two thirds of Africans perceive climate conditions for agricultural production have worsened over the past ten years. Woody plant encroachment has reduced fodder availability. {9.4.5, 9.6.1, 9.8.2}

Future warming will negatively affect food systems in Africa by shortening growing seasons and increasing water stress (*high confidence)*. By 1.5°C global warming, yields are projected to decline for olives (North Africa) and Sorghum (West Africa) with a decline in suitable areas for coffee and tea (East Africa). Although yield declines for some crops may be partially compensated by increasing atmospheric CO_2 concentrations, global warming above 2°C will result in yield reductions for staple crops across most of Africa compared to 2005 yields (e.g., 20–40% decline in West African maize yields), even when considering adaptation options and increasing CO_2 (*medium confidence*). Relative to 1986–2005, global warming of 3°C is projected to reduce labour capacity in agriculture by 30–50% in sub-Saharan Africa. {9.8.2}

Climate change threatens livestock production across Africa (*high agreement, low evidence***).** Rangeland net primary productivity is projected to decline 42% for west Africa by 2050 at 2ºC global warming. Vector-borne livestock diseases and the duration of severe heat stress are both projected to become more prevalent under warming. {9.8.2}

Climate change poses a significant threat to African marine and freshwater fisheries (*high confidence*). Fisheries provide the main source of protein for ~30% of Africa's population and support the livelihoods of 12.3 million people. At 1.5°C global warming, marine fish catch potential (MFCP) decreases 3–41% by 2081–2100 relative to 1986–2005, increasing to 12–69% at 4.3°C, with the highest declines for tropical countries. Under 1.7°C global warming, reduced fish harvests could leave 1.2–70 million people vulnerable to iron deficiencies, up to 188 million for vitamin A deficiencies, and 285 million for vitamin B_{12} and omega-3 fatty acids by mid-century. For inland fisheries, 55–68% of commercially harvested fish species are vulnerable to extinction under 2.5°C global warming by 2071–2100. {9.8.5}

Health

Climate variability and change already impacts the health of tens of millions of Africans through exposure to non-optimal temperatures and extreme weather, and increased range and transmission of infectious diseases (*high confidence).* {9.10.1}

Mortality and morbidity will escalate with further global warming, placing additional strain on health and economic systems (*high confidence*). At 1.5°C of global warming, distribution and seasonal transmission of vector-borne diseases is expected to increase, exposing tens of millions more people, mostly in East and Southern Africa (*high confidence*). Above 1.5°C risk of heat-related deaths rises sharply (*high confidence*), with at least 15 additional deaths per 100,000 annually across large parts of Africa. At 2.1°C degrees, thousands to tens of thousands of additional cases of diarrhoeal disease are projected, mainly in Central and East Africa (*medium confidence*). These changes risk undermining improvements in health from future socio-economic development (*high agreement, medium evidence*).{9.10.2}

Human Settlements

Exposure of people, assets and infrastructure to climate hazards is increasing in Africa with rapid urbanisation, infrastructure deficit, and growing population in informal settlements (*high confidence***).**

About one-third of African cities with populations over 300,000 are located in areas that are at high risk from climate hazards. Sub-Saharan Africa is the only region that has recorded increasing rates of flood mortality since the 1990s. {9.9.1, 9.9.2}

High population growth and urbanisation in low-elevation coastal zones will be a major driver of exposure to sea level rise in the next 50 years (*high confidence*). By 2030, 108–116 million people in Africa will be exposed to sea level rise in Africa (compared to 54 million in 2000), increasing to 190–245 million by 2060. {9.9.1, 9.9.4}

Africa's rapidly growing cities will be hotspots of risks from climate change and climate-induced in-migration, which could amplify pre-existing stresses related to poverty, informality, exclusion and governance (*high confidence*)**.** Urban population exposure to extreme heat is projected to increase from 2 billion person-days per year in 1985–2005 to 45 billion person-days by the 2060s (1.7°C global warming with low population growth) and to 95 billion person-days (2.8°C global warming with medium-high population growth), with greatest exposure in West Africa. Sensitive populations under 5 and over 64 years old in African cities exposed to heat waves are projected to increase from around 27 million in 2010 to 360 million (SSP1) and 440 million (SSP5) by 2100, for global warming of 1.8°C and >4°C, respectively. Compared to 2000, urbanization is projected to increase urban land extent exposed to arid conditions by around 700% and exposure to high-frequency flooding by 2,600% across West, Central and East Africa by 2030. {9.9.1, 9.9.2, 9.9.4; Box 9.8}

Migration

Most climate-related migration observed currently is within countries or between neighbouring countries, rather than to distant high-income countries (*high confidence*)**.** Urbanisation has increased when rural livelihoods were negatively impacted by low rainfall. Over 2.6 million and 3.4 million new weather-related displacements occurred in sub-Saharan Africa in 2018 and 2019. {Box 9.8}

Climate change is projected to increase migration, especially internal and rural-to-urban migration (*high agreement, medium evidence*)**.** With 1.7°C global warming by 2050, 17–40 million people could migrate internally in sub-Saharan Africa, increasing to 56–86 million for 2.5°C (>60% in West Africa) due to water stress, reduced crop productivity, and sea level rise. This is a lower-bound estimate excluding rapid-onset hazards such as floods and tropical cyclones. {Box 9.8}

Infrastructure

Climate-related infrastructure damage and repairs will be a financially significant burden to countries (*high confidence*)**.** Without adaptation, aggregate damages from sea level rise and coastal extremes to 12 major African coastal cities in 2050 under medium and high emissions scenarios will be USD 65 billion and USD 86.5 billion, respectively. Potential costs of up to USD 183.6 billion may be incurred through 2100 to maintain existing road networks damaged from temperature and precipitation changes due to climate change. Increased rainfall variability is expected to affect electricity prices in countries highly dependent on hydropower. {9.9.4; Boxes 9.4, 9.5}

Ecosystems

Increasing CO_2 levels and climate change are destroying marine biodiversity, reducing lake productivity, and changing animal and vegetation distributions (*high confidence*)**.** Impacts include repeated mass coral bleaching events in east Africa, and uphill (birds) or poleward (marine species) shifts in geographic distributions. For vegetation, the overall observed trend is woody plant expansion, particularly into grasslands and savannas, reducing grazing land and water supplies. {9.6.1}

The outcome of interacting drivers operating in opposing directions on future biome distributions is highly uncertain. Further increasing CO2 concentrations could increase woody plant cover, but increasing aridity could counteract this, destabilising forest and peatland carbon stores in central Africa (*low confidence*). {9.6.2.1}

African biodiversity loss is projected to be widespread and escalating with every 0.5ºC increase above present-day global warming (*high confidence***).** Above 1.5°C, half of assessed species are projected to lose over 30% of their population or area of suitable habitat. At 2°C, 36% of freshwater fish species are vulnerable to local extinction, 7–18% of species assessed are at risk of extinction, and over 90% of East African coral reefs could be destroyed by bleaching. Above 2°C, risk of sudden and severe biodiversity losses becomes widespread in West, Central and East Africa. Climate change is also projected to change patterns of invasive species spread. {9.6.2}

Climate security

There is increasing evidence linking increased temperatures and drought to conflict risk in Africa (*high confidence*)**.** Agriculturally dependent and politically excluded groups are especially vulnerable to drought-associated conflict risk. However, climate is one of many interacting risk factors, and may explain a small share of total variation in conflict incidence. Ameliorating ethnic tensions, strengthening political institutions, and investing in economic diversification could mitigate future impacts of climate change on conflict. {Box 9.9}

Heritage

African cultural heritage is already at risk from climate hazards, including sea level rise and coastal erosion. Most African heritage sites are neither prepared for, nor adapted to, future climate change (*high confidence*). {9.12}

Adaptation

With global warming increasing above present-day levels the ability of adaptation responses to offset risk is substantially reduced (*high confidence***).** Crop yield losses, even after adaptation, are projected to rise rapidly above 2°C global warming. Limits to adaptation are already being reached in coral reef ecosystems. Immigration of species from elsewhere may partly compensate for local extinctions and/or lead to local biodiversity gains in some regions. However, more African regions face net losses than net gains. At 1.5°C global warming, over 46% of localities face net losses in terrestrial vertebrate species richness with net increases projected for under 15% of localities. {9.6.1.4, 9.6.2.2, 9.8.2.1, 9.8.2.2, 9.8.4}

Technological, institutional, and financing factors are major barriers to climate adaptation feasibility in Africa (*high confidence*). {9.3, 9.4.1}

There is limited evidence for economic growth alone reducing climate damages, but under scenarios of inclusive and sustainable development, millions fewer people in Africa will be pushed into extreme poverty by climate change and negative impacts to health and livelihoods can be reduced by 2030 (*medium confidence*). {9.10.3, 9.11.4}

Gender-sensitive and equity-based adaptation approaches reduce vulnerability for marginalised groups across multiple sectors in Africa, including water, health, food systems and livelihoods (*high confidence*). {9.7.3, 9.8.3, 9.9.5, 9.10.3, 9.11.4; Boxes 9.1, 9.2}

Integrating climate adaptation into social protection programs, such as cash transfers, public works programmes and healthcare access, can increase resilience to climate change (*high confidence*). Nevertheless, social protection programs may increase resilience to climate-related shocks, even if they do not specifically address climate risks. {9.4.2, 9.10.3, 9.11.4}

The diversity of African indigenous knowledge and local knowledge systems provide a rich foundation for adaptation actions at local scales (*high confidence*). African indigenous knowledge systems are exceptionally rich in ecosystem-specific knowledge used for management of climate variability. Integration of indigenous knowledge systems within legal frameworks, and promotion of indigenous land tenure rights can reduce vulnerability. {9.4.4; Box 9.1, Box 9.2}

Early warning systems based on targeted climate services can be effective for disaster risk reduction, social protection programmes, and managing risks to health and food systems (e.g., vector-borne disease and crops) (*high confidence*). {9.4.5, 9.5.1, Box 9.2, 9.8.4, 9.8.5, 9.10.3, 9.11.4}

Risk-sensitive infrastructure delivery and equitable provision of basic services can reduce climate risks and provide net financial savings (*high confidence*). However, there is limited evidence of pro-active climate adaptation in African cities. Proactive adaptation policy could reduce road repair and maintenance costs by 74% compared to a reactive policy. Adapting roads for increased temperatures and investment in public transport are assessed as 'no regret' options. In contrast, hydropower development carries risk of regrets due to damages when a different climate than was expected materializes. Energy costs for cooling demands are projected to accumulate to USD 51.3 billion in 2035 at 2°C global warming and to USD 486.5 billion in 2076 at 4°C. {9.8.5}

Reduced drought and flood risk, and improved water and sanitation access, can be delivered by: water-sensitive and climate scenario planning, monitored groundwater use, waterless on-site sanitation, rainwater harvesting and water reuse, reducing risk to human settlements, food systems, economies, and human health (*high confidence*). {9.8, 9.9, 9.10, 9.11}

Water sector adaptation measures show medium social and economic feasibility but low feasibility for most African cities due to technical and institutional restrictions, particularly for large supply dams and centralised distribution systems (*medium confidence*). {9.3.1, 9.7.3} Use of integrated water management, water supply augmentation, and establishment of decentralised water management systems can reduce risk. Integrated water management measures including sub-national financing, demand management through subsidies, rates and taxes, and sustainable water technologies can reduce water insecurity caused by either drought or floods (*medium confidence*). {9.7.3; Box 9.4}

Agricultural and livelihood diversification, agroecological and conservation agriculture practices, aquaculture, on-farm engineering, and agroforestry can increase resilience and sustainability of food systems in Africa under climate change (*medium confidence*). However, smallholder farmers tend to address short-term shocks or stresses by deploying coping responses rather than transformative adaptations. Climate information services, institutional capacity building, and strategic financial investment can help overcome these barriers to adaptation (*medium confidence*). {9.4.5, 9.8.3, 9.8.5}

African countries and communities are inadequately insured against climate risk, but innovative index-based insurance schemes can help transfer risk and aid recovery, including in food systems (*medium confidence*). Despite their potential, uptake of climate insurance products remains constrained by lack of affordability, awareness and product diversity. {9.4.5, 9.8.4, 9.11.4.1}

Human migration is a potentially effective adaptation strategy across food systems, water, livelihoods and in climate-induced conflict areas, but can also be maladaptive if vulnerability is increased, particularly for health and human settlements (*high confidence*). Migration of men from rural areas can aggravate the work burden faced by women. The more agency migrants have (that is, degree of voluntarity and freedom of movement) the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*).{9.3, 9.8.3, 9.9.1–3, 9.10.2.2.2; Boxes 9.8, 9.9; Cross-Chapter Box MIGRATE in Chapter 7}

9.1 Introduction

9.1.1 Point of Departure

This chapter assesses the scientific evidence on observed and projected climate change impacts, vulnerability and adaptation options in Africa. The assessment refers to five African sub-regions – North, West, Central, East and southern – closely following the African Union (AU), but including Mauritania in West Africa and Sudan in North Africa because much of the literature assessed places these countries in these regions (Figure 9.1). Madagascar and other island states are addressed in Chapter 15.

Africa has contributed among the least to historical greenhouse gas emissions (GHG) responsible for anthropogenic climate change and has the lowest per capita GHG emissions of all regions currently (*high confidence*) (Figure 9.2). Yet Africa has already experienced widespread impacts from anthropogenic climate change (*high confidence*) (Table 9.1; Figure 9.2).

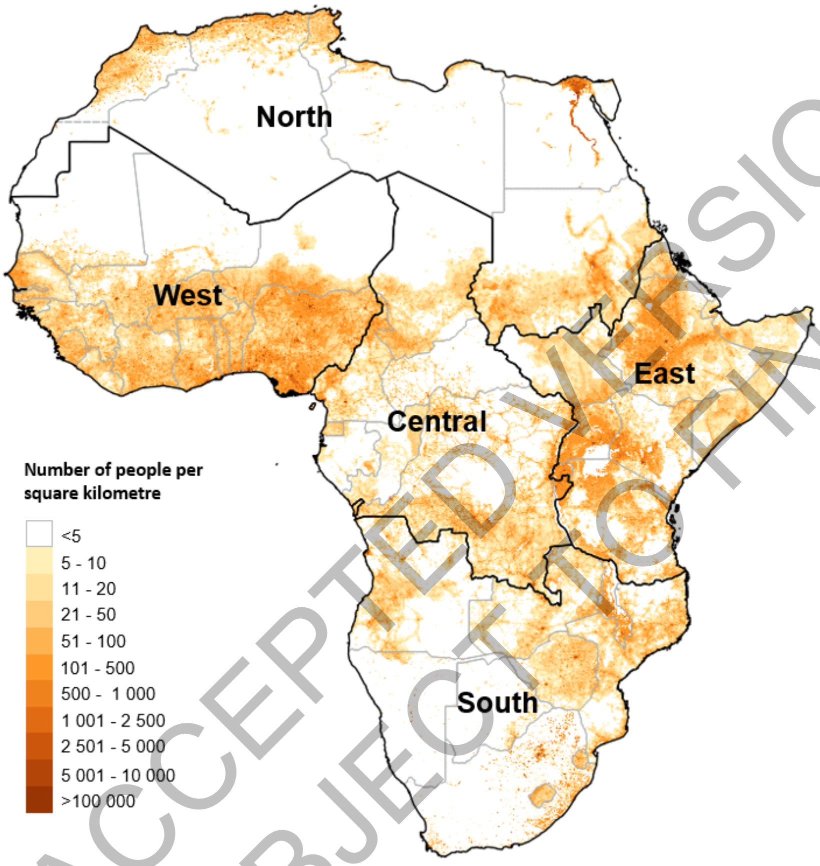


Figure 9.1: The 5 Regions of Africa used in this chapter, also showing estimated population density in 2019. The population of Africa was estimated at 1.312 billion for 2020, which is about 17% of the world population but this is projected to grow to around 40% of world population by 2100 (UNDESA, 2019a). Although 57% of the African population currently live in rural areas (43% urban), Africa is the most rapidly urbanising region globally and is projected to transition to a majority urban population in the 2030s with a 60% urban population by 2050 (UNDESA, 2019b). The 2019 Gross Domestic Product (GDP) per capita in constant 2010 averaged USD 2,250 across 43 countries reporting data, ranging from USD 202 (Burundi) to USD 8,840 (Gabon), with 40% of the population of sub-Saharan Africa living below the international poverty line of USD 1,90 per day in 2018 (World Bank, 2018). The highest life expectancy at birth is 67 (Botswana and Senegal) and the lowest is 52 (Central African Republic) (World Bank, 2018). Grid-cell population density data for mapping are from (Tatem, 2017; WorldPop, 2021).

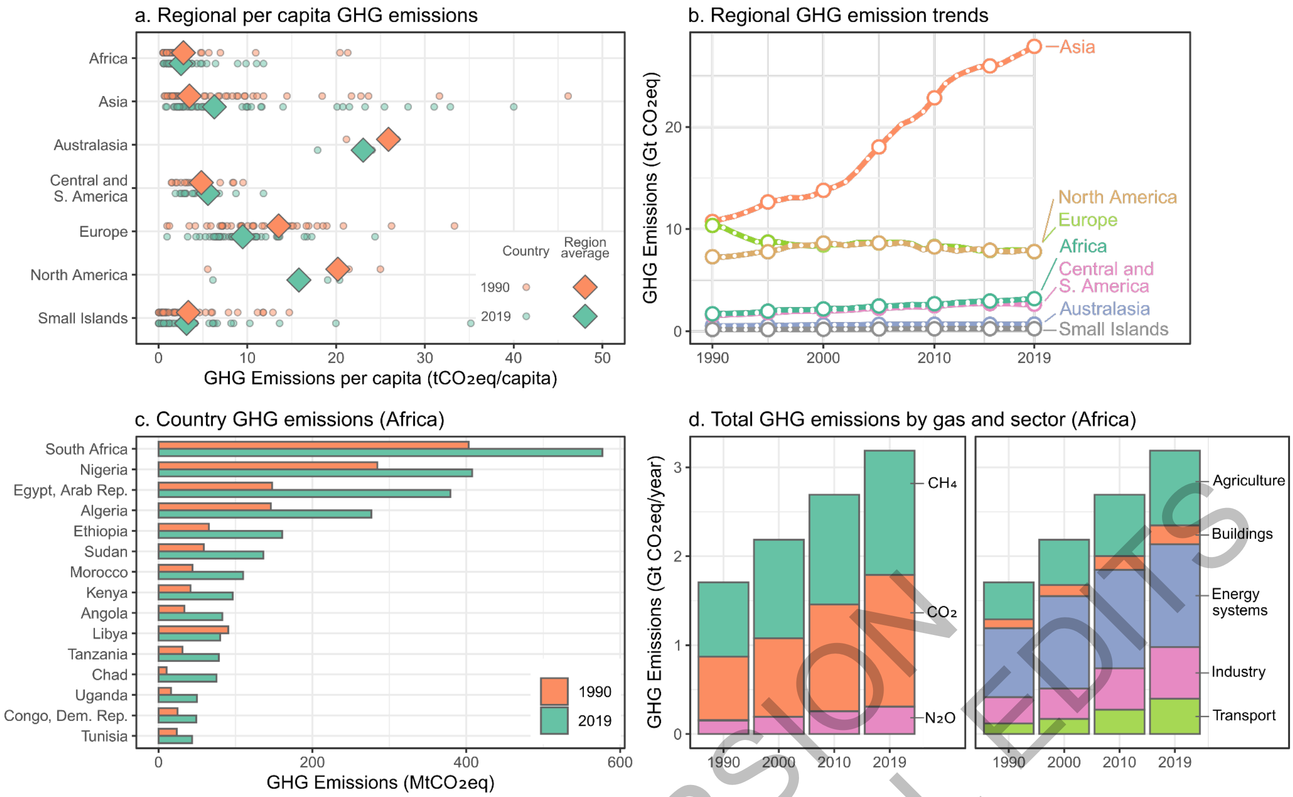


Figure 9.2: Historical greenhouse gas (GHG) emission trends for Africa compared to other world regions: (a) Per person GHG emissions by region and growth from 1990-2018 (circles represent countries, diamonds represent the region average). (b) Total GHG emissions by region since 1990. (c) The total GHG emissions in 1990 and 2018 for the 15 highest emitting countries within Africa. (d) Total emissions in Africa since 1990, broken down by GHG (left) and sector (right). Methane and CO_2 emissions comprise an almost equal share of greenhouse gas emissions in Africa, with the largest emissions sectors being energy and agriculture (Crippa et al., 2021). Agriculture emissions in panel (d) do not include land use, land use change and forestry (LULUCF CO2). One-hundred-year global warming potentials consistent with WGI estimates are used. Emissions data are from (Crippa et al., 2021), compiled by Chapter 2 of WGIII.

Since AR5, there have been notable policy changes in Africa and globally. The Paris Agreement, 2030 Sustainable Development Goals (SDGs), the Sendai Framework and Agenda 2063 emphasise interlinked aims to protect the planet, reduce disaster risk, end poverty and ensure all people enjoy peace and prosperity (AU, 2015; UNFCCC Paris Agreement, 2015; UNISDR Sendai Framework, 2015; United Nations General Assembly, 2015). To match these interlinked ambitions, this chapter assesses risks and response options both for individual sectors and cross-sectorally to assess how risks can compound and cascade across sectors, as well as the potential feasibility and effectiveness, co-benefits and trade-offs and potential for maladaptation from response options (Simpson et al., 2021b; Williams et al., 2021).

9.1.2 Major Conclusions from Previous Assessments

Based on an analysis of 1,022 mentions of Africa or African countries across the three AR6 Special Reports, the following main conclusions emerged.

- Hot days, hot nights and heatwaves have become more frequent; heatwaves have also become longer (*high confidence*). Drying is projected particularly for West and southwestern Africa (*high confidence*) (IPCC, 2018c; Shukla et al., 2019).
- Climate change is contributing to land degradation, loss of biodiversity, bush encroachment and spread of pests and invasive species (SR1.5, SRCCL, SROCC).
- Climate change has already reduced food security through losses in crop yields, rangelands, livestock and fisheries, deterioration in food nutritional quality, access and distribution and price spikes. Risks to crop yields are substantially less at 1.5°C compared with 2°C of global warming, with a large reduction

in maize cropping areas projected even for 1.5°C, as well as reduced fisheries catch potential (SR1.5, SRCCL, SROCC).
- Increased deaths from undernutrition, malaria, diarrhoea, heat stress and diseases related to exposure to dust, fire smoke and other air pollutants are projected from further warming (IPCC, 2018c; Shukla et al., 2019).
- The largest reductions in economic growth for an increase from 1.5°C to 2°C of global warming are projected for low- and middle-income countries, including in Africa (IPCC, 2018c).
- Climate change interacts with multidimensional poverty, among other vulnerabilities. Africa is projected to bear an increasing proportion of the global exposed and vulnerable population at 2°C and 3°C of global warming (IPCC, 2018c).
- Poverty and limited financing continue to undermine adaptive capacity, particularly in rapidly growing African cities (Shukla et al., 2019).
- Large-scale afforestation and bioenergy can reduce food availability and ecosystem health (IPCC, 2018c) (SRCCL 2019).
- Transitioning to renewable energy would reduce reliance on wood fuel and charcoal, especially in urban areas, with co-benefits including reduced deforestation, desertification, fire risk and improved indoor air quality, local development and agricultural yield (Shukla et al., 2019).
- Sustainable use of biodiversity, conservation agriculture, reduced deforestation, land and watershed restoration, rainwater harvesting and well-planned reforestation can have multiple benefits for adaptation and mitigation, including water security, food security, biodiversity, soil conservation and local surface cooling (IPBES, 2018; Shukla et al., 2019).
- Climate resilience can be enhanced through improvements to early warning systems, insurance, investment in safety nets, secure land tenure, transport infrastructure, communication, access to information and investments in education and strengthened local governance (Shukla et al., 2019).
- Scenarios of socio-environmental change are underused in decision-making in Africa (IPBES, 2018).
- Africa's rich biodiversity together with a wealth of indigenous knowledge and local knowledge is a key strategic asset for sustainable development (IPBES, 2018).

9.1.3 What's New on Africa in AR6?

1. Increased confidence in observed and projected changes in climate hazards, including heat and precipitation.
2. Increased regional, national and sub-national observed impacts and projected risks.
3. Loss and damage assessment.
4. Increased quantification of projected risks at 1.5°C, 2°C, 3°C and 4°C of global warming (Section 9.2; Figure 9.6).
5. Improved assessment of sea level rise risk (Sections 9.9 and 9.12).
6. Increased quantification of risk across all sectors assessed.
7. Expanded assessment of adaptation feasibility and effectiveness and limits to adaptation (Figure 9.7).
8. Assessment of adaptation finance (Section 9.4.1).
9. Increased assessment of how climate risk and adaptation and mitigation response options are interlinked across multiple key development sectors (Section 9.4.3; Boxes 9.4 and 9.5).

9.1.4 Extent of Climate Change Impacts Across Africa

In many parts of southern, East and West Africa, temperature or precipitation trends since the 1950s are attributable to anthropogenic climate change and several studies document the impacts of these climate trends on human and natural systems (*high confidence*) (Figure 9.3; Sections 9.5.6 and 9.5.7). Nevertheless, research into attribution of trends to anthropogenic climate change or climate impacts remains scarce for multiple regions, especially in North and Central Africa. This illustrates an 'attribution gap' where robust evidence for attributable impacts is twice as prevalent in high compared to low-income countries globally (Callaghan et al., 2021). Most studies on climate impacts in Africa have focused on terrestrial ecosystems or water, with fewer on marine ecosystems, agriculture, migration and health and well-being (Callaghan et al., 2021). Specific factors driving these knowledge gaps include limited data collection, data access and research funding for African researchers (see next section).

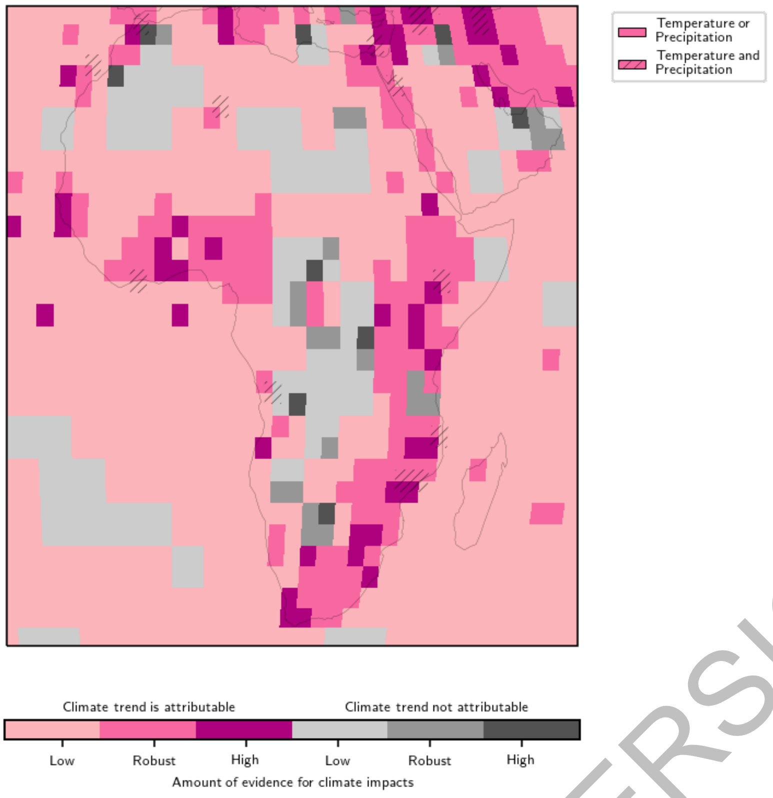


Figure 9.3: Climate impacts on human and natural systems are widespread across Africa, as are climate trends attributable to human-induced climate change. This machine-learning-assisted evidence map shows the presence of historical trends in temperature and precipitation attributable to human-induced climate change (pinks vs. greys) and the amount of evidence (intensity of colours) documenting the impacts of these climate trends on human and natural systems (e.g., ecosystems, agriculture, health) across Africa. 'Robust' indicates more than 5 studies document impacts per grid cell. A 'high' amount of evidence indicates more than 20 studies documented impacts for a grid cell. Climate impact studies from the literature were identified and categorised using machine learning. A language representation model was trained on a set of 2,373 climate impact studies coded by hand. This supervised machine learning model identified 102,160 published studies predicted to be relevant for climate impacts globally; references to places in Africa were found in 5,081 studies (5% of global studies). Temperature trends were calculated from 1951-2018 and precipitation from 1951-2016. Hatching shows regions where trends in both temperature and precipitation are attributable to human-induced climate change. Data from (Callaghan et al., 2021).

9.1.5 Extent of Climate Change Data and Research Gaps Across Africa

Since AR5, there have been rapid advances in climate impacts research due to increased computing power, data access and new developments in statistical analysis (Carleton and Hsiang, 2016). However, sparse and intermittent weather station data limit attribution of climate trends to anthropogenic climate change for large areas of Africa, especially for precipitation and extreme events, and hinder more accurate climate change projections (Otto et al., 2020) (Section 9.5.2; Figure 9.3). Outside of South Africa and Kenya, digitally accessible data on biodiversity is limited (Meyer et al., 2015). Lack of comprehensive socioeconomic data also limits researchers' ability to predict climate change impacts. Ideally, multiple surveys over time are needed to identify effects of a location's changing climate on changing socioeconomic conditions. Twenty-five African countries conducted only one nationally representative survey that could be used to construct measures of poverty during 2000-2010 and 14 conducted none over this period (Jean et al., 2016). Because of these challenges, much of what is known about climate impacts and risks in Africa relies on evidence from global studies that use data largely from outside Africa (e.g., Zhao et al., 2021). These studies generate estimates of average impacts across the globe, but may not have the statistical power to distinguish whether African nations display differential vulnerability, exposure or adaptive capacity. In sections of this chapter, we have relied when necessary on such studies, as they often provide best available evidence for Africa.

Increasing data coverage and availability would increase the ability to discern important differences in risk both among and within African countries.

Climate-related research in Africa faces severe funding constraints with unequal funding relationships between countries and with research partners in Europe and North America (*high confidence*). Based on analysis of over 4 million research grants from 521 funding organisations globally, it is estimated from 1990-2020 USD 1,26 billion funded Africa-related research on climate impacts, mitigation and adaptation. This represents only 3.8% of global funding for climate-related research – a figure incommensurate with Africa's high vulnerability to climate change (Overland et al., 2021) (Box 9.1; Chapter 8). Almost all funding for Africa-related climate research originates outside Africa and goes to research institutions outside Africa (Blicharska et al., 2017; Bendana, 2019; Siders, 2019; Overland et al., 2021). From 1990–2020, 78% of funding for Africa-related climate research flowed to institutions in Europe and the United States – only 14.5% flowed to institutions in Africa (Overland et al., 2021) (Figure 9.4). Kenya (2.3% of total funding) and South Africa (2.2%) are the only African countries among the top 10 countries in the world in terms of hosting institutions receiving funding for climate-related research on Africa (Overland et al., 2021).

These unequal funding relations influence inequalities in climate-related research design, participation, and dissemination between African researchers and researchers from high-income countries outside Africa, in ways that can reduce adaptive capacity in Africa (*very high confidence*). Those empowered to shape research agendas can shape research answers: climate research agendas, skills gaps and eligible researchers are frequently defined by funding agencies, often from a Global North perspective (Vincent et al., 2020a). Larger funding allocations for research focused on Ghana, South Africa, Kenya, Tanzania and Ethiopia are reflected in higher concentrations of empirical research on impacts and adaptation options in these countries, and there is a general lack of adaptation research for multiple of the most vulnerable countries in Africa (Figure 9.5) (Callaghan et al., 2021; Overland et al., 2021; Sietsma et al., 2021; Vincent and Cundill, 2021). The combination of Northern-led identification of both knowledge and skills gaps can result in projects where African partners are positioned primarily as recipients engaged to support research and/or have their 'capacity built' rather than also leading research projects on an equal basis (Vincent et al., 2020a; Trisos et al., 2021). Analysis of >15,000 climate change publications found for over 75% of African countries 60–100% of climate change publications on these countries did not include a single local author, with authorship dominated by researchers from richer countries outside Africa (Pasgaard et al., 2015). This can reduce adaptive capacity in Africa as researchers at Global North institutions may shape research questions and outputs for a Northern audience rather than providing actionable insights on priority issues for African partners (Pasgaard et al., 2015; Nago and Krott, 2020). Moreover, in order to access research publications in a timely manner, many researchers in Africa are forced to use shadow websites bypassing journal paywalls (Bohannon, 2016). Ways to enhance research partnerships to produce actionable insights on climate impacts and solutions in Africa include increased funding from African and non-African sources, projects funded by non-African agencies, increasing direct control of resources for African partners and having African research and user priorities set research questions, identify skills gaps and lead research, open access policies for research outputs (ESPA Directorate, 2018; Vogel et al., 2019; Vincent et al., 2020a; IDRC, 2021; Trisos et al., 2021).

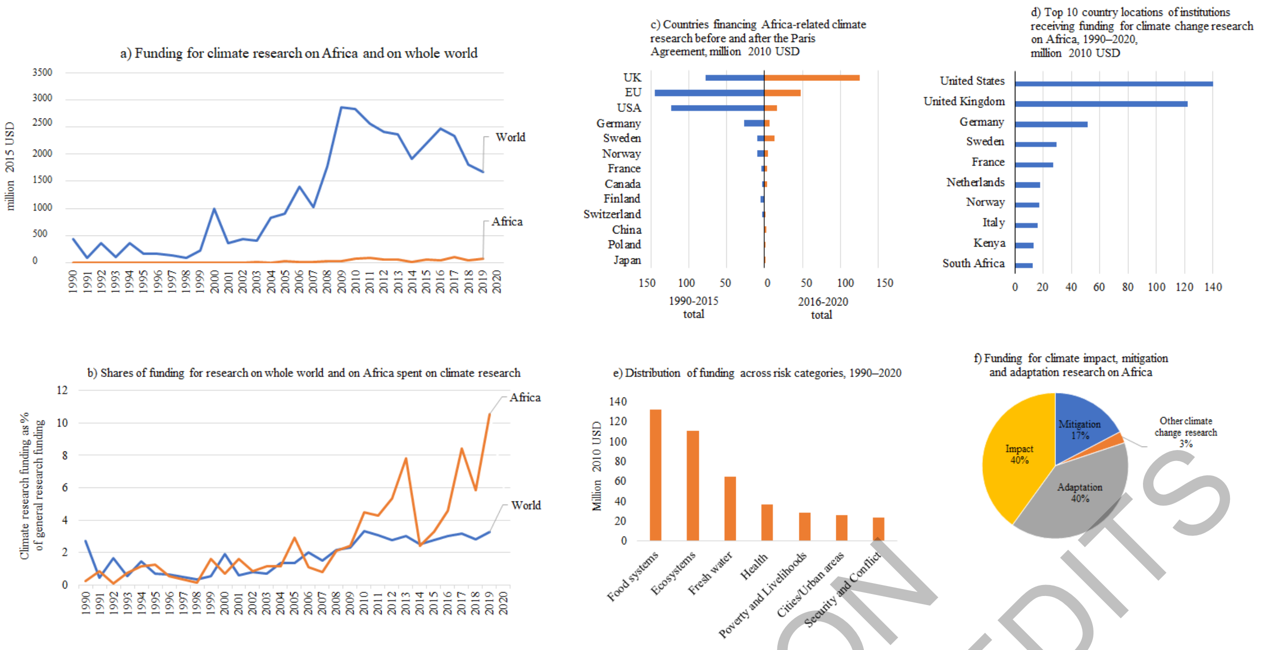


Figure 9.4: Climate-related research on Africa receives a small proportion of global climate research funding (a, b), with most funding for climate-related research on Africa flowing to institutions based in the Europe and the USA (d). Major funding countries are the UK, EU, USA, Germany and Sweden (d) . Funding comes mainly from government organisations with private philanthropy providing only around 1% (Overland et al., 2021). Africa-related climate research funding focuses mostly on food systems, ecosystems and freshwater, while security and conflict and urban areas have received the least (e). Research on climate mitigation received only 17% of funding while climate impacts and adaptation each received 40% (f). Since 2010, climate research has made up a larger share (5%) of Africa-related research funding than is the case for research globally (3%) with a greater proportion of this Africa-focused climate funding going to social sciences and humanities (28%) than is the case globally (12%) (Overland et al., 2021). Data are from an analysis of 4,458,719 research grants in the Dimensions database with a combined value of USD 1.51 trillion awarded by 521 funding organisations globally (Overland et al. 2021). The Dimensions database is the world's largest database on research funding flows (Overland et al. 2021). It draws on official data from all major funding organisations in the world, mainly government research councils or similar institutions. Note: The South African National Research Foundation is the only African research funding body that is sufficiently large to be included in Dimensions.

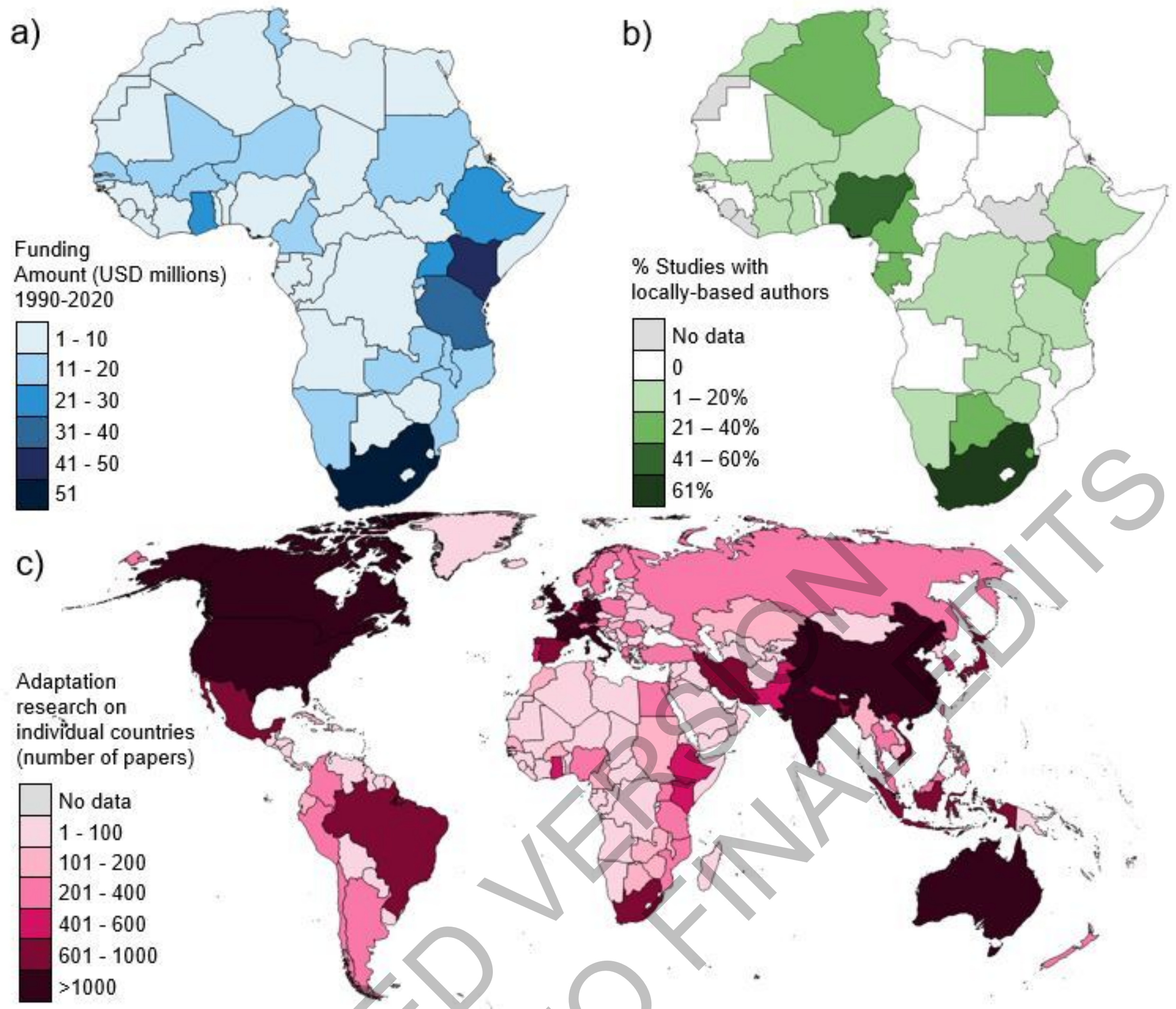


Figure 9.5: Major gaps in climate change research funding, participation and publication exist within Africa, and for Africa compared to the rest of the world. (a) Funding: Amount of climate change research funding focused on African countries 1990-2020 (Overland et al., 2021). Considering population size, research on Egypt and Nigeria stands out as particularly underfinanced (b) Participation: Percentage of climate change papers (impacts and adaptation) published on a given country that also include at least one based in that country (Pasgaard et al. 2015). (c) Number of publications of climate change adaptation research focused on individual countries identified from a global sample of 62,191 adaptation-relevant peer-reviewed articles published from 1988-2020 (Sietsma et al., 2021). There is a general lack of adaptation-related research on many vulnerable countries in Africa. Topic biases in adaptation-relevant research also exist where research focuses more on disaster and development-related topics in Southern countries (but published authors from the global North), while Northern countries dominate governance topics (Sietsma et al., 2021).

9.1.6 Loss and Damage from Climate Change

Assessment of impacts, vulnerability, risks and adaptation highlights climate change is leading to irreversible and existential impacts across Africa which breach current and projected adaptation limits (Table 9.1) (Cross-Chapter Box LOSS in Chapter 17).

Table 9.1: Loss and damage from climate change across sectors covered in this report. Loss and damage arise from adverse climate-related impacts and risks from both sudden-onset events, such as floods and cyclones, and slower-onset processes, including droughts, sea level rise, glacial retreat and desertification and includes both include both economic (e.g., loss of assets and crops) and non-economic types (e.g., loss of biodiversity, heritage and health) (UNFCCC Paris Agreement, 2015; IPCC, 2018a; Mechler et al., 2020). Section marked with * and in bold highlights Loss and Damage attributed to anthropogenic climate change (16.1.3).

Sector	**Loss and damage from climate change**	**Observed**	**Projected**
Ecosystems	Local, regional and global extinction	9.6.2	9.6.2

	Reduced ecosystem goods and services	9.6.1; 9.6.2	9.6.2
	Declining natural coastal protection and habitats	9.6.1; 9.6.2	9.6.2
	Altered ecosystem structure and declining ecosystem functioning	9.6.1	9.6.2
	Nature–based tourism	9.6.3	9.6.3
	Biodiversity loss	**9.6.2***	
Water	Declining lake and river resources	9.7.1	9.7.2
	Reduced hydro-electricity and irrigation	9.7.2; 9.9.1 -	9.7.2; 9.9.3; Box 9.5
	Disappearing glaciers	**9.5.9***; 9.7.1	9.5.9
	Reduced groundwater recharge and salinization	-	9.7.2
	Drought	**Box 9.4***	
Food systems	Reduced crop productivity and revenues	**9.7.2***, 9.8.1; 9.8.2; 9.11.1; Box 9.5	9.8.2; 9.8.3; Box 9.5
	Increased livestock mortality and price shocks	9.8.2	9.8.2
	Decreased fodder and pasture availability	9.8.2	9.8.2
	Reduced fisheries catch and fisher livelihoods	9.6.1; 9.8.5	9.8.5
Human settlements and Infrastructure	Loss or damage to formal and informal dwellings	9.9.2	9.9.4
	Damage to transport systems	9.9.2	9.9.4
	Damage to energy systems	9.9.2	9.7.2; 9.9.4
	Water supply, sanitation, education and health infrastructure	9.9.2; 9.10; 9.11.1	9.7.3; 9.9.4; 9.10; 9.11.1
	Migration	9.9.1; Box 9.8	9.9.4; Box 9.8
Health	Loss of life	**9.9.2***; 9.10.2; Box 9.9	9.9.4; 9.10.2
	Loss of productivity	9.10.3; 9.11.1	9.10.2; 9.11.2
	Reduced nutrition	9.8.1; 9.10.2	9.10.2
Economy, poverty and Livelihoods	Loss of livelihoods, jobs and income	9.9.2; 9.10.2; 9.11.1	9.10.2; 9.11.2
	Reduced productive land	9.8.2	9.8.2
	Reduced economic growth and increased inequality	**9.11.1***; Box 9.5	9.11.2
	Community and involuntary displacement	9.9.3; Box 9.8	9.9.4; Box 9.8
	Reduced labour productivity and earning potential	9.11.1	9.11.2
	Delayed and poorer education progress	9.11.1	9.11.1
	Reduced tourism	9.6.3	9.5.9, 9.6.3, 9.12.2
	Increased urban in-migration	9.8.1; 9.9.1; Table Box 9.8	9.9.4; Table Box 9.8
Heritage	Loss of traditional cultures and ways of life	Box 9.2; 9.12.1	9.12.2
	Loss of language and knowledge systems	-	9.12.1
	Damage to heritage sites	9.12.1	9.12.2

9.2 Key Risks for Africa

A key risk is defined as a potentially severe risk. In line with AR5, 'severity' relates to dangerous anthropogenic interference with the climate system, the prevention of which is the ultimate objective of the UNFCCC as stated in its Article 2 (Oppenheimer et al., 2014). The process for identifying key risks for Africa included reviewing risks from the Africa chapter of AR5, and assessing new evidence on observed impacts and projected risks in this chapter.

Several key risks were identified for both ecosystems and people including species extinction and ecosystem disruption, loss of food production, reduced economic output and increased poverty, increased disease and loss of human life, increased water and energy insecurity, loss of natural and cultural heritage, and compound extreme events harming human settlements and critical infrastructure (Table 9.2). In order to provide a sector and continent-level perspective, the key risks aggregate across different regions and combine multiple risks within sectors. For detailed assessments of observed impacts and future risks within each sector and each sub-region of Africa, see the sector-specific sections of this chapter (Sections 9.6.1 and 9.12.1).

Several expert elicitation workshops of lead and contributing authors were held to develop 'burning embers' assessing how risk increases with further global warming for a subset of key risks, specifically risk of food production losses, risk of biodiversity loss and risk of mortality and morbidity from heat and infectious disease (Figure 9.6). These key risks were selected in part because of underlying assessment work in the chapter to connect multiple studies to observed impacts and/or risk at increasing global warming levels (Sections 9.6.2, 9.8.2, 9.8.5.2 and 9.10.2).

All three of these key risks are assessed to have already transitioned completely into moderate risk—that is, negative impacts have been detected and attributed to climate change—before the 2010–2020 level of global warming (1.09°C) (IPCC, 2021), with *medium confidence* for increased mortality and morbidity and *high confidence* for losses of food productivity and biodiversity (Figure 9.6). For biodiversity, these impacts include repeated mass die-offs of coral reefs due to marine heat (Section 9.6.1.4), reductions in lake productivity due to warming (Section 9.6.1.3), and woody encroachment of grasslands and savannas due to increased atmospheric CO_2 concentrations (Section 9.6.1.1), with negative impacts on livelihoods (Section 9.6.1). For food production, climate change impacts include up to 5.8% mean reduction in maize productivity due to increased temperatures in sub-Saharan Africa (Section 9.8.2.1 and 9.8.2.2) and reduced fisheries catches due to increased temperatures, especially in tropical regions (Section 9.8.2). For health, climate change impacts include increased mortality and morbidity from changes in the distribution and incidence of malaria and cholera and the direct effects of increasing temperatures (Section 9.10.2).

In scenarios with low adaptation (that is largely localised and incremental), the transition to high risk—widespread and severe impacts—has already begun at the current level of global warming for biodiversity loss (*high confidence*), and begins below 1.5°C global warming for both food production (*medium confidence*) and mortality and morbidity from heat and infectious disease (*high confidence*). Across all risks, the best estimate for the transition to high risk is at 1.5°C of global warming, with transition to high risk completing before 2°C (Figure 9.6). Projected impacts considered high risk around 1.5°C include: across more than 90% of Africa, more than 10% of species are at risk of local extinction (Figure 9.6; Table 9.1); the further expansion of woody plants into grass-dominated biomes (Section 9.6.2.1); 9% declines in maize yield for West Africa and 20–60% decline in wheat yield for southern and northern Africa, as well as declines in coffee and tea in East Africa and sorghum in West Africa (Figures 9.22 and 9.23; Section 9.8.2.1 and 9.8.2.2), and >12% decline in marine fisheries catch potential for multiple West African countries, potentially leaving millions at risk of nutritional deficiencies (Figure 9.25; Section 9.8.5); tens of millions more people exposed to vector-borne diseases in East and southern Africa (malaria), and North, East and southern Africa (dengue, zika), increased risk of malnutrition in Central, East and West Africa, and more than 15 additional deaths per 100,000 annually due to heat in parts of West, East and North Africa (Figures 9.32 and 9.35; Sections 9.10.2 and 9.9.4.1).

The transition from high to very high risk—that is severe and widespread impacts with limited ability to adapt—begins either at or just below 2°C for all three risks (Figure 9.6). The assessed temperature range for the transition to very high risk is wider for food production than for biodiversity and health. Projected impacts for food include: 10–30% decline in marine fisheries catch potential for the Horn of Africa region and southern Africa and more than 30% decline for West Africa at 2°C global warming, with greater declines at higher levels of warming (Section 9.8.2). Beyond 2°C global warming, over 50% of commercially important freshwater fish species across Africa are projected to be vulnerable to extinction (Figure 9.26). Between 2°C and 4°C, wheat, maize and rice yields are projected, on average, to be lower than 2005 yields across all regions of Africa. From 2°C global warming, over 40% losses in rangeland productivity are projected for western Africa. By 3.75°C, severe heat stress may be near year-round for cattle across tropical Africa (Figure 9.24). Multiple countries in West, Central and East Africa are projected to be at risk from simultaneous negative impacts on crops, fisheries and livestock (Thiault et al., 2019) (9.8.2; 9.8.5).

The best estimate for the onset of very high risk for biodiversity and health is at 2.1°C. Projected impacts considered very high risk for biodiversity include potential destabilisation of the African tropical forest carbon sink, risk of local extinction of more than 50% of plants, vertebrate and insect species across one-fifth of Africa, 7–18% of African species at risk of total extinction including, a third of freshwater fish, and more than 90% warm-water coral reefs lost (Section 9.6.2). For health, projected impacts considered high risk include potentially lethal heat exposure for more than 100 days per year in West, Central and East Africa, with more than 50 additional heat-related deaths per 100,000 annually across large parts of Africa, and hundreds of millions more people exposed to extreme heat in cities (Section 9.5, 9.10.2 and 9.9.4.1; Figure 9.35), tens to hundreds of thousands of additional cases of diarrhoeal disease in East, Central and West Africa, and tens of millions more people exposed to mosquito-borne arboviruses like dengue or zika in North, East and southern Africa (Section 9.10.2).

The feasibility and effectiveness of existing adaptation options under current levels of warming are assessed in Section 9.10.2 and adaptation options considering future levels of warming are assessed in the chapter section for each sector.

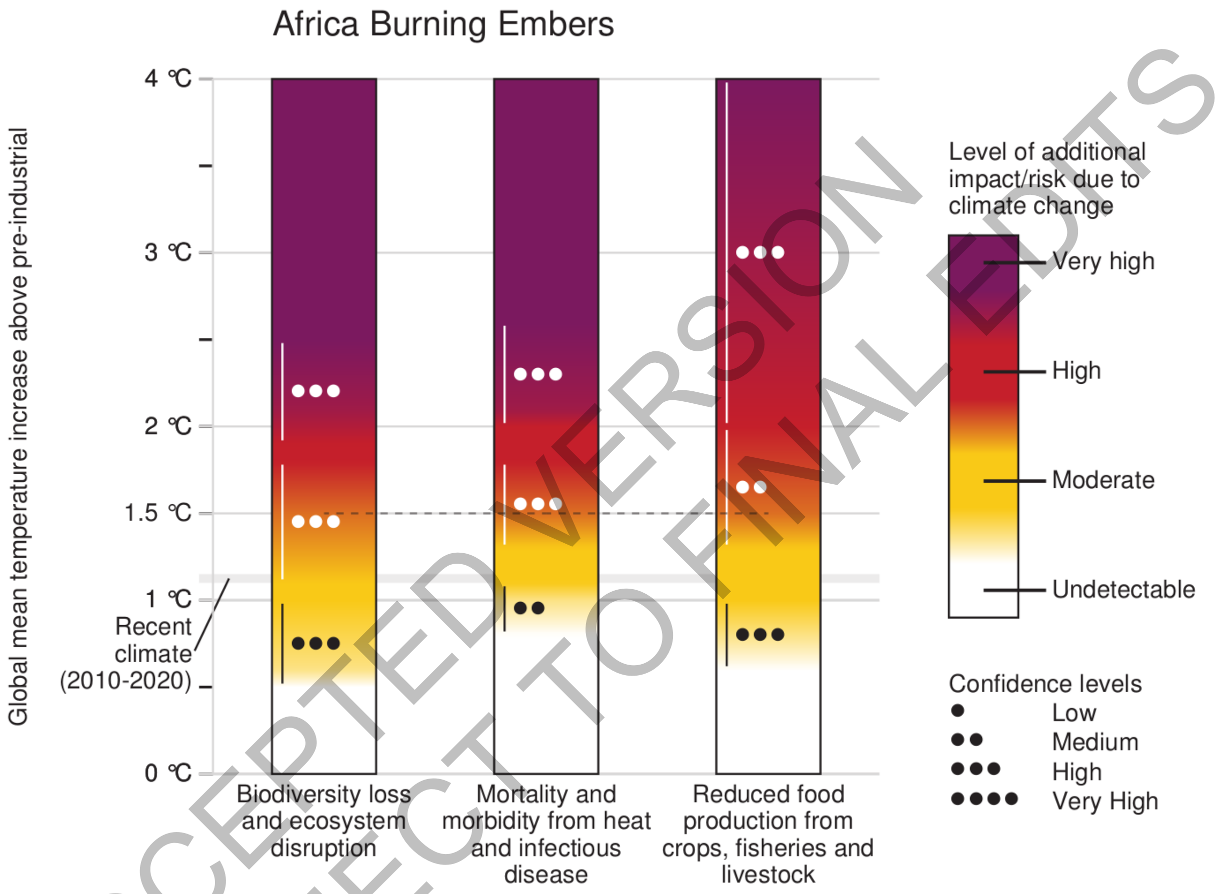


Figure 9.6: Burning Embers showing increasing risk due to climate change for selected key risks in Africa. Projected increase is assessed for global warming increasing above pre-industrial levels (1850–1900). All three risks are assessed to have already transitioned to moderate risk by the recent level of global warming 2010–2020 (1.09°C). Risks are characterized as undetectable, moderate, high, or very high, and the transition between risk levels as a function of global warming is represented by the colour change of each bar (IPCC, 2021). For range of global warming levels for each risk transition used to make this figure see Supplementary Material Table SM 9.1.

Table 9.2: Key risks from climate change in Africa

Key climate change risk	Climate impact driver	Vulnerability	Chapter section
Local or global extinction of species and reduction or irreversible loss of ecosyste§ms and their services, including freshwater, land and ocean ecosystems	Increasing temperatures of freshwaters, ocean and on land; heatwaves; precipitation changes (both increases and decreases); increased atmospheric CO_2	Vulnerability highest among poorly dispersing organisms (plants) and species with narrow and disappearing niches (e.g. mountain endemics), and is exacerbated by non-	9.6

	concentrations; sea level rise; ocean acidification	climate hazards (e.g. habitat loss for agriculture or afforestation projects); Vulnerability is high for Protected Areas surrounded by transformed land preventing species' dispersal and areas with limited elevational gradients that reduce their potential to act as climate refugia	
Loss of food production from crops, livestock and fisheries	Increasing temperatures and heat waves for freshwaters, ocean and on land; precipitation changes; drought; increased atmospheric CO_2 concentrations	High for low-income coastal and riparian communities whose livelihood depends on healthy ocean and freshwater ecosystems, and for populations reliant on fish for protein and micronutrients. Vulnerability is high for many food producers dependent on rainfall and temperature conditions, including subsistence farmers, the rural poor, and pastoralists. Lack of access to climate information and services increases vulnerability.	9.8
Mortality and morbidity from heat and infectious diseases	Increasing temperatures; heatwaves; precipitation change (both increases and decreases)	Vulnerability is highest for the elderly, pregnant women, individuals with underlying conditions, immune-compromised individuals (e.g., from HIV), and young children. Regions without vector control programmes in place or without detection and treatment regimens. Inadequate insulation in housing in informal settlements in urban heat islands. Inadequate improvements in public health systems. Inadequate water and sanitation infrastructure, especially in rapidly expanding urban areas and informal settlements.	9.10

Reduced economic output and growth, and increased inequality and poverty rates	Increased temperatures; reduced rainfall; extreme weather events	Conditions underlying severe risk are lower income growth, higher population levels, low rates of structural economic change with more of the labour force engaged in agriculture and other more climate-exposed sectors due in part to physical labour outdoors.	9.11
Water and energy insecurity due to shortage of irrigation and hydropower.	Heat and drought	High reliance on hydropower for national electricity generation, especially East and Southern African countries. Planned for high reliance on irrigated food production. Concentrations of hydropower plants within river basins experiencing similar rainfall and run-off patterns. Limited electricity trade between major river basins.	9.7, 9.9, Box 9.5
Cascading and compounding risks of loss of life, livelihoods and infrastructure in human settlements.	Extreme heat; floods; drought; sea level rise and associated coastal hazards; compound climate hazards (e.g., coinciding heat and drought)	Coastal and low-lying urban areas and those in dryland regions with rapidly growing populations. People living in informal settlements. Increased magnitude of heat waves due to urban heat island effects. Climate-shocks to municipal revenues (e.g., from water). Unaffordable maintenance of transport and protective infrastructure with increasing climate impacts. Greater water resource demand from urban and non-urban populations and key economic sectors	9.9

9.3 Climate Adaptation Options

9.3.1 Adaptation Feasibility and Effectiveness

Based on a systematic assessment of observed climate adaptation responses in the scientific literature covering 827 adaptation response types in 553 studies (2013–2021), and expert elicitation process, 24 categories of adaptation responses in Africa were identified (Williams et al., 2021). This assessment excluded autonomous adaptation in ecosystems, such as migration and evolution of animal and plant species.

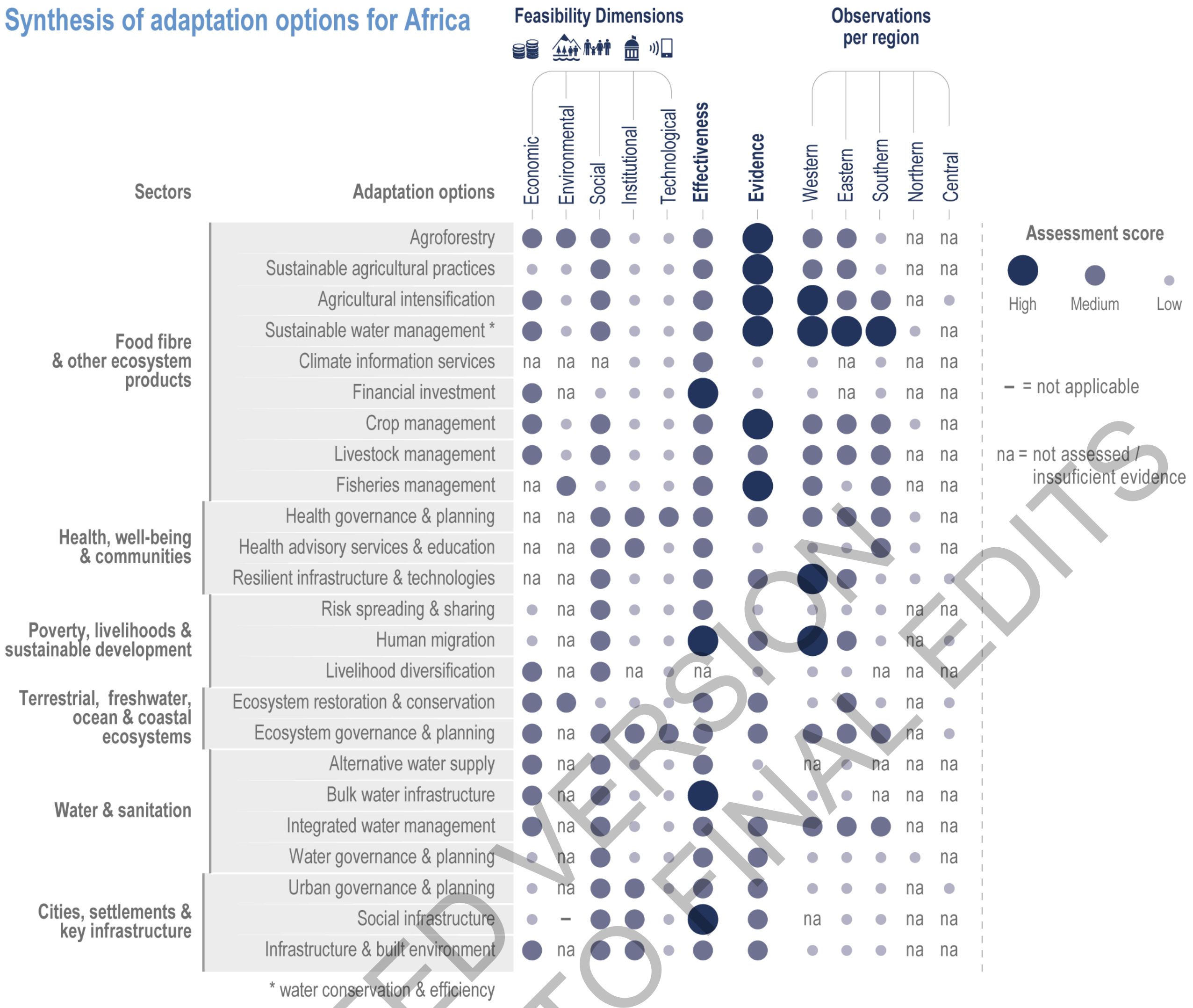


Figure 9.7: Assessment of feasibility of observed climate adaptation responses under current climate conditions for 24 categories of adaptation responses across regions of Africa. The assessment comprised evaluation of each adaptation category along six feasibility dimensions: economic viability, environmental sustainability, social validity, institutional relevance, technological availability, and potential for risk reduction (considering current climate conditions) (Williams et al., 2021). Fifty-six experts on the African region were consulted using a structured, expert-driven elicitation process to increase the coverage and robustness of the continent-wide adaptation feasibility and effectiveness assessment in Williams et al. (2021). Assessment included both peer-reviewed articles and grey literature.

At the current global warming level, 83% of adaptation response categories assessed showed medium potential for risk reduction (that is, mixed evidence of effectiveness). Bulk water infrastructure (including managed aquifer recharge, dams, pipelines, pump stations, water treatment plants and distribution networks), human migration, financial investment for agricultural intensification, and social infrastructure (including decentralised management, strong community structures and informal support networks) show high potential for risk reduction (high evidence of option's effectiveness) (Sections 9.6.4 and 9.7.3; Boxes 9.8, 9.9, 9.10 and 9.11). However, there was limited evidence to assess the continued effectiveness of these options at higher global warming levels (Williams et al., 2021) with some options, such as bulk water infrastructure (particularly large dams), expected to face increasing risk with continued warming with damages cascading to other sectors (see Box 9.5), while others, such as crop irrigation and adjusting planting times, may increasingly reach adaptation limits above 1.5°C and 2°C global warming (Sections 9.8.3 and 9.8.4)

The majority of adaptation studies were in West and East Africa (Ghana, Ethiopia, Kenya and Tanzania), followed by southern Africa, with the least coming from Central and North Africa (Figure 9.7) (Williams et al., 2021). Most studies were on adaptation actions in the food sector, with the least on health (Figure 9.7). The five adaptation response categories with the highest number of reported actions were sustainable water management (food sector), resilient infrastructure and technologies (health sector), agricultural intensification (food sector), human migration (poverty and livelihoods) and crop management (food sector).

No adaptation response categories were assessed to have high feasibility of implementation. Technological barriers dominate factors limiting implementation (92% of adaptation categories have low technological feasibility) followed by institutional barriers (71% of adaptation categories have low institutional feasibility). This assessment matches review studies finding institutional responses to be least common in Africa and highlight inadequate institutional capacities as key limits to human adaptation (Berrang-Ford et al., 2021; Thomas et al., 2021) (Cross-Chapter Box FEASIB in Chapter 18). Feasibility is higher for the social dimension of adaptation responses (with moderate feasibility for 88% of categories). The largest evidence gap is for environmental feasibility for which 67% could not be assessed due to insufficient evidence (Figure 9.7).

Sustainable Water Management (SWM) includes rainwater harvesting for irrigation, watershed restoration, water conservation practices (e.g., efficient irrigation) and less water-intensive cropping (also see Section 9.8.3), and was the most reported adaptation response in the food sector. SWM was assessed with medium economic and social feasibility and low environmental, institutional and technological feasibility. The feasibility of this adaptation category may depend largely on socioeconomic conditions (Amamou et al., 2018; Harmanny and Malek, 2019; Schilling et al., 2020), as many African farmers cannot afford the cost of sustainable water management facilities (Section 9.8.4).

Resilient Infrastructure and Technologies (RIT) for health include improved housing to limit exposure to climate hazards (Stringer et al., 2020), and improved water quality, sanitation and hygiene infrastructure (e.g., technology across all sectors to prevent contamination and pollution of water, improved water, sanitation and hygiene (WASH) approaches such as promotion of diverse water sources for water supply, improving health infrastructure) (Section 9.10.3). Overall, RIT had medium social feasibility and low institutional and technological feasibility. Bulk water infrastructure was assessed to have high effectiveness, but low institutional and technological feasibility. Increasing variability in climate and environmental challenges has made sustainable and resilient infrastructure design a key priority (Minsker et al., 2015). RIT is, however, generally new in the African context (Cumming et al., 2017) and that may be why there is limited evidence to assess some of its dimensions (economic and environmental feasibility). Construction of resilient public water infrastructures that include safeguards for sanitation and hygiene are expensive and, across national and local levels, planning for its construction poses multiple challenges (Choko et al., 2019).

Agricultural intensification (including mixed cropping, mixed farming, no soil disturbance, mulching) in many smallholder farming systems remains a key response option to secure food for the growing African population (Nziguheba et al., 2015; Ritzema et al., 2017). Yet this option faces low environmental, institutional and technological feasibility (Figure 9.7). Social and economic feasibility is higher, but barriers include high cost of farm inputs (land, capital and labour), lack of access to timely weather information and lack of water resources can make this option quite challenging for African smallholder farmers (Kihila, 2017; Williams et al., 2019b) (Sections 9.8.1 and 9.11.4).

Crop management includes adjusting crop choices, planting times, or the size, type and location of planted areas (Altieri et al., 2015; Nyagumbo et al., 2017; Dayamba et al., 2018). This option faces environmental, institutional and technological barriers to feasibility. Social and economic barriers to implementation are fewer. Factors such as tenure and ownership rights, labour requirements, high investment costs and lack of skills and knowledge on how to use the practices are reported to hinder implementation of crop management options by smallholder farmers (Muller and Shackleton, 2013; Nyasimi et al., 2017). For instance, when improved seed varieties are available, high price limits access for rural households (Amare et al., 2018) (see Sections 9.8.3 and 9.8.4).

Human migration was assessed to have high potential for risk reduction (Rao et al., 2019; Sitati et al., 2021) (Cross-Chapter Box MIGRATE in Chapter 7, Box 9.8). However, it had low feasibility for economic, institutional and technological dimensions, with limited evidence on environmental feasibility. Institutional factors such as the implementation of top-down policies have been reported as limiting options for coping locally, resulting in migration (Brockhaus et al., 2013). Limited financial and technical support for migration limits the extent to which it can make meaningful contributions to climate resilience (Djalante et al., 2013;

Trabacchi and Mazza, 2015). International and domestic remittances are an important resource that can help aid recovery from climate shocks, but inadequate finance and banking infrastructure can limit cash transfers (Box 9.8). Male migration can increase burdens of household and agricultural work, especially for women (Poudel et al., 2020; Rao et al., 2020; Zhou et al., 2020). The more agency migrants have (that is, degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*) (Cross-Chapter Box MIGRATE in Chapter 7, Box 9.8)

Adaptation options within a number of categories, including sustainable agriculture practices, agricultural intensification, fisheries management, health advisory services and education, social infrastructure, infrastructure and built environment and livelihood diversification were observed to reduce socioeconomic inequalities (Williams et al., 2021). Whether adaptation options reduce inequality can be a key consideration enhancing acceptability of policies and adaptation implementation (Islam and Winkel, 2017) (Box 9.1; Section 9.11.4).

9.3.2 Adaptation Co-Benefits and Trade-Offs with Mitigation and SDGs

Synergies between the adaptation and progress towards the Sustainable Development Goals (SDGs) present potential co-benefits for realising multiple objectives towards Climate Resilient Development in Africa, increasing the efficiency and cost-effectiveness of climate actions (Cohen et al., 2021). However, designing adaptation policy under conditions of scarcity, common to many African countries, can inadvertently lead to trade-offs between adaptation options, as well as between adaptation and mitigation options, can reinforce inequality, and fail to address underlying social vulnerabilities (Kuhl, 2021).

Adaptation options such as access to climate information, provision of climate information services, growing of early maturing varieties, agroforestry systems, agricultural diversification and growing of drought-resistant varieties of crops may deliver co-benefits, providing synergies that result in positive outcomes. For instance, in SSA drylands including northern Ghana and Burkina Faso and large parts of the Sahel, migration as a result of unfavourable environmental conditions closely linked to climate change has often provided opportunities for farmers to earn income (SDG 1) and mitigate the effects of climate-related fluctuations in crop and livestock productivity (SDG 2) (Zampaligré et al., 2014; Antwi-Agyei et al., 2018; Wiederkehr et al., 2018). Renewable energy can mitigate climate effects (SDG 13), improve air quality (SDG 3), wealth and development (SDGs 1, 2).

Different types of irrigation including drip and small-scale irrigation can contribute towards increased agricultural productivity (SDG 2), improved income (SDG 1) and food security (SDG 2) and increase resilience to long-term changes in precipitation (SDG 13) (Bjornlund et al., 2020). In Kenya and Tanzania, small-scale irrigation provides employment opportunities and income to both farmers and private businesses (SDGs 8 and 9) (Lefore et al., 2021; Simpson et al., 2021c). Land management practices including the use of fertilizers and mulching have also been highlighted as adaptation options improving soil fertility for better yields (SDG 2) and delivering opportunities to reduce the climate change effects (SDG 13) (Muchuru and Nhamo, 2019).

Climate smart agriculture (CSA) offers opportunities for smallholder farmers to increase productivity (SDG 2), build adaptive capacity whilst reducing the emission of greenhouse gases (SDG 13) from agricultural systems (Lipper et al., 2014; Mutenje et al., 2019). CSA practices including conservation agriculture, access to climate information, agroforestry systems, drip irrigation, planting pits and erosion control techniques (Partey et al., 2018; Antwi-Agyei et al., 2021) can improve soil fertility, increase yield and household food security (Zougmoré et al., 2016; Zougmoré et al., 2018), thereby contributing to the realisation of SDG 2 in Africa (Mbow et al., 2014).

On the contrary, adaptation actions may induce trade-offs with mitigation objectives, as well as other adaptation and developmental outcomes, delivering negative impacts and compromising the attainment of the SDGs. For example, increased deployment of renewable energy technologies can drive future land use changes (Frank et al., 2021) and threaten important biodiversity areas if poorly deployed (Rehbein et al., 2020). The use of early-maturing or drought-tolerant crop varieties may increase resilience (SDGs 1, 2), but adoption by smallholder farmers can also be hindered by affordability of seed. Cultivation of biodiesel crops also can hinder food security (SDG 2) at local and national levels (Tankari, 2017; Brinkman et al., 2020).

Additionally, the use of fertilizers in intense systems can result in increased environmental degradation (Akinyi et al., 2021). When farmers migrate, it puts pressure on inadequate social services provision and facilities at their destination (SDG 8) and leads to reduced farm labour and a deterioration of the workforce and assets (SDG 2) (Gemenne and Blocher, 2017a), which negatively affects farm operations and non-migrants, particularly women, elderly and children, at the point of origin (Nyantakyi-Frimpong and Bezner-Kerr, 2015; Ahmed et al., 2016; Otto et al., 2017; Eastin, 2018). Farmers may also miss critical periods during the farming season that eventually makes them food insecure (SDG 2) and vulnerable to climate change (SDG 13) (Antwi-Agyei et al., 2018). Migrants should be supported to reduce their overall shocks to climate vulnerability at the points of origin and destination. Small-scale irrigation infrastructure if not managed properly, may lead to negative environmental effects and compromise the integrity of riparian ecosystems (SDG 15) (Loucks and van Beek, 2017) and serve as breeding grounds for malaria-causing mosquitoes (SDG 3) (Attu and Adjei, 2018).

9.4 Climate Resilient Development

Climate resilient development (CRD) is a process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all (Denton et al., 2014; Andrijevic et al., 2020; Owen, 2020; Cornforth et al., 2021). It emphasises equity as a core element of sustainable development as well as conditions for inclusive and sustained economic growth, shared prosperity and decent work for all, taking into account different levels of national development and capacities as encoded in the SDGs (Section 9.3.2; Chapter 18, Section 18.1). This chapter section identifies five key dimensions of CRD for Africa: climate finance, governance, cross-sectoral and transboundary solutions, adaptation law and climate services and literacy.

9.4.1 Climate Finance

Access to adequate financial resources is crucial for climate change adaptation (Cross-Chapter Box FINANCE in Chapter 17). Since the Copenhagen Accord (UNFCCC, 2009), and then extended by the Paris Agreement (UNFCCC Paris Agreement, 2015 see Article 4.4, and also 4.8, 4.9), developed countries are expected to scale up climate finance for developing countries toward a collective goal of USD 100 billion per year by 2020, with a balanced allocation between adaptation and mitigation.

9.4.1.1 How Much Adaptation Finance is Needed?

There is limited research providing quantitative estimates of adaptation costs across Africa. Adaptation costs in Africa have been estimated at USD 7–15 billion per year by 2020 (Schaeffer et al., 2013), corresponding to USD 5–11 per capita per year. The African Development Bank estimates costs of near-term adaptation needs identified in the Intended NDCs (INDCS) of African countries as USD 7.4 billion per year from 2020, recognising INDCs describes only a limited subset of adaptation needs (AfDB, 2019). Many African countries, particularly Least Developed Countries (LDCs), express a stronger demand for adaptation finance – a study of financial demands in INDCs for 16 African countries suggests a ratio around 2:1 for adaptation to mitigation finance with demand for Eritrea and Uganda approximately 80% for adaptation (Zhang and Pan, 2016).

Adaptation costs in Africa are expected to rise rapidly as global warming increases (*high confidence*). A meta-analysis of adaptation costs identified in 44 NDCs and NAPs from developing countries estimated a median adaptation cost around USD 17 per capita per year for 2020–2030 (Chapagain et al., 2020). Adaptation cost estimates for Africa increase from USD 20–50 billion per year for RCP2.6 in 2050 (around 1.5°C of warming), to USD18–60 billion per year for just over 2°C, to USD 100–437 billion per year for 4°C of global warming above pre-industrial levels (Schaeffer et al., 2013; UNEP, 2015; Chapagain et al., 2020). Focusing on individual sectors, the average country-level cost is projected to be USD 0.8 billion per year for adapting to temperature-related mortality under 4°C global warming (Carleton et al., 2018), with cumulative energy costs for cooling demand projected to reach USD 51 billion by 2°C and USD 486 billion by 4°C global warming (Parkes et al., 2019). Transport infrastructure repair costs are also projected to be substantial (Section 9.8.2) More precise estimates are limited by methodological difficulties and data gaps for costing adaptation, uncertainties about future levels of global warming and associated climate hazards, and ethical choices such as the desired level of protection achieved (Fankhauser, 2010; Hallegatte et al., 2018; UNFCCC, 2018) (Cross-Chapter Box FINANCE in Chapter 17). As such, existing estimates are expected to substantially underestimate eventual costs with adaptation costs possibly 2–3 times higher than current global estimates by 2030, and 4–5 times higher by 2050 (UNEP, 2016a).

9.4.1.2 Benefit-Cost Ratios in Adaptation

Although analysts face challenges related to the nature of climate change impacts (Sussman et al., 2014) and data limitations (Li et al., 2014) when estimating all costs and benefits for adaptation measures in specific contexts, adaptation generally is cost-effective (*high confidence*). The Global Commission on Adaptation estimated the benefits and costs of five illustrative investments and found benefit-cost ratios ranging from 2:1 to 10:1. However, it also noted that 'actual returns depend on many factors, such as economic growth and demand, policy context, institutional capacities and condition of assets' (The Global Commission on Adaptation, 2019). A review of ex-ante cost-benefit analyses for 19 adaptation-focused projects in Africa financed by the Green Climate Fund (GCF) shows benefit-cost ratios in a similar range. Using a 10% discount rate, as used by many of GCF's accredited entities, the benefit-cost ratio for individual projects ranges from 0.9:1 to 7.3:1, the median benefit-cost ratio is 1.8:1 and total ratio across all 19 projects is 2.6:1. When using lower discount rates, as some entities do for climate projects, the benefit-cost ratio is even higher, reflecting the front-loaded costs and back-loaded benefits of many adaptation investments. Using a 5% discount rate, the overall benefit-cost ratio of the GCF projects is 3.5:1, with a range from 1:1 to 11.5:1 and a median ratio of 2.4:1 (Breitbarth, 2020). In addition, many proposals have activities for which further benefits were not estimated due to the difficulty of attributing benefits directly to the intervention. The benefits of adaptation measures for infrastructure and others with clear market impacts are often easier to estimate than for policy interventions and where markets may not exist, such as ecosystem services (Li et al., 2014).

9.4.1.3 How Much Finance is Being Mobilised?

The amounts of finance being mobilised internationally to support adaptation in African countries are billions of USD less than adaptation cost estimates, and finance has targeted mitigation more than adaptation (*high confidence*). The OECD (2020) estimates an average of USD 17.3 billion per year in public finance targeting mitigation and adaptation from developed countries to Africa from 2016-2018, with adaptation expected to be a small share of this amount: Of the global total only 21% in 2018 targeted adaptation (there is no breakdown provided for Africa). Analysis of OECD data that is reported by the funders, covering bilateral and multilateral funding sources, estimated international public finance (grants and concessional lending) committed to Africa for climate change for 2014-2018 at USD 49.9 billion: 61% (30.6 billion) for mitigation, 33% (16.5 billion) for adaptation and 5% (2.7 billion) for both objectives simultaneously (Savvidou and Atteridge, 2021) (Figure 9.8a). This equates to an average of USD 3.8 billion per year targeting adaptation (Savvidou and Atteridge, 2021). In per capita terms, only two countries (Djibouti and Gabon) were supported with more than USD 15 per person per year, most were supported with less than USD 5 per person per year (Savvidou and Atteridge, 2021).

The multilateral development banks (MDBs) report 43% of their climate-related commitments to sub-Saharan Africa in 2018 targeted adaptation (EBRD et al., 2021). Sources other than international public finance are more difficult to track and there is limited data on Africa (Cross-Chapter Box FINANCE in Chapter 17). Considering a wider range of finance types (including private flows and domestic mobilisation), an estimated annual average of roughly USD 19 billion in climate finance for 2017-2018 went to sub-Saharan Africa, of which only 5% was for adaptation (CPI, 2019; Adhikari and Safaee Chalkasra, 2021). The mobilisation of private finance by developed country governments, through bilateral and multilateral financial support, is lower in Africa relative to other world regions. Globally, in 2016-2018, Africa made up only 17% of mobilised private finance relevant for climate change (OECD, 2020).

Strong differences exist among African sub-regions. Finance commitments targeting adaptation increased from 2014-2018 for East and West Africa but decreased in Central Africa (Savvidou and Atteridge, 2021) (Figure 9.8b). Climate-related finance was >50% for adaptation in 19 countries, while 26 received >50% for mitigation (Savvidou and Atteridge, 2021).

African countries expect grants to play a crucial role in supporting adaptation efforts because loans add to already high debt levels that exacerbate fiscal challenges, especially in light of high sovereign debt levels from the COVID-19 pandemic (Bulow et al., 2020; Estevão, 2020). From 2014-2018, more finance commitments targeting adaptation in Africa were debt instruments (57%) than grants (42%) (Savvidou and Atteridge, 2021) (Figure 9.8c).

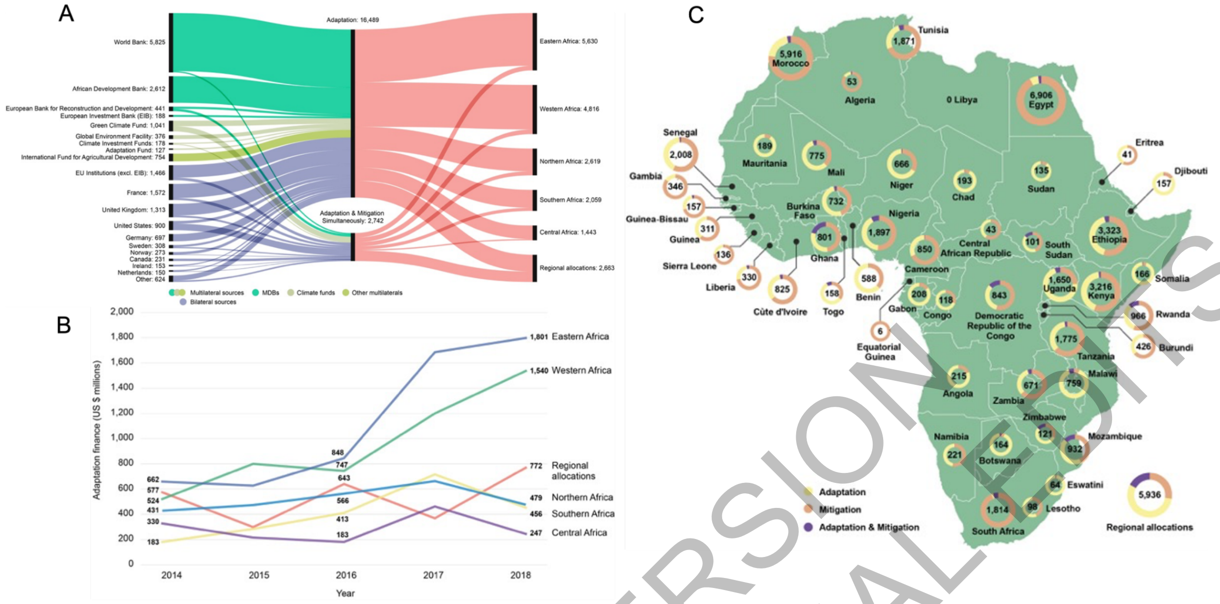


Figure 9.8: Finance targeting climate adaptation by sector and percentages of climate finance commitments that have been disbursed in Africa (2014-2018) as reported to OECD. (a) Flows of committed finance targeting adaptation, (b) trend over time in international development finance commitments targeting adaptation in Africa, and (c) country-level shares of total climate finance that targeted adaptation or mitigation or both simultaneously. Source: (Savvidou and Atteridge, 2021).

For Africa combined, the sectors targeted with most support for adaptation are Agriculture and Water Supply and Sanitation, which account for half of total adaptation finance from 2014-2018 (Figure 9.9a). The sectoral distribution has changed little over these years, suggesting adaptation planners and funders are maintaining a relatively narrow view of where support is needed and how to build climate resilience (Savvidou and Atteridge, 2021).

However, to understand actual expenditure on adaptation, it is necessary to look at disbursements (that is, the amounts paid out versus committed amounts). Low ratios of disbursements to commitments suggest difficulties in project implementation. Disbursement ratios for climate-related finance from all funders other than MDBs (for which data is not published) in Africa are very low (Savvidou and Atteridge, 2021) (Figure 9.9b). Only 46% of 2014–2018 commitments targeting adaptation were dispersed (Savvidou and Atteridge, 2021). Regions faring worst are North Africa (15%), Central Africa (33%) and West Africa (33%) (Figure 9.9c). These disbursement ratios for adaptation and mitigation finance in Africa are lower than the global average (Savvidou and Atteridge, 2021), which suggests greater capacity problems in implementing climate-related projects and, in turn, means lost opportunities to build resilience and adaptive capacity and a wider gap in adaptation finance for Africa (Omari-Motsumi et al., 2019).

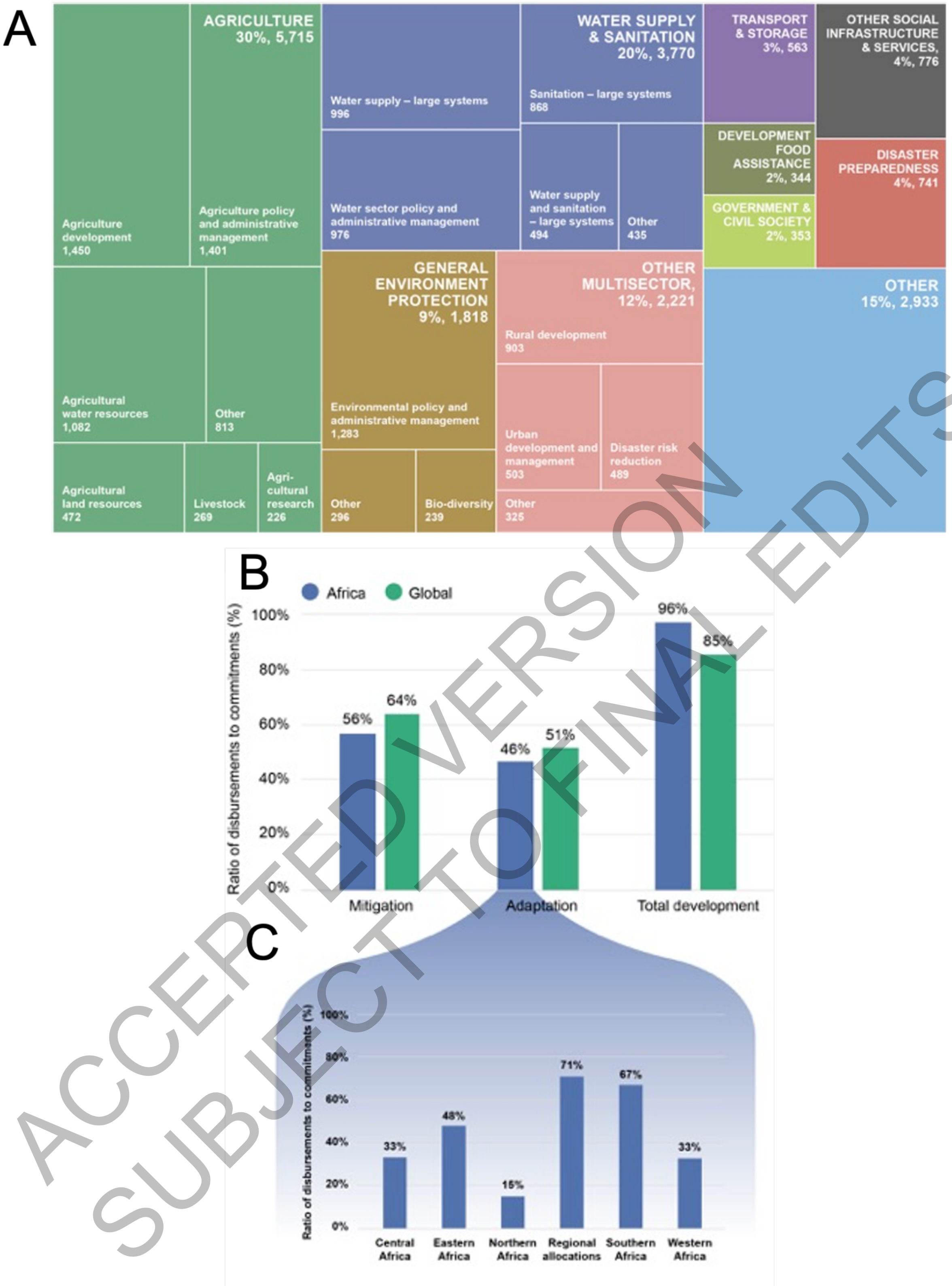


Figure 9.9: (a) Sectoral distribution of adaptation finance commitments to Africa 2014-2018 (Savvidou and Atteridge, 2021). Disbursement ratio (disbursements expressed as percentage of commitments) targeting mitigation, adaptation and for total development finance, (b) disbursement ratios for Africa compared to global average, and (c) disbursement ratios for adaptation finance broken down by each African sub-region. 2014-2018 (for all funders reporting to OECD except Multilateral Development Banks). Source: (Savvidou and Atteridge, 2021).

9.4.1.4 What are the Barriers and Enabling Conditions for Adaptation Finance?

The present situation reflects not only an insufficient level of finance being mobilised to support African adaptation needs (Section 9.4.1) but also problems in accessing and using funding that is available. The direct access modality introduced by the Adaptation Fund and GCF, whereby national and regional entities from developing countries can be accredited to access funds directly, is aimed at reducing transaction costs for recipient countries, increasing national ownership and agency for adaptation actions, and enhancing decision-making responsibilities by national actors, thereby contributing to strengthening local capacity for sustained and transformational adaptation (CDKN, 2013; Masullo et al., 2015). Indeed, direct-access projects from the Adaptation Fund tend to be more community focussed than indirect-access projects (Manuamorn and Biesbroek, 2020). Country institutions in Africa, however, are struggling to be accredited for direct access because of the complicated, lengthy and bureaucratic processes of accreditation, which requires, for example, strong institutional and fiduciary standards and capacity to be in place (Brown et al., 2013; Omari-Motsumi et al., 2019). As of December 2019, over 80% of all developing countries had no national Direct Access Entities (DAEs) (Asfaw et al., 2019). Capacity to develop fundable projects in Africa is also inadequate. An analysis of proposals submitted to the GCF up to 2017 revealed that, while African countries were able to submit proposals to the GCF, they had the lowest percentage of approvals (39%) compared to all other regions (Fonta et al., 2018). This suggests the quality of proposals and therefore the capacity to develop fundable proposals remains inadequate in the region.

Even when accredited, some countries experience significant institutional and financial challenges in programming and implementing activities to support concrete adaptation measures (Omari-Motsumi et al., 2019). Low disbursement ratios suggest inadequate capacity to implement projects once they are approved (Savvidou and Atteridge, 2021). Systemic barriers have been highlighted in relation to the multilateral climate funds, including funds not providing full-cost adaptation funding, capacity barriers in the design and implementation of adaptation actions (including the development of fundable project proposals) and barriers in recognising and enabling the involvement of sub-national actors in the delivery and implementation of adaptation action (Omari-Motsumi et al., 2019). As of 2017, most GCF disbursements to Africa (61.9%) were directed to support national stakeholders' engagement with regards to readiness activities, with only 11% directed to support DAEs in implementation of concrete projects/pipeline development (Fonta et al., 2018). While supporting readiness activities is important for strengthening country ownership and institutional development, research suggests adaptation finance needs to shift towards implementation of concrete projects and more pipeline development if the goal of transformative and sustained adaptation in Africa is to be realised (Fonta et al., 2018; Omari-Motsumi et al., 2019). The source of these problems needs to be better understood so that the prospects for future climate-related investments can be improved and institutional strengthening and targeted project preparation can be supported (Omari-Motsumi et al., 2019; Doshi and Garschagen, 2020; Savvidou and Atteridge, 2021).

Some progress has been made in supporting developing countries to enhance their adaptation actions. The process to formulate and implement NAPs was established by parties under the UNFCCC to support developing countries identify their vulnerabilities, and determine their medium- and long-term adaptation needs (UNFCCC Paris Agreement, 2015). NAPs provide a means of developing and implementing strategies and programmes to address those needs. In 2016, the parties agreed for the GCF to fund up to USD 3 million per country for adaptation planning instruments, including NAPs. However, accessing funding through the GCF for NAP formulation is challenging (Fonta et al., 2018) and, as of October 2020, four years after the decision to fund NAPs, only six African countries had completed their NAPs (UNFCCC NAP Central). The next step is to convert adaptation planning documents into programming pipeline projects that are fundable and implementable, which presents a significant barrier to enhanced adaptation action (Omari-Motsumi et al., 2019).

Adaptation finance has not been targeted more towards more vulnerable countries (Barrett, 2014; Weiler and Sanubi, 2019; Doshi and Garschagen, 2020; Savvidou and Atteridge, 2021). Reasons for this include fast-growing middle-income countries offering larger gains in emission reductions, so finance has favoured mitigation in these economies, even within sub-Saharan Africa, and as more climate finance uses debt instruments, mitigation projects are further preferred because returns are perceived to be more certain (Rai et al., 2016; Lee and Hong, 2018; Carty et al., 2020; Simpson et al., 2021c).

Many adaptation interventions for most vulnerable countries and communities provide no adequate financial return on investments and can therefore only be funded with concessional public finance (Cross-Chapter Box

FINANCE in Chapter 17). Yet, public funds alone are insufficient to meet rapidly growing adaptation needs. Public mechanisms can help leverage private sector finance for adaptation by reducing regulatory, cost and market barriers through blended finance approaches, public-private partnerships, or innovative financial instruments and structuring in support of private sector requirements for risk and investment returns, such as green bonds (Cross-Chapter Box FINANCE in Chapter 17). Subnational actors can be core agents to conceptualize, drive, and deliver adaptation responses and unlock domestic resources in the implementation of adaptation action (CoM SSA, 2019; Omari-Motsumi et al., 2019), provided they are sufficiently resourced and their participation and agency are supported.

Many African countries are at high risk of debt distress, especially due to the COVID-19 pandemic, and will need to decrease their debt levels to have the fiscal space to invest in climate resilience (Estevão, 2020; Dibley et al., 2021). As of mid-2021, the G20's Debt Service Suspension Initiative is providing temporary relief for repayment of bilateral credit, but this has largely not been taken up by private lenders (Dibley et al., 2021; World Bank, 2021). The total external debt servicing payments combined for 44 African countries in 2019 were USD 75 billion (World Bank, 2018), far exceeding discussed levels of near-term climate finance. Aligning debt relief with Paris Agreement goals could provide an important channel for increased financing for climate action, for example, by allowing African countries to use their debt-servicing payments to finance climate change mitigation and adaptation (Fenton et al., 2014). Governments can disclose climate risks when taking on sovereign debt, and debt-for-climate resilience swaps could be used to reduce debt burdens for low-income countries while supporting adaptation and mitigation (Dibley et al., 2021).

9.4.2 Governance

9.4.2.1 Governance Barriers

Overcoming governance barriers is a precondition to ensure successful adaptation and climate-resilient development (Pasquini et al., 2015; Owen, 2020). Despite the ambitious climate targets across African countries and renewed commitments in recent years (Zheng et al., 2019; Ozor and Nyambane, 2020), governance barriers include, among others, slow policy implementation progress (Shackleton et al., 2015; Taylor, 2016), incoherent and fragmented approaches (Zinngrebe et al., 2020; Nemakonde et al., 2021), inadequate governance systems to manage climate finance (Granoff et al., 2016; Banga, 2019), poor stakeholder participation (Sherman and Ford, 2014), gender inequalities (Andrijevic et al., 2020), unaligned development and climate agendas (Musah-Surugu et al., 2019; Robinson, 2020), elite capture of climate governance systems (Kita, 2019), hierarchical and complex state bureaucracy (Meissner and Jacobs, 2016; Biesbroek et al., 2018) and weak, non-existent or fragmented subnational institutions (Paterson et al., 2017; Musah-Surugu et al., 2019). Further, adaptation planning involves cross-cutting themes, multiple actors and institutions with different objectives, jurisdictional authority and levels of power and resources, yet there is often a lack of coordination, clear leadership or governance mandates (Shackleton et al., 2015; Leck and Simon, 2018) and unequal power relations between African countries and developed countries can hinder progress on governance of financial markets, budget allocations and technology transfer to address addressing climate technology gaps in Africa (Rennkamp and Boyd, 2015; Olawuyi, 2018).

Policy implementation can be slow due to the absence of support mechanisms and dependency on funding by international partners (Leck and Roberts, 2015; Ozor and Nyambane, 2020). In many countries, commitment to climate policy objectives is low (Naess et al., 2015), particularly in light of competing development imperatives and post-COVID-19 recovery efforts (Caetano et al., 2020), although COVID-19 recovery efforts offer significant opportunities for health, economic and climate resilience co-benefits (Sections 9.4.3 and 9.11.5; Cross-Chapter Box COVID in Chapter 7). Another challenge relates to long-term planning and decision-making which is hampered by uncertainty related to future socio-economic and GHG emissions scenarios (Coen, 2021), political cycles and short-term political appointment terms (Pasquini et al., 2015).

Lack of community agency in climate governance affects ability for citizen-led climate interventions in Africa (Antwi-Agyei et al., 2015; Mersha and Van Laerhoven, 2016). This is attributed partly to low civic education, limited participation power of citizens and tokenism due to perceived lack of immediate benefits (Odei Erdiaw-Kwasie et al., 2020), as well as low rates of climate change literacy in many regions (Simpson et al., 2021a) (Section 9.4.3). Participation in climate policy also extends to the private sector, which has been relatively uninvolved in adaptation discussions to date (Crick et al., 2018).

Africa requires substantial resources and support to adapt to the unavoidable consequences of climate change, a pertinent climate justice concern for governments. However, the mechanisms needed to redress current power imbalances, structural and systemic inequality are often absent (Saraswat and Kumar, 2016) (see Section 9.11.4) and policies that underpin environmental justice concerns, including distributive justice, participation, recognition and capability (Shi et al., 2016; Chu et al., 2017) are also needed.

9.4.2.2 Good Governance

Good governance can contribute to positive climate outcomes and climate-resilient development in Africa through long-term planning, development-focused policy environments, the development of robust and transformational policy architecture, inclusive participation and timely implementation of NDCs (Bataille et al., 2016; Werners et al., 2021) (see Table 9.3 for examples).

Table 9.3: Characteristics and examples of governance that contribute towards climate-resilient development in Africa

Governance characteristic	Example
Long-term development planning	Countries are mainstreaming adaptation into their long-term development cycles (UNFCCC Adaptation Committee, 2019). For example, Burkina Faso's National Adaptation Plan elaborates its perspective to 2050 and links to its development pathways (Government of Burkina Faso, 2015). Many African countries are also enhancing the adaptation components of their long-term low emissions strategies.
Climate justice and inequality-focused policies	Climate policies can be designed to include specific policy mechanisms (e.g., carbon taxes, renewable energy subsidies) to maximise developmental gains while reducing inequality (Andrijevic et al., 2020). For example, revenues from a carbon tax can be used to increase social assistance programs that benefit poor people and reduce their vulnerability to climate change (Hallegatte et al., 2016). Climate risk management can be integrated into social protection and assistance programs, such as public works programs that increase climate resilience (9.11)
Interlinkages between adaptation and development pathways	Cross-sectoral and multi-level governance approaches can harness synergies with the SDGs, Paris Agreement and Agenda 2063 aspirations, helping to counter the adaptation deficit, promote sustainable resource use and contribute to poverty reduction (Niang et al., 2014; IPBES, 2018; Roy et al., 2018b). Ghana, Namibia, Rwanda and Uganda all link adaptation with disaster risk reduction in their NDCs (UNFCCC Adaptation Committee, 2019).
High-level engagement	Climate policies, traditionally overseen by environment ministries, are increasingly receiving priority from finance and planning ministries. Zambia's Climate Change Secretariat is currently led by the Ministry of Finance (Government of the Republic of Zambia, 2010), while Tanzania's environmental division sits in the office of the Vice-President (Governmet of the United Republic of Tanzania, 2011).
All-of-government approach	In Kenya, the Climate Change Directorate is the secretariat for the National Climate Change Commission, serving as an overarching mechanism to coordinate sectoral and county level action (Government of the Republic of Kenya, 2018). In South Africa, the National Committee on Climate Change, the Intergovernmental Committee on Climate Change and the Presidential Climate Change Commission have been established to enhance intergovernmental and multisectoral coordination on climate action (Climate Action Tracker, 2021).
Participatory engagement	Polycentric, bottom-up and locally implemented approaches are more able to include the emergence of new actors (e.g., city networks, multinational companies and sub-state entities), new instruments and levels (soft law instruments or transnational dynamics) and new guiding principles and values (fairness, transparency and co-participation) (Leal Filho et al., 2018; Sapiains et al., 2021). Case studies include the community-based, participatory scenario planning approach used in Malawi to generate information for farmers from seasonal forecasts, as well as the integration of climate risk into Lusaka's Strategic Plan through engagement with city planners (Conway and Vincent, 2021; Vincent and Conway, 2021). Many innovative solutions have been designed to promote participation, such as Pamoja Voices toolkits in pastoralist communities in Northern Tanzania (Greene et al., 2020).

Inclusive and diverse stakeholders	Kenya's Climate Change Directorate has a designated team to integrate gender into its national climate policies (Murray, 2019), while Seychelles' National Climate Change Council has allocated a seat exclusively for a youth candidate (Government of The Seychelles, 2020). Tanzanian Climate-Smart Agriculture Alliance supports the integration of farmers and builds strategic alliances to support climate processes (Nyasimi et al., 2017).
Partnerships	Ghana, Kenya, Uganda and Zambia are developing anticipatory scenarios for low-carbon climate-resilient development pathways for the agricultural sector, aimed at informing input into national climate policy (Balié et al., 2019). This science to policy to practice interface is bridged through the inclusion of policymakers, practitioners and academics (Dinesh et al., 2018). In Lusaka, Durban and other African cities, processes of engagement and learning have built the trust and capacities needed to inform city-scale, climate-resilient decisions and associated actions (Taylor et al., 2021a; Taylor et al., 2021b).
NDC implementation	Rwanda has developed an indicator-based Monitoring, Reporting and Verification (MRV) framework for tracking its NDC implementation and associated financial flows (Government of Republic of Rwanda, 2020). Zambia has also integrated gender indicators into its NDC implementation plan and is incorporating gender considerations into its MRV framework (Murray, 2019).

African governments are developing and revising ambitious adaptation policies that are enforceable and aligned with wider societal development goals, including an enabling environment for finance and investment in the jobs and skills development necessary to support a just transition (ILO, 2019) (Section 9.4.5). If appropriately designed, such institutions offer the opportunity to foster adaptive governance which is collaborative, multi-level and decentralised, offering integration of policy domains, flexibility and an emphasis on non-coerciveness and adaptation (Ruhl, 2010).

Coordination across multiple sectors, supported with leadership from the highest levels of government, has shown to improve implementation effectiveness and anticipated scaling up (Rigaud et al., 2018). This high-level engagement promotes the inclusion of climate resilience and adaptation targets in national planning and budgeting. Financial and capacity support is essential (Adenle et al., 2017; UNEP, 2021), as is the tracking of national progress towards development goals (Box 9.6).

In Africa, climate governance occurs in a context of deep inequality and asymmetric power relations – both within countries and between countries – making adequate mechanisms for multi-stakeholder participation essential (Sapiains et al., 2021). This requires creation of avenues for the voices of marginalised groups in policy processes and enabling policy environments that can catalyse inclusive action and transformational responses to climate change (Totin et al., 2018; Revi et al., 2020; Ziervogel et al., 2021), safeguarding protection against the climate harms of the most vulnerable in society, particularly of women and children (see also Box 9.1). Community-based natural resource management in pastoral communities was observed to improve institutional governance outcomes through involving community members in decision-making, increasing the capacity of these communities to respond to climate change (Reid, 2014).

Specific indicators can be included in the performance metrics and monitoring frameworks for each sector, policy intervention and budget planning cycle (Wojewska et al., 2021). Many countries in Africa are also revamping their institutional coordination mechanisms to reflect an all-of-government approach and partnership with non-State stakeholders with diverse capabilities and expertise (see examples from Rwanda and Zambia in Table 9.3). This includes Cape Town's drought response in 2017/2018 where non-State actors actively partnered with the state response around water management/savings practices (Simpson et al., 2020a; Simpson et al., 2020b; Cole et al., 2021b).

9.4.3 Cross-Sectoral and Transboundary Solutions

Climate change does not present its problems and opportunities conveniently aligned with traditional sectors, so mechanisms are needed to facilitate interactions and collaborations between people working in widely different sectors (Simpson et al., 2021b). Traditional risk assessments typically only consider one climate hazard and one sector at a time, but this can lead to substantial misestimation of risk because multiple climate risks can interact to cause extreme impacts (Zscheischler et al., 2018; Simpson et al., 2021b).

Because multiple risks are interlinked and can cascade and amplify risk across sectors, cross-sectoral approaches that consider these interlinkages are essential for climate-resilient development, especially for managing trade-offs and co-benefits between SDGs, mitigation and adaptation responses (Liu et al., 2018a).

In Africa, placing cross-sectoral approaches at the core of climate-resilient development provides significant opportunities to deliver large benefits and/or avoids damages across multiple sectors including water, health, ecosystems and economies (*very high confidence*) (Boxes 9.5, 9.6 and 9.7). They can also prevent adaptation or mitigation action in one sector, exacerbating risks in other sectors and resulting in maladaptation, for example, from large-scale dam construction or large-scale re/afforestation (e.g., water-energy-food nexus and large-scale tree planting efforts) (Boxes 9.3 and 9.5).

Cross-sectoral or 'nexus' approaches can improve the ability of decision-makers to foresee and prevent major climate impacts. Barriers to developing nexus approaches arise from rigid sectoral planning, regulatory and implementation procedures, entrenched interests and power structures and established sectoral communication structures. Opportunities for overcoming these barriers include creating a dedicated home for co-development of nexus risk assessment and solutions, promoting co-leadership of projects by multiple sectors, specific budget allocations for nexus projects, facilitating and coordinating services, compiling useful strategies into toolkits, ameliorating inequitable power relations among participants and measuring progress on nexus approaches through metrics (Palmer et al., 2016; Baron et al., 2017).

Beyond cross-sectoral collaboration, international cooperation is vital to avert dangerous climate change as its impacts reach beyond the jurisdiction of individual states. International good practice and regional agreements, protocols and policies together recognise that regional integration, cooperative governance and benefit-sharing approaches are cornerstones of effective resource security and climate change responses in Africa (Jensen and Lange, 2013; World Bank, 2017a; Dombrowsky and Hensengerth, 2018). Natural resource development, particularly governance of shared river basins, exemplifies opportunities for governance responses for African nations that can be cooperative, regionally integrated and climate-resilient.

In Africa, climate vulnerability crosses geopolitical divides as regional clusters of fragile and high vulnerability countries exist, emphasising the need for transboundary cooperation (Birkmann et al., 2021; Buhaug and von Uexkull, 2021). Natural resource security is increasingly reliant on transboundary governance, regional integration and cooperation (Namara and Giordano, 2017). There are 60 international or shared river basins on the continent, a function of colonial divides and topography, with some basins shared by four or more countries (UNECA, 2016; Popelka and Smith, 2020). Climate changes which result in impact and risk pathways across country boundaries and regions (although with different levels of impact) accelerate the urgency for integrated approaches to manage and benefit from shared resources and promote their security for populations and economies (Namara and Giordano, 2017; Frame et al., 2018; Carter et al., 2021). At the same time, natural resources such as water generate economic benefits shared across boundaries, such as hydroelectric power generation and regional food security (Dombrowsky and Hensengerth, 2018).

Poor governance, particularly at the transboundary level, can undermine water security and climate change is likely to add new challenges to pre-existing dynamics, emphasising the necessity of formal transboundary arrangements (Jensen and Lange, 2013; UNECA, 2016). Further, it can constrain access to critical financial resources at a time when it is needed most. This is particularly the case when climate impact pathways manifest at the transboundary level (Challinor et al., 2018; Simpson et al., 2021b), but where the need to protect sovereign interests can block regionally integrated institutional arrangements that are pivotal for accessing the multilateral climate funds for transboundary climate investments that include resilient infrastructure and greater water benefits across Africa's shared river basins (Carter et al., 2021) (Cross-Chapter Box INTEREG in Chapter 16).

In response, the African Development Bank is supporting two of the most climate-vulnerable and larger African river basins to leverage GCF and GEF funds to finance Programmes for Integrated Development and Adaptation to Climate Change (PIDACC). PIDACC finance is approved at the multinational level in the Niger basin which is shared by 9 West and Central African States (AfDB, 2018c; GCF, 2018a), while a PIDACC proposal is currently under development for the Zambezi basin (Zambezi Watercourse Commission, 2021).

Stakeholders across Africa are recognising the scale and severity of transboundary risks to water. Such risks are twofold in nature, arising both from potential impacts due to climate change and from responses to climate change (Simpson et al., 2021b). This awareness amongst stakeholders is leading to increasingly progressive approaches to natural resource development which can also reduce risk across boundaries within regions. For example, river basin organisations (RBOs) in southern Africa such as the Orange-Senqu and the Okavango River Basin Commissions are revising treaties considered to predate the interrelated issues of climate change, growing populations and water scarcity (OKACOM, 2020). In parts of West Africa, where climate change is characterised by reduction of precipitation (Barry et al., 2018), regionally integrated and climate-resilient economic investments for water resource development are enabled by the Senegal River Basin Organisation (OMVS) which emphasises programme and project development, financing and implementation in ensuing work plans (World Bank, 2020e), as does the Nile Basin Initiative (NBI) in North and East Africa (Schmeier, 2017; Blumstein and Petersen-Perlman, 2021).

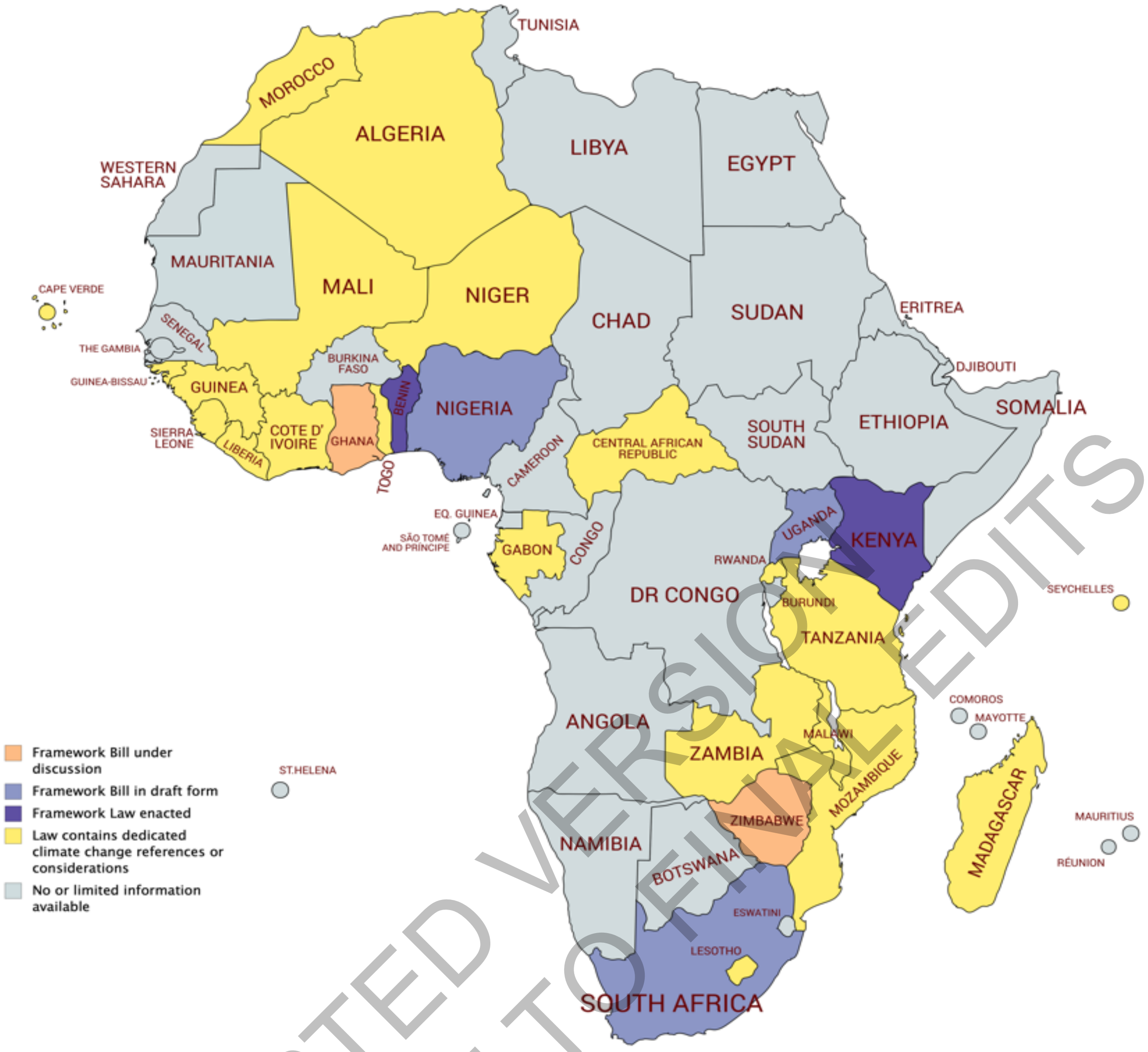
Enhanced transboundary governance arrangements suggest that countries are joining forces to coherently manage and protect natural resources (Spalding-Fecher et al., 2014; AfDB, 2021). Underlying governance issues and political economy interests block or advance such transitions to regionally integrated resource management and benefit-sharing, the market drivers of water security (AMCOW, 2012; Soliev et al., 2015). Angola, for example, outlines regional adaptation as a priority and one of its unconditional adaptation strategies (which is already funded) is enhancing resilience in the Benguela fisheries system, a project shared with Namibia and South Africa (GEF and FAO, 2021). Another example is The Great Green Wall for the Sahara and Sahel Initiative which was launched in 2007, with the aim of tackling land degradation in Africa (UNCCD, 2020). This transboundary project, led by the African Union Commission, is being implemented in more than 20 countries across Africa's Sahel region, in cooperation with international partners including UNCCD, GEF and the World Bank among others. Approximately USD 10 billion have been mobilised and/or promised for this initiative (UNCCD, 2020). Such statements demonstrate the increasing identification of transboundary risks and approaches to manage and adapt to them as areas of 'common concern' that require cooperative adaptation actions. Accelerating strengthened transboundary water and climate governance needs to integrate these climate drivers of compromised water security. The role of institutions such as OVMS and the NBI have demonstrated they can be played in influencing economic behaviour among riparian countries of shared river basins highlighting that institutions are an integral part of climate governance in evolving economic systems (Hodgson, 2000).

9.4.4 Climate Change Adaptation Law in Africa

9.4.4.1 The Rise of Climate Change Adaptation Law

Robust legislative frameworks, both climate change specific and non-specific, can foster adaptive responses to climate change, particularly in Least Developed Countries (LDCs) (Nachmany et al., 2017). As discussed in Chapter 17, there are multiple reasons for this. The successful implementation of policy objectives across the continent is often contingent upon or at least supported by an underlying legislative framework (Averchenkova and Matikainen, 2017; Scotford et al., 2017). There are also wider systemic and structural reasons for developing climate change legislation, including the promotion of coordination within government, its policy entrenching role, its symbolic value and its potential to support climate finance flows (Nachmany et al., 2017; Scotford and Minas, 2019).

Legal systems, however, also have the potential to be maladaptive. Laws may be brittle, often assuming and reinforcing a static state, and the boundary of the law may not align to the relevant location, scale or impact (Craig, 2010; Arnold and Gunderson, 2013; Wenta et al., 2019). This necessitates the review and revision of existing laws to remove such barriers and foster adaptive management (Craig, 2010; Ruhl, 2010; Cosens et al., 2017) and, where necessary, the promulgation of new laws.



Created with mapchart.net ©

Figure 9.10: Progress in development of climate change framework law in Africa derived from an analysis of public databases of African laws (author's own map), data drawn from (Government of Niger, 1998; Government of Liberia, 2002; Government of Algeria, 2004; Government of Tanzania, 2004; Government of Central African Republic, 2008; Government of Lesotho, 2008; Government of Togo, 2008; Government of Guinea Bissau, 2011; Government of Ivory Coast, 2012; Government of Rwanda, 2012; Government of Sierra Leone, 2012; Government of Cape Verde, 2014; Government of Morocco, 2014; Government of Mozambique, 2014; Government of Madagascar, 2015; Government of the Seychelles, 2015; Government of Gabon, 2016; Government of Kenya, 2016; Government of Mali, 2016; Government of Zambia, 2016; Government of Malawi, 2017; Government of Nigeria, 2017; Government of Benin, 2018; Government of Ghana, 2018; Government of South Africa, 2018; Government of Uganda, 2018; Government of Zimbabwe, 2019 sources quoted as of September 2019).

There has been a rise in framework and sectoral climate change laws across Africa, as illustrated in Figure 9.10 above. The map illustrates the two framework statutes which have been promulgated in Benin and Kenya, as well as the three framework Bills which have been drafted in Nigeria, South Africa and Uganda. There are also discussions taking place in Zimbabwe and Ghana regarding the potential development of a draft framework Climate Change Bill. A review of the climate change framework laws indicates evidence of cross-pollination in design across African jurisdictions, creating the potential for a unique and regionally appropriate body of law with a strong focus on adaptation responses (Rumble, 2019). As discussed in Chapter 17, however, there remains the need for in-country expert input on how the domestic legal landscape may influence their operation, and for each jurisdiction to independently interrogate its adaptation needs and objectives (Scotford et al., 2017).

Numerous African states have also included dedicated climate change-related provisions within various existing statutes which regulate the environment or disaster management. For example, Tanzania's Environmental Management Act 20 of 2004 contains dedicated provisions to address climate change. Rwanda's Law on Environment 48/2018 also contains detailed provisions on mainstreaming climate change into development planning processes, education on climate change, vulnerability assessments and the promotion of measures to enhance adaptive capacity. Some countries have also developed laws dedicated to a specific aspect of adaptation. For example, the Conservation and Climate Adaptation Trust of Seychelles Act 18 of 2015 establishes a trust fund to finance climate change adaptation responses in Seychelles. Similarly, many countries including Algeria, Burkina Faso, Djibouti, Ghana, Namibia, Malawi, Mauritius, Madagascar, Mozambique, Tanzania and South Africa have dedicated disaster management laws. At this stage, it is still too early to determine whether these laws are having any substantive influence in strengthening resilience and reducing vulnerability and, as discussed in Chapter 17, this is identified as a knowledge gap requiring further research.

9.4.4.2 Common Themes in Framework Laws

Laws are now being developed to formalise and entrench institutional structures, specifying their mandate, function, membership and related procedures. A useful example of such an approach can be found in the Nigerian Climate Change Bill which establishes the National Climate Council on Climate Change headed and chaired by the Vice-President, with a wide membership of Ministers, the Chairmen of the Governors' Forum and Association of Local Governments, as well as the private sector and non-governmental organisation (NGO) representatives.

Climate change framework laws can play an instrumental role in achieving mainstreaming by directing relevant actors to integrate adaptation considerations into existing mandates, operations and planning instruments (Rumble, 2019). By way of example, the South African Draft Climate Change Bill contains a general duty to 'coordinate and harmonise the policies, plans, programmes and decisions of the national, provincial and local spheres of government' to achieve, among other things, the climate change objectives of the Bill and national adaptation objectives.

Another common theme is the requirement to develop national climate change adaptation strategies and plans. Many laws further entrench their longevity by requiring them to be subject to strong community participation and consultation, as demonstrated by the Kenyan Climate Change Act and the Nigerian Climate Change Bill.

9.4.4.3 Local Climate Change Laws and Indigenous Knowledge Systems

The Paris Agreement acknowledges, in Article 7.5, that adaptation should be based on and guided by, among other things, 'traditional knowledge, knowledge of indigenous peoples and local knowledge systems'. The accumulated knowledge within indigenous knowledge systems is particularly important as it can assist governments in determining how the climate is changing, how to characterise these impacts and provide lessons for adaptation (Salick and Ross, 2009). In this context, indigenous knowledge systems can play an important role in the effective design of local laws (Mwanga, 2019) as well as national laws. Doing so can contribute to the success of climate change response strategies, including enhancing local participation and the implementation of community-based and ecosystem-based adaptations (Chanza and de Wit, 2016; Mwanga, 2019). For example, the Makorongo Village Forest Management By-Law in Tanzania codifies local customary practices relating to forest management and sustainable harvesting with associated dual adaptation and mitigation benefits and includes all villagers in the decision-making processes relating to forest management (Mwanga, 2019). The inclusion of beneficial indigenous knowledge systems within local by-laws is contingent on the active involvement of members of the indigenous community and awareness of climate change considerations within the local sphere of government, and a willingness to foster such practices (Mwanga, 2019).

In addition to the advancement of indigenous knowledge in adaptive responses, it has been suggested that the protection of the rights of indigenous peoples can have adaptive benefits, in particular through the protection of land tenure rights (Ayanlade and Jegede, 2016). It has been argued that doing so will protect indigenous peoples' lands and resources from overconsumption, secure the recognition of their cultural stewardship over the environment, provide the financial incentive for land stewardship and promote the application of their unique knowledge on the sustainable development of that land and its preservation (Jaksa, 2006; Ayanlade and Jegede, 2016). Not only can a lack of protection of indigenous legal tenure undermine these objectives, but a number of African laws may actively work against them. For example, a review of Tanzanian and Zambian laws highlighted existing provisions that empowered the state to terminate or criminalise the occupation of vacant, undeveloped or fallow lands, which undermined the occupation by indigenous peoples of forests and other uncultivated lands (Ayanlade and Jegede, 2016).

9.4.5 Climate Services, Perception and Literacy.

Policy actors across Africa perceive that anthropogenic climate change is already impacting their locales through a range of negative socioeconomic and environmental effects (Pasquini, 2020; Steynor and Pasquini, 2020). They are highly concerned about and motivated to address these impacts (Hambira and Saarinen, 2015; Pasquini, 2020). Transformative responses to the impacts of climate change facilitate climate-resilient development and are informed by perceptions of climate variability and change and climate change literacy (Figure 9.11).

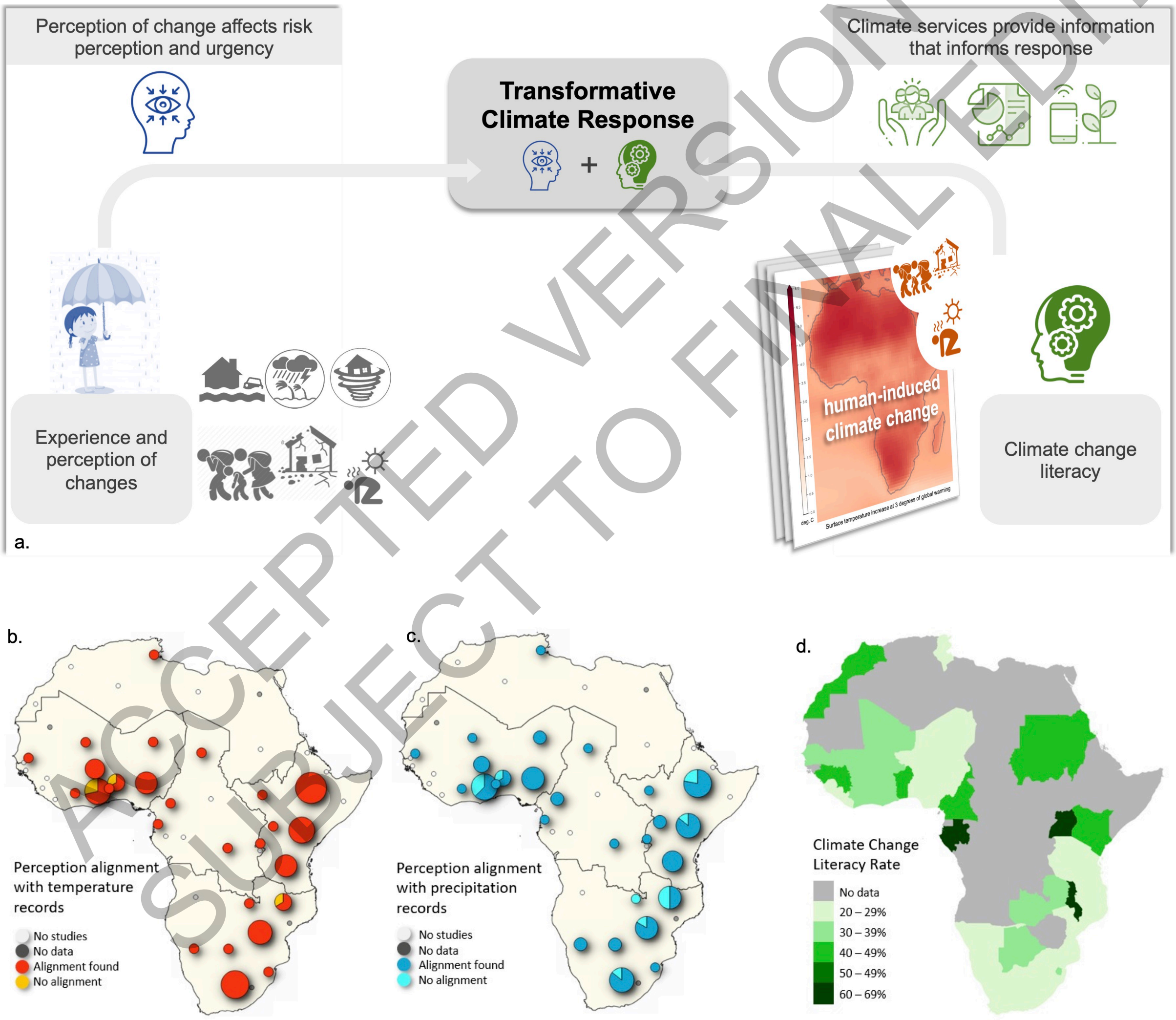


Figure 9.11: The importance of climate services and climate change literacy for more transformative responses to climate change in Africa (adapted from Simpson et al., 2021a). Climate services promote Climate Resilient Development by providing climate information for adaptation decision-making (Street, 2016; Vaughan et al., 2018). However, scalable uptake of climate services relies on climate risk perception of users which is largely driven in Africa by experience and perception of local climate changes (Jacobs and Street, 2020; Steynor et al., 2020b; Steynor and Pasquini, 2020). Perception of climate change in Africa can occur without the knowledge of its anthropogenic causes and its effect on risk, as awareness of the concept of climate change is generally low across Africa (Lee et al., 2015; Alemayehu and Bewket, 2017; Andrews and Smirnov, 2020). This can lead to coping responses to climate change which fall short of adaptation. Climate change literacy can fill this knowledge gap and, together with climate services,

extend responses to climate change to include consideration of future risk through awareness of the anthropogenic cause of climate change and its effect on risk (IPCC, 2019b; Simpson et al., 2021a). Maps a-c: (a) Percentage of times scholarship on Africa record that perception of temperature changes (left), (b) precipitation changes (centre), aligned with available meteorological or climate records for 144 country studies across 33 African countries (Size of bubble indicates number of studies per country for both Panels a and b; Panel b, alignment with temperature changes is indicated for all studies within a country in red, and articles indicating no alignment in orange; while in panel c, alignment with precipitation changes is indicated per country in dark blue and articles indicating no alignment in light blue). Panel c) country-level rates of climate change literacy for 33 African countries (that is, percentage of the population that have heard about climate change and think that human activity is wholly or partly the cause of climate change) (adapted from Simpson et al., 2021a).

9.4.5.1 Climate Information and Services

Climate services (CS) broadly include the generation, tailoring and provision of climate information for use in decision-making at all levels of society (Street, 2016; Vaughan et al., 2018). There is a range of climate service providers in Africa, including primarily National Meteorological and Hydrological Services (NMHS) and partner institutions, complemented by NGOs, the private sector and research institutions (Snow et al., 2016; Harvey et al., 2019), which offer the potential for public-private partnerships (Winrock, 2018; Harvey et al., 2019).

International development funding has progressed the provision of climate services and, together with technological advances and capacity-building initiatives, has increased the reliability of climate services across Africa (Vogel et al., 2019). Most CS investments have been towards the agricultural sector, with other focal sectors including pastoralism, health, water, energy and disaster risk reduction having only small CS initiatives directed towards them (Nkiaka et al., 2019; Carr et al., 2020). Despite this focus and investment, however, there remains a mismatch between the supply and uptake of CS in Africa as information is often inaccessible, unaffordable, not relevant to context or scale and is poorly communicated (Singh et al., 2018; Antwi-Agyei et al., 2021) (Table 9.4; Sections 9.4.1.5.1 and 9.13.4.1). Observational data required for effective regional climate services, including trend analyses, seasonal climate assessment, modelling and model evaluation, is sparse and often of poor quality (Figure 9.11) and usually requires payment which renders it unaffordable (Winrock, 2018).

A number of these challenges may be addressed through the transdisciplinary co-production of climate services (Alexander and Dessai, 2019; Vogel et al., 2019; Carter et al., 2020). Co-production of climate services involves climate information producers, practitioners and stakeholders, and other knowledge holders participating in equitable partnerships and dialogues to collaboratively identify climate-based risk and develop scale-relevant climate information to address this risk (Table 9.4) (Vincent et al., 2018; Carter et al., 2020).

Table 9.4: Challenges and opportunities for Climate Services in Africa for the supply and uptake of climate services.

Challenges	*Opportunities/Solutions*	*References*	*Examples of Programmes that address these challenges. Reproduced from (Carter et al., 2020) with permission.*
Supply of climate services			
Poor infrastructure (e.g., non-functioning observational networks; limited Internet bandwidth; lack of climate modelling capacity; keeping pace with changing technology).	• International funding for observation networks, data rescue and data sharing • Regular NMHS budgets from governments • Public-private partnerships	(Winrock, 2018; Harvey et al., 2019) (Snow et al., 2016; World Bank Group, 2016; Winrock, 2018; Cullmann et al., 2020; Meque et al., 2021)	*East Africa and the West African Sahel (ENACTS programme).* Work with NMHS to provide enhanced services by overcoming the challenges of data quality, availability and access. Creation of reliable climate information suitable for national and local decision-making using station observations and satellite data to provide greater accuracy in smaller space and time scales.

Fragmented delivery of climate services.	• Greater collaboration between the NMHS and sector-specific specialists to create a central database of sector-based climate services	(Winrock, 2018; Hansen et al., 2019a)	*Rwanda (RCSA programme).* improving climate services and agricultural risk management at local and national government levels in the face of a variable and changing climate
Mismatch in timescales: short-term information more desirable, e.g., seasonal predictions as opposed to decadal or end of century projections.	• Co-production of CS climate service products	(Jones et al., 2015; Vincent et al., 2018; Hansen et al., 2019a; Carr et al., 2020; Sultan et al., 2020)	*Burkina Faso (BRACED project).* Strengthening technical and communication capacities of national meteorological services to enable partners to jointly develop forecasts tailored to support agro-pastoralists.
Development funding interventions operate on timescales that inhibit or restrict effective adaptation and neglect to build in considerations for sustainability post the funded intervention.	• Co-production of climate service CS products • Endogenously driven climate services (services that are developed by regional actors, not by remote, usually developed nation actors)	(Vincent et al., 2018; Vogel et al., 2019) (Vincent et al., 2020a)	*Burkina Faso (BRACED project).* Actors recognised the need to ensure continuation of climate services post-project. Burkina Faso NMHS (ANAM) and National Council for Emergency Assistance and Rehabilitation (CONASUR) budgeted for the continued communication of climate services and training of focal weather intermediaries. Local radio stations agreed to continue transmitting climate services.
Use of climate services			
Insufficient access to usable data, including station data, and information suited to the decision context (including accessibility limitations based on gender and social inequalities)	• Capacity development initiatives for CS providers, intermediaries (including extension agents, NGO workers and others) and users • User needs assessments • Consistent monitoring and evaluation of climate services interventions	(Jones et al., 2015; Winrock, 2018; Hansen et al., 2019a; Hansen et al., 2019c; Mercy Corps, 2019; Nkiaka et al., 2019; Carr et al., 2020; Cullmann et al., 2020; Gumucio et al., 2020; Sultan et al., 2020) (Figure 9.11)	*Kenya, Ethiopia, Ghana, Niger and Malawi (ALP Programme).* Co-production of relevant information for decision-making and planning at seasonal time scales. The methods and media for communication and messages differ between different users. Strong emphasis on participation by women.
Limited capacity of users to understand or request appropriate CS products	• Co-production of climate service products • Capacity development	(Snow et al., 2016; Singh et al., 2018; Vincent et al., 2018; Nkiaka et al., 2019; Daniels et al., 2020)	*Cities in Zambia, Namibia, Mozambique, Zimbabwe, Botswana, Malawi and South Africa (FRACTAL programme).* Repeated interactions between each represented sector to learn and more completely understand the different contexts of each represented party and build understanding through an ethic of collaboration for solving climate-related problems in each unique city.

Lack of user trust in the information	• Co-production of climate service products • Combine scientific and indigenous forecasts • Demonstrate added value of the climate service	(Vincent et al., 2018; Nkiaka et al., 2019; Vaughan et al., 2019; Vogel et al., 2019; Nyadzi et al., 2021)	*Tanzania (ENACTS programme).* Co-production to inform malaria decisions systematically and change relationships, trust, and demand in a manner that had not been realised through previous singular and siloed approaches.
Socio-economic, and institutional barriers (limited professional mandates, financing limitations, institutional cooperation)	• Regular NMHS budgets from governments • Public-private partnerships • Supportive institutions, policy frameworks and individual capacity and agency	(Snow et al., 2016; World Bank Group, 2016; Winrock, 2018; Harvey et al., 2019; Vincent et al., 2020b)	

However, the effectiveness of co-production processes are hindered by aspects such as inequitable power relationships between different types of knowledge holders (e.g., scientists and practitioners), inequitable distribution of funding between developed country versus African partners that favours developed country partners, an inability to develop sustained trust relationships as a result of short-funding cycles, a lack of flexibility due to product-focused engagements and the scalability of co-production to enable widespread reach across Africa as the process is usually context-specific (*high confidence*) (Vincent et al., 2018; Vogel et al., 2019; Vincent et al., 2020a).

Despite these challenges, the inclusive nature of co-production has had a positive influence on the uptake of climate services into decision-making where it has been applied (Vincent et al., 2018; Vogel et al., 2019; Carter et al., 2020; Chiputwa et al., 2020) (Table 9.4; Figure 9.12) (*medium confidence*), through sustained inter/transdisciplinary relationships and capacity development (Norström et al., 2020), strategic financial investment (Section 9.13.4.1), fostering of ownership of resulting products and the combining of scientific and other knowledge systems (Carter et al., 2020; Steynor et al., 2020a). There is *high confidence* that together with improved institutional capacity building and strategic financial investment, climate services can help African stakeholders adapt to projected climate risks (Section 9.13.4.1; Figure 9.11).

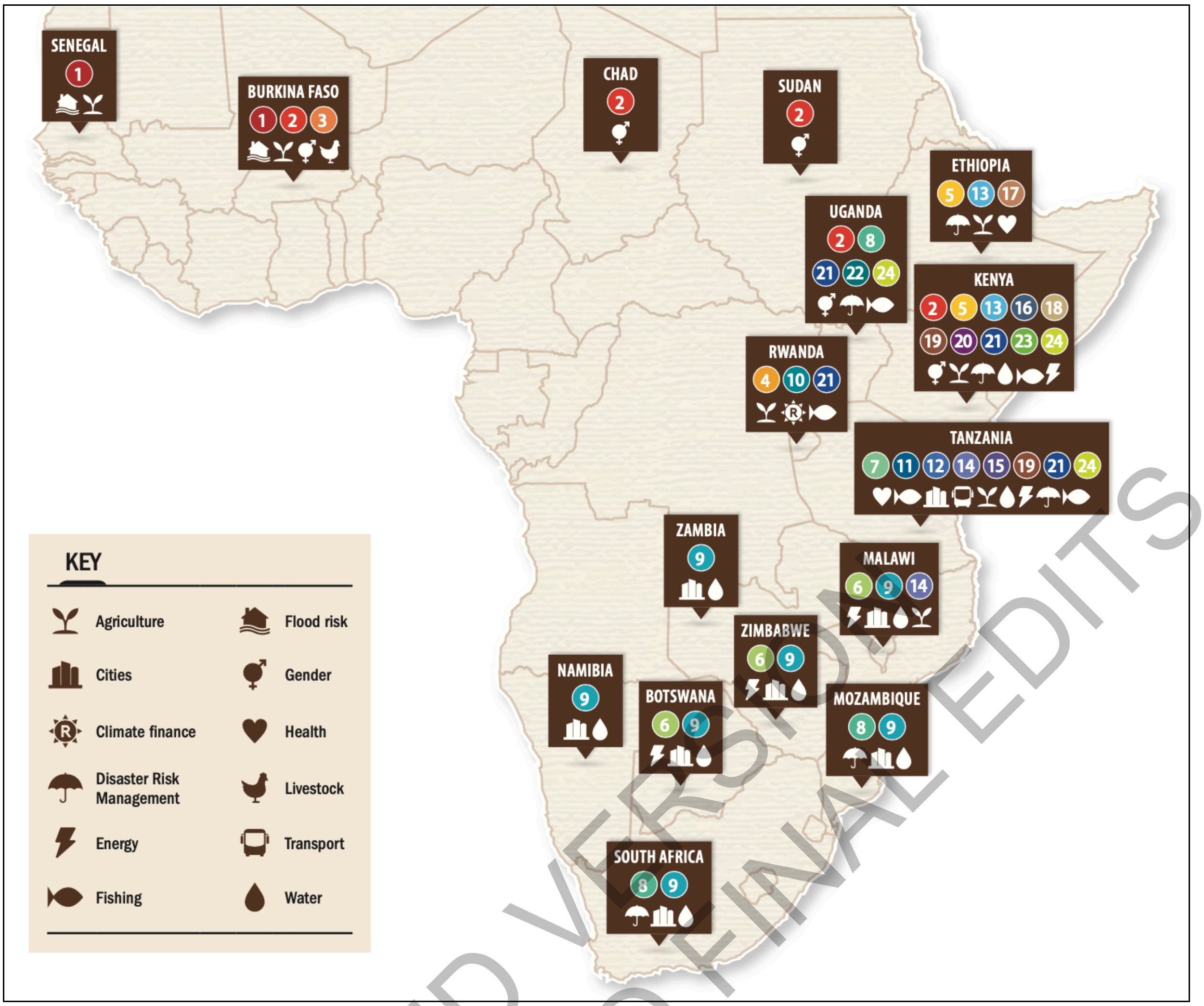


Figure 9.12: Case studies of co-production programmes, the countries they occurred in, sectors involved (icons – see key) and programmes under which the engagements occurred (numbers). Programmes listed are (1) AMMA-2050, (2,3) BRACED, (4) RCSA, (5) ALP, (6) Climate Risk Narratives, (7) ENACTS, (8) FATHUM, (9) FRACTAL, (10) FONERWA, (11) MHEWS, (12) Resilient Transport Strategic Assessment , (13) RRA, (14) UMFULA, (15) IRRP, (16) PRISE, (17) NMA ENACTS, (18) REACH, (19) DARAJA, (20) ForPAc, (21) HIWAY, (22) HyCRYSTAL, (23) SCIPEA, (24) Weather Wise. See Carter et al. (2020) for details and outcomes of each engagement. Source (Carter et al., 2020).

9.4.5.2 Community Perceptions of Climate Variability and Change

Perceptions of climate variability and change affect whether and how individuals and institutions act, and thus contribute to the success or failure of adaptation policies related to weather and climate (Silvestri et al., 2012; Arbuckle et al., 2015; Simpson et al., 2021a).

A recent Afrobarometer study covering 34 African countries found 67% of Africans perceive climate conditions for agricultural production to have worsened over time, and report drought as the main extreme weather event to have worsened in the past decade (Selormey et al., 2019). Of these participants, across all socioeconomic strata, 71% of those who were aware of the concept of climate change agreed that it needs to be stopped, but only 51% expressed confidence about their ability to make a difference. East Africans (63%) were almost twice as likely as North Africans (35%) to report that the weather for growing crops had worsened. Additionally, people engaged in occupations related to agriculture (farming, fishing or forestry) were more likely to report negative weather effects (59%) than those with other livelihoods (45%) (Selormey et al., 2019). Similar perceptions have been reported among a diversity of rural communities in many sub-Saharan African countries (Asiyanbi, 2015; Mahl et al., 2020; Simpson et al., 2021a).

Rural communities, particularly farmers, have been the most studied groups for climate change perception. They perceive the climate to be changing, most often reporting changes in rainfall variability, increased dry spells, decreases in rainfall and increased temperatures or temperature extremes, and perceive these changes to bring a range of negative socioeconomic and environmental effects (Alemayehu and Bewket, 2017; Liverpool-Tasie et al., 2020; Simpson et al., 2021a). In some cases, farmers' perceptions of changes in weather and climate frequently match climate records for decreased precipitation totals, increased drought frequency, shorter rainy season and rainy season delay and increased temperatures (Rurinda et al., 2014; Boansi et al., 2017; Ayanlade et al., 2018) (Figure 9.11), but not in all cases or not for all perceived changes, with common discrepancies in perceived lower rainfall totals (Alemayehu and Bewket, 2017; Ayal and Leal Filho, 2017; Simpson et al., 2021a).

Farming experience, access to extension services and increasing age are the most frequently cited factors positively influencing the perceptions of climate changes (Alemayehu and Bewket, 2017; Oduniyi and Tekana, 2019). Personal experience of climate-related changes and their impacts appears to be an important factor influencing perceptions through shaping negative associations, for example, experience of flash floods (Elshirbiny and Abrahamse, 2020) or direct effect on economic activity, indicating that perception is not restricted to crop farmers (Liverpool-Tasie et al., 2020). However, perception commonly has misconceptions about the causes of climate change which has implications for climate action (Elshirbiny and Abrahamse, 2020), highlighting the importance of climate change literacy.

9.4.5.3 Climate Change Literacy

Understanding the human cause of climate change has been shown to be a strong predictor of climate change risk perception (Lee et al., 2015) and a critical knowledge foundation that can affect the difference between coping responses and more informed and transformative adaptation (Oladipo, 2015; Mutandwa et al., 2019) (Figure 9.11). At a minimum, climate change literacy includes both having heard of climate change and understanding it is, at least in part, caused by people (Simpson et al., 2021a). However, large inequalities in climate change literacy exist between and within countries and communities across Africa.

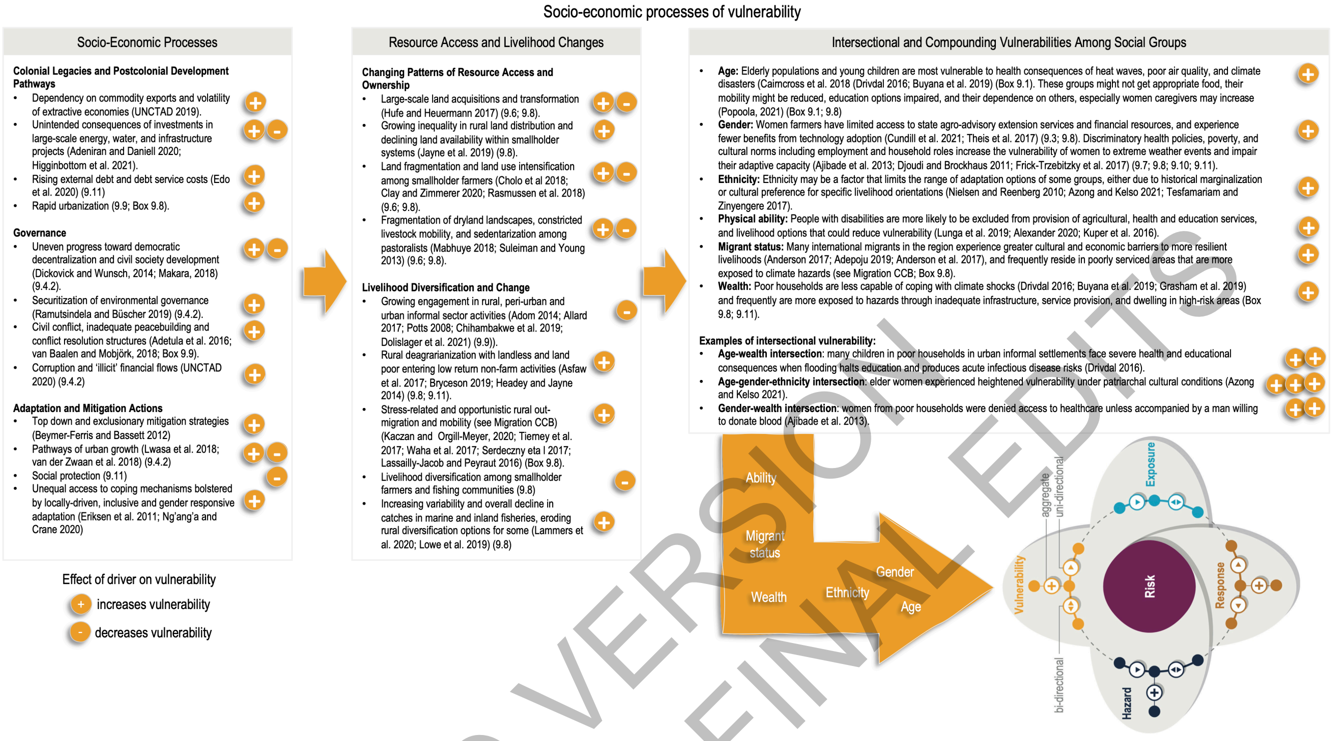
The average national climate change literacy rate in Africa is only 39% (country rates range from 23-66%) (Figure 9.11). Of 394 sub-national regions surveyed by Afrobarometer, 8% (37 regions in 16 countries) have a climate change literacy rate lower than 20%, while only 2% (8 regions) score higher than 80% which is common across European countries (Simpson et al., 2021a). Striking differences exist when comparing sub-national units within countries. Climate change literacy rates in Nigeria range from 71% in Kwara to 5% in Kano, and within Botswana from 69% in Lobatse to only 6% in Kweneng West (Simpson et al., 2021a). Education is the strongest positive predictor of climate change literacy, particularly tertiary education, but poverty decreases climate change literacy and climate change literacy rates average 12.8% lower for women than men (Simpson et al., 2021a).

As the identified drivers of climate change literacy overlap with broader developmental challenges on the continent, policies targeting these predictors can potentially yield co-benefits for both climate change adaptation as well as progress towards SDGs, particularly education and gender equality (Simpson et al., 2021a). Progress towards greater climate change literacy affords a concrete opportunity to mainstream climate change within core national and sub-national developmental agendas in Africa towards more climate-resilient development pathways. Synergies with climate services can also overcome gendered deficits, for example, although women are generally less climate change aware and more vulnerable to climate change than men in Africa, they are generally more likely to adopt climate-resilient crops when they are climate change aware and have exposure to extension services (Acevedo et al., 2020; Simpson et al., 2021a).

[START BOX 9.1 HERE]

Box 9.1: Vulnerability Synthesis

Vulnerability in Africa is socially, culturally and geographically differentiated among climatic regions, countries and local communities, with climate change impacting the health, livelihoods and food security of different groups to different extents (Gan et al., 2016; Onyango et al., 2016a; Gumucio et al., 2020). This synthesis emphasises intersectional diversity within vulnerable groups as well as their position within dynamic social and cultural contexts (Wisner, 2016; Kuran et al., 2020), and highlights the differential impacts of climate change and restricted adaptation options available to vulnerable groups across African countries (see also Cross-Chapter Box GENDER in Chapter 18).



Socio-economic processes of vulnerability

Socio-Economic Processes

Colonial Legacies and Postcolonial Development Pathways
- Dependency on commodity exports and volatility of extractive economies (UNCTAD 2019). +
- Unintended consequences of investments in large-scale energy, water, and infrastructure projects (Adeniran and Daniell 2020; Higginbottom et al. 2021). + -
- Rising external debt and debt service costs (Edo et al. 2020) (9.11) +
- Rapid urbanization (9.9; Box 9.8). +

Governance
- Uneven progress toward democratic decentralization and civil society development (Dickovick and Wunsch, 2014; Makara, 2018) (9.4.2). + -
- Securitization of environmental governance (Ramutsindela and Büscher 2019) (9.4.2). +
- Civil conflict, inadequate peacebuilding and conflict resolution structures (Adetula et al. 2016; van Baalen and Mobjörk, 2018; Box 9.9). +
- Corruption and 'illicit' financial flows (UNCTAD 2020) (9.4.2) +

Adaptation and Mitigation Actions
- Top down and exclusionary mitigation strategies (Beymer-Ferris and Bassett 2012) +
- Pathways of urban growth (Lwasa et al. 2018; van der Zwaan et al. 2018) (9.4.2) + -
- Social protection (9.11) -
- Unequal access to coping mechanisms bolstered by locally-driven, inclusive and gender responsive adaptation (Eriksen et al. 2011; Ng'ang'a and Crane 2020) +

Resource Access and Livelihood Changes

Changing Patterns of Resource Access and Ownership
- Large-scale land acquisitions and transformation (Hufe and Heuermann 2017) (9.6; 9.8). + -
- Growing inequality in rural land distribution and declining land availability within smallholder systems (Jayne et al. 2019) (9.8). +
- Land fragmentation and land use intensification among smallholder farmers (Cholo et al 2018; Clay and Zimmerer 2020; Rasmussen et al. 2018) (9.6; 9.8). + -
- Fragmentation of dryland landscapes, constricted livestock mobility, and sedentarization among pastoralists (Mabhuye 2018; Suleiman and Young 2013) (9.6; 9.8). + -

Livelihood Diversification and Change
- Growing engagement in rural, peri-urban and urban informal sector activities (Adom 2014; Allard 2017; Potts 2008; Chihambakwe et al. 2019; Dolislager et al. 2021) (9.9)). -
- Rural deagrarianization with landless and land poor entering low return non-farm activities (Asfaw et al. 2017; Bryceson 2019; Headey and Jayne 2014) (9.8; 9.11). +
- Stress-related and opportunistic rural out-migration and mobility (see Migration CCB) (Kaczan and Orgill-Meyer, 2020; Tierney et al. 2017; Waha et al. 2017; Serdeczny eta l 2017; Lassailly-Jacob and Peyraut 2016) (Box 9.8). +
- Livelihood diversification among smallholder farmers and fishing communities (9.8) -
- Increasing variability and overall decline in catches in marine and inland fisheries, eroding rural diversification options for some (Lammers et al. 2020; Lowe et al. 2019) (9.8) +

Intersectional and Compounding Vulnerabilities Among Social Groups

- **Age:** Elderly populations and young children are most vulnerable to health consequences of heat waves, poor air quality, and climate disasters (Cairncross et al. 2018 (Drivdal 2016; Buyana et al. 2019) (Box 9.1). These groups might not get appropriate food, their mobility might be reduced, education options impaired, and their dependence on others, especially women caregivers may increase (Popoola, 2021) (Box 9.1; 9.8) +
- **Gender:** Women farmers have limited access to state agro-advisory extension services and financial resources, and experience fewer benefits from technology adoption (Cundill et al. 2021; Theis et al. 2017) (9.3; 9.8). Discriminatory health policies, poverty, and cultural norms including employment and household roles increase the vulnerability of women to extreme weather events and impair their adaptive capacity (Ajibade et al. 2013; Djoudi and Brockhaus 2011; Frick-Trzebitzky et al. 2017) (9.7; 9.8; 9.10; 9.11). +
- **Ethnicity:** Ethnicity may be a factor that limits the range of adaptation options of some groups, either due to historical marginalization or cultural preference for specific livelihood orientations (Nielsen and Reenberg 2010; Azong and Kelso 2021; Tesfamariam and Zinyengere 2017). +
- **Physical ability:** People with disabilities are more likely to be excluded from provision of agricultural, health and education services, and livelihood options that could reduce vulnerability (Lunga et al. 2019; Alexander 2020; Kuper et al. 2016). +
- **Migrant status:** Many international migrants in the region experience greater cultural and economic barriers to more resilient livelihoods (Anderson 2017; Adepoju 2019; Anderson et al. 2017), and frequently reside in poorly serviced areas that are more exposed to climate hazards (see Migration CCB; Box 9.8). +
- **Wealth:** Poor households are less capable of coping with climate shocks (Drivdal 2016; Buyana et al. 2019; Grasham et al. 2019) and frequently are more exposed to hazards through inadequate infrastructure, service provision, and dwelling in high-risk areas (Box 9.8; 9.11). +

Examples of intersectional vulnerability:
- **Age-wealth intersection**: many children in poor households in urban informal settlements face severe health and educational consequences when flooding halts education and produces acute infectious disease risks (Drivdal 2016). + +
- **Age-gender-ethnicity intersection**: elder women experienced heightened vulnerability under patriarchal cultural conditions (Azong and Kelso 2021). + + +
- **Gender-wealth intersection**: women from poor households were denied access to healthcare unless accompanied by a man willing to donate blood (Ajibade et al. 2013). + +

Effect of driver on vulnerability

+ increases vulnerability

- decreases vulnerability

Figure Box 9.1.1: Factors contributing to the progression of vulnerability in African contexts considering their socioeconomic processes, resource access and livelihood changes, and intersectional vulnerability among social groups. Figure reflects a synthesis of vulnerability across sections of this chapter and highlights the compounding interactions of multiple dimensions of vulnerability (Potts, 2008; Nielsen and Reenberg, 2010; Akresh et al., 2011; Eriksen et al., 2011; Beymer-Farris and Bassett, 2012; Davis et al., 2012; Adom, 2014; Akello, 2014; Dickovick, 2014; Headey and Jayne, 2014; Otzelberger, 2014; Conteh, 2015; Huntjens and Nachbar, 2015; Spencer, 2015; Adetula et al., 2016; Djoudi et al., 2016; Kuper et al., 2016; Stark and Landis, 2016; Allard, 2017; Anderson, 2017; Asfaw et al., 2017; Hufe and Heuermann, 2017; Hulme, 2017; Paul and wa Gĩthĩnji, 2017; Rao et al., 2017; Serdeczny et al., 2017; Tesfamariam and Zinyengere, 2017; Tierney et al., 2017; Waha et al., 2017; Chihambakwe et al., 2018; Cholo et al., 2018; Jenkins et al., 2018; Keahey, 2018; Lwasa et al., 2018; Makara, 2018; Nyasimi et al., 2018; Petesch et al., 2018; Schuman et al., 2018; Theis et al., 2018; van Baalen and Mobjörk, 2018; van der Zwaan et al., 2018; Adepoju, 2019; Adzawla et al., 2019b; Bryceson, 2019; Grasham et al., 2019; Jayne et al., 2019a; Lowe et al., 2019; Lunga et al., 2019; OGAR and Bassey, 2019; Onwutuebe, 2019; Ramutsindela and Büscher, 2019; Sulieman and Young, 2019; Torabi and Noori, 2019; Adeniran and Daniell, 2020; Alexander, 2020; Clay and Zimmerer, 2020; Devonald et al., 2020; Dolislager et al., 2020; Edo et al., 2020; Kaczan and Orgill-Meyer, 2020; Lammers et al., 2020; World Bank, 2020b; Asiama et al., 2021; Azong and Kelso, 2021; Birgen, 2021; Paalo and Issifu, 2021).

Vulnerability and exposure to the impacts of climate change are complex and affected by multiple, interacting non-climatic processes, which together influence risk including socioeconomic processes (Lwasa et al., 2018; UNCTAD, 2020), resource access and livelihood changes (Jayne et al., 2019b), and intersectional vulnerability among social groups (Rao et al., 2020) (Figure Box 9.1.1). Socioeconomic processes encompass broader social, economic and governance trends, such as expanded investment in large energy and transportation infrastructure projects (Adeniran and Daniell, 2020), rising external debt (Edo et al., 2020), changing role of the state in social development (Dickovick, 2014), environmental management (Ramutsindela and Büscher, 2019) and conflict, as well as those emanating from climate change mitigation and adaptation projects (Beymer-Farris and Bassett, 2012; van Baalen and Mobjörk, 2018; Simpson et al., 2021b). These macro trends shape both urban and rural livelihoods, including the growing diversification of rural livelihoods through engagement in the informal sector and other non-farm activities, and are mediated by complex and intersecting factors like gender, ethnicity, class, age, disability and other dimensions of social status that influence access to resources (Luo et al., 2019). Research increasingly highlights the intersectionality of multiple dimensions of social identity and status that are associated with greater susceptibility to loss and harm (Caparoci Nogueira et al., 2018; Li et al., 2018).

Arid and semi-arid countries in the Sahelian belt and the greater Horn of Africa are often identified as the most vulnerable regions on the continent (Closset et al., 2017; Serdeczny et al., 2017). Particularly vulnerable groups include pastoralists (Wangui, 2018; Ayanlade and Ojebisi, 2019), fishing communities (Belhabib et al., 2016; Muringai et al., 2019a), small-scale farmers (Ayanlade et al., 2017; Mogomotsi et al., 2020) (see Section 9.8.1) and residents of formal and informal urban settlements (see Section 9.9.2). Research has identified key macro drivers as well as the multiple dimensions of social status that mediate differential vulnerability in different African contexts. For example, the contemporary vulnerability of small-scale rural producers in semi-arid northern Ghana has been shaped by colonial economic transformations (Ahmed et al., 2016), more recent neoliberal reforms reducing state support (Fieldman, 2011) and the disruption of local food systems due to increasing grain imports (Nyantakyi-Frimpong and Bezner-Kerr, 2015). Age interacts with other dimensions of social status, shaping differential vulnerability in several ways. Projected increases in mean temperatures and longer and more intense heat waves (Figure Box 9.1.1) may increase health risks for children and elderly populations by increasing risks associated with heat stress (Bangira et al., 2015; Cairncross et al., 2018). Temperature extremes are associated with increased risk of mortality in Ghana, Burkina Faso, Kenya and South Africa, with greatest increases among children and the elderly (Bangira et al., 2015; Amegah et al., 2016; Omonijo, 2017; Wiru et al., 2019) (see Section 9.10.2.3.1).

Rural African women are often disadvantaged by traditional, patriarchal decision-making processes and lack of access to land – issues compounded by kinship systems (that, is matrilineal or patrilineal), migrant status, age, type of household, livelihood orientation and disability in determining their adaptive options (Ahmed et al., 2016) (sees Section 9.8.1 and 9.11.1.2; Box 9.8). Differential agricultural productivity between men and women is about 20–30% or more in dryland regions of Ethiopia and Nigeria (Ghanem, 2011) and challenges women's ability to adapt to climate change. Limited access to agricultural resources and limited benefits from agricultural policies, compounded by other social and cultural factors, make women more vulnerable to climatic risks (Shukla et al., 2021). Kinship systems can contribute to their vulnerability and capacity to adapt. Women in matrilineal systems have greater bargaining power and have access to more resources than those in patrilineal systems (Chigbu, 2019; Robinson and Gottlieb, 2021) (see Sections 9.8.1 and 9.11.1.2).

Knowledge Gaps and Recommendations

The differential impacts of climate change on and adaptation options available to vulnerable groups in Africa are a critical knowledge gap. More research is needed to examine the intersection of different dimensions of social status on climate change vulnerability in Africa (Thompson-Hall et al., 2016; Oluwatimilehin and Ayanlade, 2021). More analysis of vulnerability based on gender and other social and cultural factors is needed to fully understand the impacts of climate change, the interaction of divergent adaptive strategies, as well as the development of targeted adaptation and mitigation strategies, for example, for women in patrilineal kinship systems, people living with disabilities, youth, girls and the elderly. Finally, there is an urgent need to build capacity among those conducting vulnerability assessments, so that they are familiar with this intersectionality lens.

Additional information and capacity development through education and early warning systems could enhance vulnerable groups' ability to cope and adapt their livelihoods (Jaka and Shava, 2018). However, some groups of people may struggle to translate information into actual changes (Makate et al., 2019; McOmber et al., 2019). Lack of access to assets and social networks, for example, among older populations, are critical limitations to locally-driven or autonomous adaptation and limit potential benefits from planned adaptation actions (e.g., adoption of agricultural technologies or effective use of early warning systems). There is an urgent need for societal and political change to realise potential benefits for these vulnerable groups in the long term (Nyasimi et al., 2018). There is a need for gender-sensitive climate change policies in many African countries and gender-responsive policies, implementation plans and budgets for all local-level initiatives (Wrigley-Asante et al., 2019).

[END BOX 9.1 HERE]

9.5 Observed and Projected Climate Change

This section assesses observed and projected climate change over Africa. In Working Group I of the IPCC AR6 (WGI), four chapters make regional assessments of observed and projected climate change (Doblas-Reyes et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021), which facilitates a more nuanced assessment in this section of climate and ocean phenomena that impact African systems.

9.5.1 Climate Hazards in Africa

Human-caused temperature increases are detected across Africa and many regions have warmed more rapidly than the global average (Figure 9.13a) (Ranasinghe et al., 2021) and a signal of increased annual heatwave frequency has already emerged from the background natural variability over the whole continent (Engdaw et al., 2021) (Figure 9.14). However, detection of statistically significant rainfall trends is evident in only a few regions (Figure 9.13b), and in some regions different observed precipitation datasets disagree on the direction of rainfall trends (Panitz et al., 2013; Sylla et al., 2013; Contractor et al., 2020). The uncertainty of observed rainfall trends results from a number of sources, including high interannual and decadal rainfall variability, different methodologies used in developing rainfall products and a lack of and poor quality of rainfall station data (Figure 9.15) (Gutiérrez et al., 2021).

With increased greenhouse gas emissions, mean temperature is projected to increase over the whole continent, as are temperature extremes over most of the continent (Figure 9.16a,b). Increased mean annual rainfall is projected over the eastern Sahel, eastern East Africa and Central Africa (Figures 9.16c and 9.14). In contrast, reduced mean annual rainfall and increased drought (meteorological and agricultural) are projected over southwestern Southern Africa and coastal North Africa, with drought in part as a result of increasing atmospheric evaporative demand due to higher temperatures (Figure 9.16e) (Ukkola et al., 2020; Ranasinghe et al., 2021; Seneviratne et al., 2021). The frequency and intensity of heavy precipitation are projected to increase across most of Africa, except northern and southwestern Africa (Figures 9.16d and 9.14).

Most African countries are expected to experience high temperatures unprecedented in their recent history earlier in this century than generally wealthier, higher latitude countries (*high confidence*). As low latitudes have lower internal climate variability (e.g. low seasonality), low-latitude African countries are projected to have their populations exposed to large increases in frequency of daily temperature extremes (hotter than 99.9% of their historical records) earlier in the 21st century compared to generally wealthier nations at higher latitudes (Harrington et al., 2016; Chen et al., 2021; Doblas-Reyes et al., 2021; Gutiérrez et al., 2021). Although higher warming rates are projected over high latitudes during the first half of this century, societies and environments in low-latitude, low-income countries are projected to become exposed to unprecedented climates before those in high latitude, developed countries (Frame et al., 2017; Harrington et al., 2017; Gutiérrez et al., 2021). For example, beyond 2050, in Central Africa and coastal West Africa 10 months of every year will be hotter than any month in the period 1950–2000 under a high emissions scenario (RCP8.5) (Harrington et al., 2017; Gutiérrez et al., 2021). Ambitious, near-term mitigation will provide the largest reductions in exposure to unprecedented high temperatures for populations in low-latitude regions, such as across tropical Africa (Harrington et al., 2016; Frame et al., 2017).

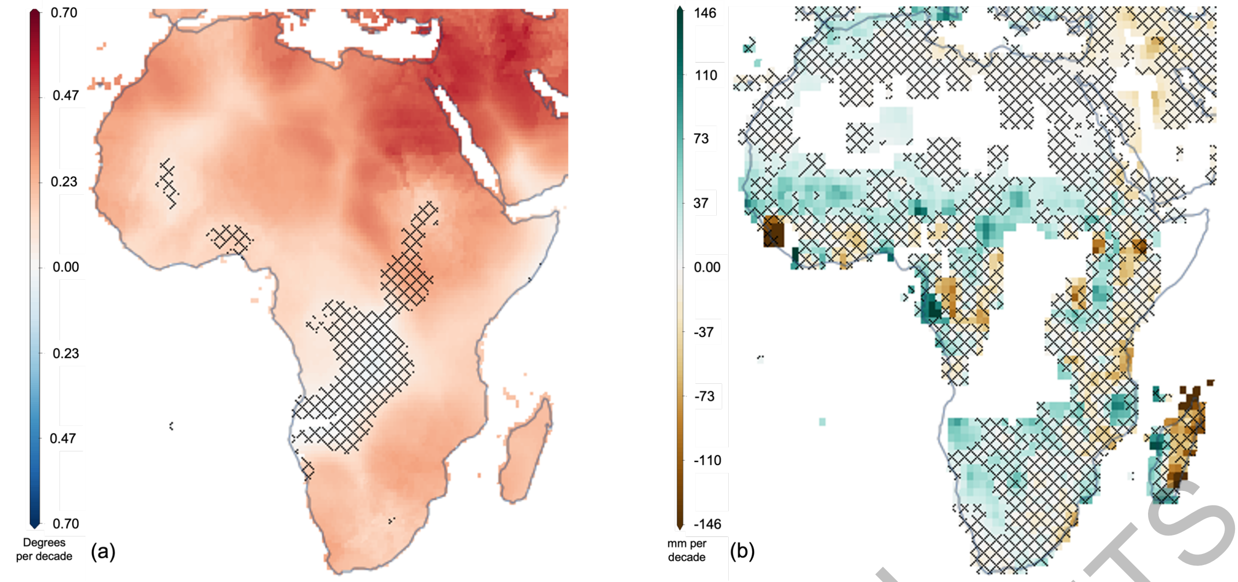
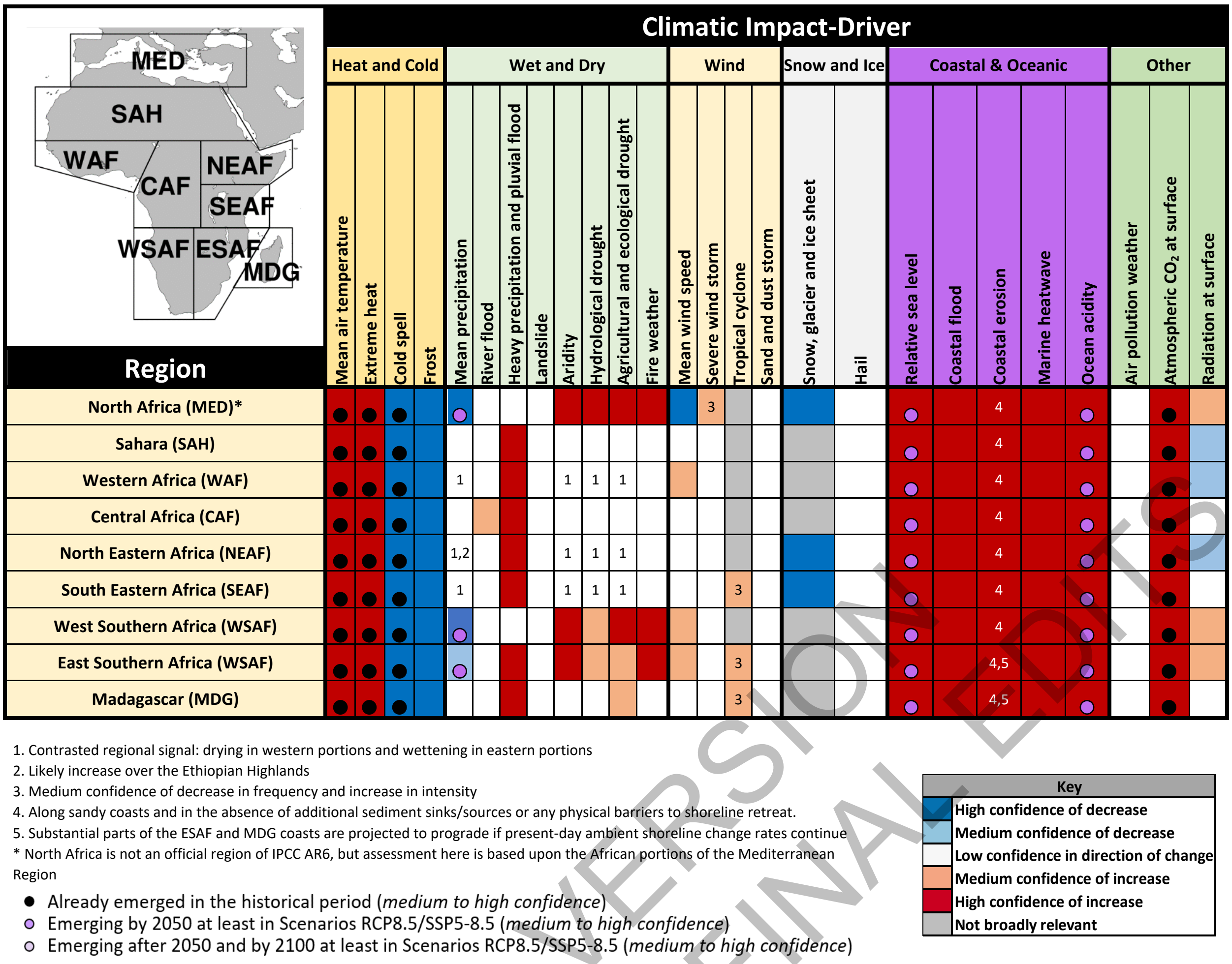


Figure 9.13: Mean observed trends calculated for the common 1980-2015 period in (a) 2-meter temperature in degrees Celsius per decade and (b) precipitation in millimetres per decade with respect to the climatological mean over this period. The Climate Research Unit Time Series data (CRU TS) are used to compute temperature trends and the Global Precipitation Climatology Centre data (GPCC) precipitation trends. Regions with no 'x' hatching indicate statistically significant trends over this period. The figures are derived from (Gutiérrez et al., 2021).

9.5.1.1 Station Data Limitations

Sustained station observation networks (Figure 9.15) are essential for the long-term analysis of local and regional climate trends, including for temperature and rainfall, the calibration of satellite-derived climate products, development of gridded climate datasets using interpolated and blended station-satellite products that form the baseline from which climate change departures are measured, development and running of early warning systems, climate projection and impact studies and extreme event attribution studies (Harrison et al., 2019; Otto et al., 2020). However, production of salient climate information in Africa is hindered by limited availability of and access to weather and climate data, especially in Central and North Africa (Figure 9.15) (Coulibaly et al., 2017; Hansen et al., 2019a). Existing weather infrastructure remains suboptimal for development of reliable early warning systems (Africa Adaptation Initiative, 2018; Krell et al., 2021). For example, it is estimated only 10% of ground-based observation networks are in Africa, and that 54% of Africa's surface weather stations cannot capture data accurately (Africa Adaptation Initiative, 2018; World Bank, 2020d). Some programmes are trying to address this issue, including the trans-African hydro-meteorological observatory (van de Giesen et al., 2014), the West African Science Service Centre on Climate Change and Adaptive Land Management (WASCAL) (Salack et al., 2019), the Southern African Science Service Centre for Climate Change, Adaptive Land Management (SASSCAL) (Kaspar et al., 2015) and AMMA-CATCH (Galle et al., 2018). However, the sustainability of observation networks beyond the life of these programmes is uncertain as many African National Meteorological and Hydrology Services experience structural, financial and technical barriers to maintaining these systems (Section 9.4.5).



Climatic Impact-Driver

Region	Heat and Cold				Wet and Dry								Wind				Snow and Ice		Coastal & Oceanic					Other		
	Mean air temperature	Extreme heat	Cold spell	Frost	Mean precipitation	River flood	Heavy precipitation and pluvial flood	Landslide	Aridity	Hydrological drought	Agricultural and ecological drought	Fire weather	Mean wind speed	Severe wind storm	Tropical cyclone	Sand and dust storm	Snow, glacier and ice sheet	Hail	Relative sea level	Coastal flood	Coastal erosion	Marine heatwave	Ocean acidity	Air pollution weather	Atmospheric CO_2 at surface	Radiation at surface
North Africa (MED)*	🟥 ●	🟥 ●	🟦 ●	🟦	🟦 🟣	⬜	⬜	⬜	🟥	🟥	🟥	🟥	🟦	🟧 3	▒	⬜	🟦	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	🟧
Sahara (SAH)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒	⬜	▒	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	🔷
Western Africa (WAF)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜ 1	⬜	🟥	⬜	⬜ 1	⬜ 1	⬜ 1	⬜	🟧	⬜	▒	⬜	▒	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	🔷
Central Africa (CAF)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜	🟧	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒	⬜	▒	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	⬜
North Eastern Africa (NEAF)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜ 1,2	⬜	🟥	⬜	⬜ 1	⬜ 1	⬜ 1	⬜	⬜	⬜	▒	⬜	🟦	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	🔷
South Eastern Africa (SEAF)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜ 1	⬜	🟥	⬜	⬜ 1	⬜ 1	⬜ 1	⬜	⬜	⬜	🟧 3	⬜	🟦	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	⬜
West Southern Africa (WSAF)	🟥 ●	🟥 ●	🟦 ●	🟦	🟦 🟣	⬜	⬜	⬜	🟥	🟧	🟥	🟥	🟧	⬜	▒	⬜	▒	⬜	🟥 🟣	🟥	🟥 4	🟥	🟥 🟣	⬜	🟥 ●	🟧
East Southern Africa (WSAF)	🟥 ●	🟥 ●	🟦 ●	🟦	🔷 🟣	⬜	🟥	⬜	🟥	🟧	🟧	🟥	🟧	⬜	🟧 3	⬜	▒	⬜	🟥 🟣	🟥	🟥 4,5	🟥	🟥 🟣	⬜	🟥 ●	🟧
Madagascar (MDG)	🟥 ●	🟥 ●	🟦 ●	🟦	⬜	⬜	🟥	⬜	⬜	⬜	🟧	⬜	⬜	⬜	🟧 3	⬜	▒	⬜	🟥 🟣	🟥	🟥 4,5	🟥	🟥 🟣	⬜	🟥 ●	⬜

1. Contrasted regional signal: drying in western portions and wettening in eastern portions
2. Likely increase over the Ethiopian Highlands
3. Medium confidence of decrease in frequency and increase in intensity
4. Along sandy coasts and in the absence of additional sediment sinks/sources or any physical barriers to shoreline retreat.
5. Substantial parts of the ESAF and MDG coasts are projected to prograde if present-day ambient shoreline change rates continue

* North Africa is not an official region of IPCC AR6, but assessment here is based upon the African portions of the Mediterranean Region

● Already emerged in the historical period (*medium to high confidence*)
🟣 Emerging by 2050 at least in Scenarios RCP8.5/SSP5-8.5 (*medium to high confidence*)
○ Emerging after 2050 and by 2100 at least in Scenarios RCP8.5/SSP5-8.5 (*medium to high confidence*)

Key	
🟦	High confidence of decrease
🔷	Medium confidence of decrease
⬜	Low confidence in direction of change
🟧	Medium confidence of increase
🟥	High confidence of increase
▒	Not broadly relevant

Figure 9.14: Summary of confidence in direction of projected change in climatic impact-drivers (CIDs) in Africa, representing their aggregate characteristic changes for mid-century for medium emission scenarios RCP4.5, SSP3–4.5, SRES A1B, or higher emissions scenarios (e.g., RCP8.5, SSP5–RCP8.5), within each AR6 WGI region (inset map) approximately corresponding to global warming levels between 2°C and 2.4°C (for CIDs that are independent of sea-level rise). CIDs are drivers of impacts that are of climatic origin (that is, physical climate system conditions including means and extremes) that affect an element of society or ecosystems. The table also includes the assessment of observed or projected time-of-emergence of the CID change signal from the natural inter-annual variability if found with at least *medium confidence* (dots). Emergence of a climate change signal or trend refers to when a change in climate (the 'signal') becomes larger than the amplitude of natural or internal variations (the 'noise'). The figure is a modified version of Table 12.3 in Chapter 12 (Ranasinghe et al., 2021), please see this chapter for definitions of the various climate impact drivers and the basis for confidence levels of the assessment. Please note these WGI regions do not directly correspond to the regionalisation in this chapter nor do we assess climate risks for Madagascar.

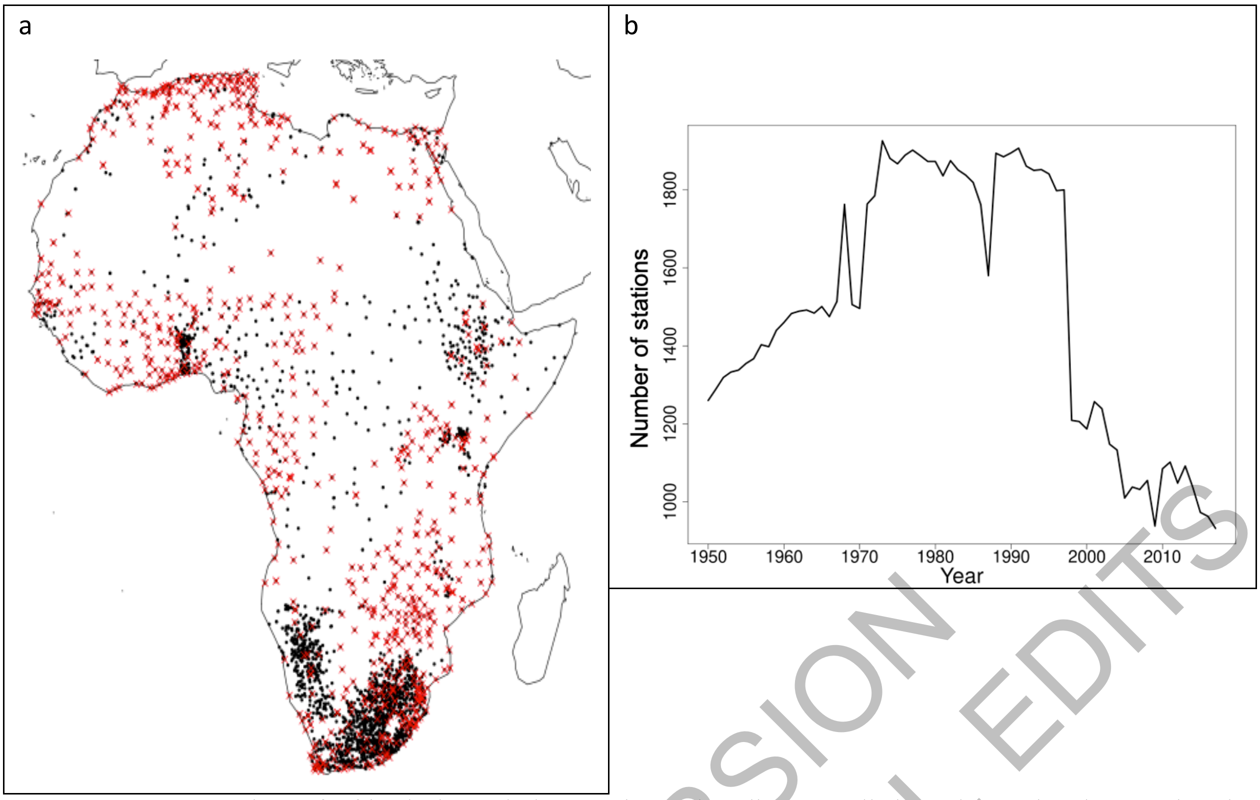


Figure 9.15: Large regions of Africa lack regularly reporting and quality-controlled weather station data. Stations in Africa with quality-controlled station data used in developing the Rainfall Estimates on a Gridded Network (REGEN) interpolated rainfall product (Harrison et al., 2019). Panel (a) provides a spatial representation of stations across the continent since 1950 as black dots and red crosses, where red crosses represent stations that were still active in 2017. Panel (b) demonstrates the decline in operational stations or stations with quality-controlled data since *circa* 1998, which is largely a function of declining networks in a subset of countries. Figure is derived from (Contractor et al., 2020).

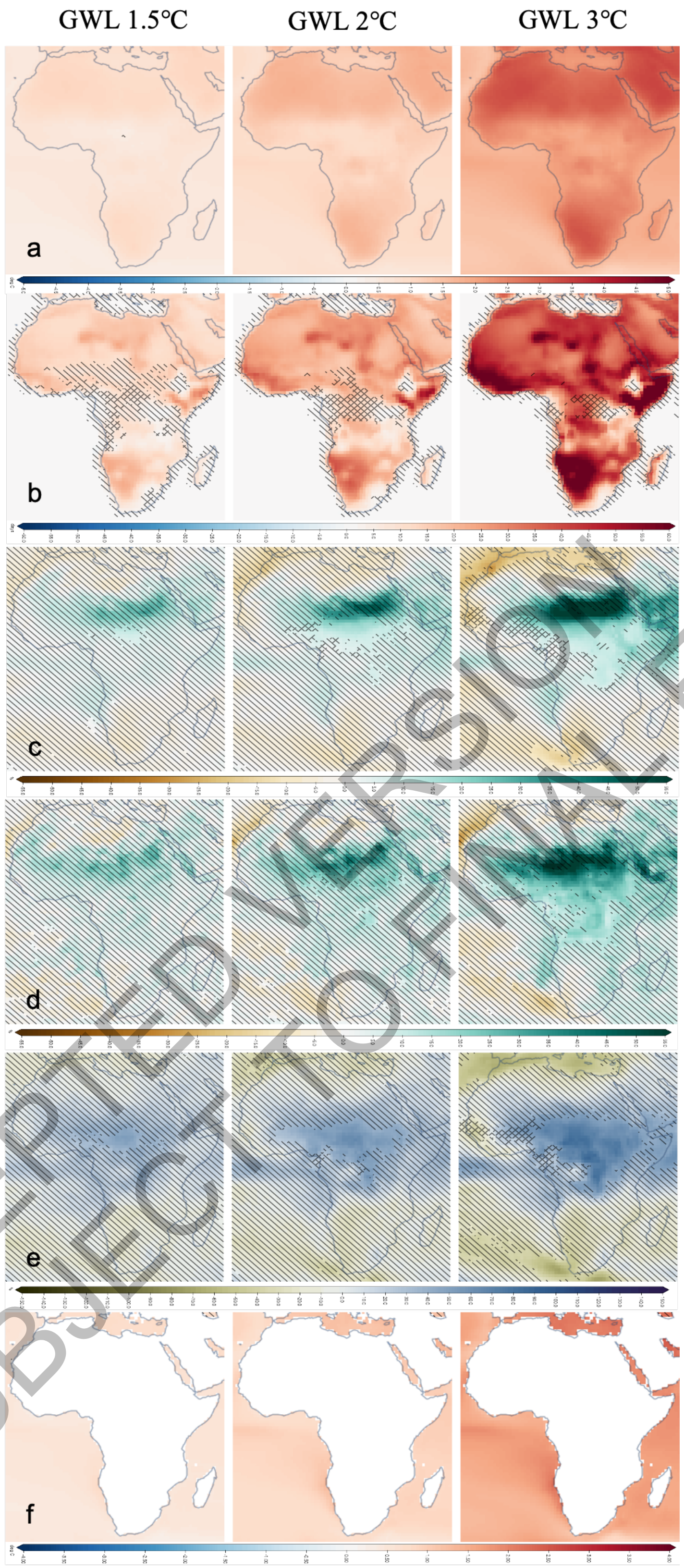


Figure 9.16: Projected changes of climate variables and hazards (relative to 1995–2014 average) at 1.5°C, 2°C and 3°C of global warming above pre-industrial (1850–1900). Rows are (a) Increase in mean annual temperature; (b) Increase in number of days per year above 35 °C; (c) Change in average annual rainfall (%); (d) Change in heavy precipitation represented by maximum 5-day precipitation (%); (e) Change in drought represented as the six-month standardized precipitation index (%). Negative changes indicate areas where drought frequency, intensity and/or duration is projected to increase. Positive changes show the opposite; (f) Increase in mean annual sea surface temperature (°C). All figures are derived from the WGI Interactive Atlas and show results from between 26 to 33 CMIP6 global climate models, depending on the climate variable. CMIP6 models include improved representations of physical, biological and chemical processes as well as higher spatial resolutions compared to previous CMIP5 models (WGI CH3). Three

categories of trend robustness are shown in the projection figures: (1) No hatching indicates a projected change is robust and likely greater than natural climate variability (that is, ≥66% of models show change greater than natural variability, and ≥80% of all models agree on sign of change); (2) Diagonal lines (\) indicate no robust change (<66% of models show change greater than natural variability); (3) Crossed lines (X) indicate conflicting signals where at least 66% of the models show change greater than natural variability, but <80% of all models agree on direction of change (Gutiérrez et al., 2021).

9.5.2 North Africa

9.5.2.1 Temperature

Observations

Mean and seasonal temperatures have increased at twice the global rate over most regions in North Africa due to anthropogenic climate change (Ranasinghe et al., 2021) (Figures 9.13a and 9.14) (*high confidence).* Increasing temperature trends are particularly strong since the 1970s (between 0.2°C/decade and 0.4°C/decade), especially in the summer (Tanarhte et al., 2012; Donat et al., 2014a; Lelieveld et al., 2016). Similar warming signals have been observed since the mid-1960s over the Sahara and the Sahel (Fontaine et al., 2013; Moron et al., 2016). Trends in mean maximum (TX) and minimum (TN) temperatures range between +2°C and +3°C per century over North Africa, and the frequencies of hot days (TX >90th percentile, TX90p) and tropical nights (TN >20°C), as well as the frequencies of warm days and nights, roughly follow these mean TX and TN trends (Fontaine et al., 2013; Moron et al., 2016; Ranasinghe et al., 2021; Seneviratne et al., 2021). Warm spell duration has increased in many North African countries (Donat et al., 2014a; Filahi et al., 2016; Lelieveld et al., 2016; Nashwan et al., 2018) and heatwave magnitude and spatial extent have increased across North Africa since 1980, with an increase in the number of events since 2000 that is beyond the level of natural climate variability (Russo et al., 2016; Ceccherini et al., 2017; Engdaw et al., 2021).

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in North Africa are projected to be on average, 0.9°C, 1.5°C and 2.6°C warmer than the 1994–2005 average respectively (Figure 9.16a). Warming is projected to be stronger in summer than winter (Lelieveld et al., 2016; Dosio, 2017). The number of hot days is *likely* to increase by up to 90% by the end of the century under RCP8.5 (global warming level [GWL] 4.4°C) (Gutiérrez et al., 2021; Ranasinghe et al., 2021) and hot nights and the duration of warm spells to increase in the first half of the 21st century in both intermediate and high emission scenarios (Patricola and Cook, 2010; Vizy and Cook, 2012; Lelieveld et al., 2016; Dosio, 2017; Filahi et al., 2017). Heatwaves are projected to become more frequent and intense even at 1.5°C of global warming (Gutiérrez et al., 2021; Ranasinghe et al., 2021). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 4–6 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 9–10 times more heatwaves for emission reduction pledges, limiting global warming to 2.4°C (Thiery et al., 2021).

9.5.2.2 Precipitation

Observations

Mean annual precipitation decreased over most of North Africa between 1971–2000 (Donat et al., 2014a; Hertig et al., 2014; Nicholson et al., 2018; Zittis, 2018), with a gradual recovery to normal or wetter conditions in Algeria and Tunisia since 2000 and over Morocco since 2008 (Nouaceur and Murărescu, 2016). Since the 1960s days with more than 10 mm of rainfall have decreased and the number of consecutive dry days have increased in the eastern parts of North Africa, while in the western parts of North Africa heavy rainfall and flooding has increased (Donat et al., 2014a). Aridity, the ratio of potential evaporation to precipitation, has increased over the Mediterranean and North Africa due to significant decreases in precipitation (Greve et al., 2019).

Projections

Mean annual precipitation is projected to decrease in North Africa at warming levels of 2°C and higher (*high confidence*) with the most pronounced decreases in the northwestern parts (Schilling et al., 2012; Filahi et al., 2017; Barcikowska et al., 2018; Ranasinghe et al., 2021) (Figures 9.14 and 9.16c). Meteorological drought over Mediterranean North Africa in CMIP5 and CMIP6 models are projected to increase in duration from approximately 2 months during 1950–2014 to approximately 4 months in the period 2050–2100 under RCP8.5 and SSP5-85 (Ukkola et al., 2020). Extreme rainfall (monthly maximum 1-day rainfall – RX1day) in the region is projected to decrease (Donat et al., 2019).

During 1984–2012, North Africa experienced a decreasing dust trend with North African dust explaining more than 60% of global dust variations (Shao et al., 2013). Dust loadings and related air pollution hazards (from fine particles that affect health) are projected to decrease in many regions of the Sahara as a result of decreased wind speeds (Evan et al., 2016; Ranasinghe et al., 2021).

9.5.3 West Africa

9.5.3.1 Temperature

Observations

Observed mean annual and seasonal temperatures have increased 1–3°C since the mid-1970s with the highest increases in the Sahara and Sahel (Cook and Vizy, 2015; Lelieveld et al., 2016; Dosio, 2017; Nikiema et al., 2017; Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Figure 9.13a) and positive trends in mean annual maximum (TX) and minimum (TN) of 0.16°C and 0.28°C per decade, respectively (Mouhamed et al., 2013; Moron et al., 2016; Russo et al., 2016; Barry et al., 2018). The frequency of very hot days (TX >35°C) and tropical nights has increased by 1–9 days and 4–13 nights per decade between 1961–2014 (Moron et al 2016), and cold nights have become less frequent (Fontaine et al., 2013; Mouhamed et al., 2013; Barry et al., 2018). In the 21st century, heatwaves have become hotter, longer and more extended compared to the last two decades of the 20th century (Mouhamed et al., 2013; Moron et al., 2016; Russo et al., 2016; Barbier et al., 2018).

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in West Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average respectively (Figure 9.16a). Under mid- and high-emission scenarios end of century summer temperatures are projected to increase by 2°C and 5°C, respectively (Sylla et al., 2015a; Russo et al., 2016; Dosio, 2017). The annual number of hot days is projected to increase at all global warming levels with larger increases at higher warming levels (Figure 9.16b). By 2060 the frequency of hot nights is projected to be almost double the 1981–2010 average at GWL 2°C (Dosio, 2017; Bathiany et al., 2018; Gutiérrez et al., 2021; Ranasinghe et al., 2021). Heatwave frequency and intensity are projected to increase under all scenarios, but limiting global warming to 1.5°C leads to a decreased heatwave magnitude (–35%) and frequency (–37%) compared to 2°C global warming (Dosio, 2017; Weber et al., 2018; Nangombe et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 4–6 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 7–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021).

The number of dangerous heat days (TX >40.6°C) is projected to increase from approximately 60 per year in 1985–2005 to approximately 110, 130 and 140 under RCPs 2.6, 4.5 and 8.5, respectively, in the 2060s and to 105, 145 and 196 in the 2090s (Rohat et al., 2019). Over tropical West Africa, heat-related mortality risk through increased heat and humidity is 6–9 times higher than the 1950–2005 average at GWL 2°C, 8–15 times at GWL 2.65°C and 15–30 times at GWL 4.12°C (Ahmadalipour and Moradkhani, 2018) (Coffel et al., 2018). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to 50–150 at GWL 1.6°C, 100–250 at GWL 2.5°C and 250–350 at GWL 4.4°C, with highest increases in coastal regions (Mora et al., 2017). Increasing urbanization concentrates this exposure in cities, such as Lagos, Niamey, Kano and Dakar (Coffel et al., 2018; Rohat et al., 2019) (Section 9.9.3.1).

9.5.3.2 Precipitation

Observations

Negative trends in rainfall accompanied by increased rainfall variability were observed between 1960s–1980s over West Africa (Nicholson et al., 2018; Thomas and Nigam, 2018), caused by a combination of anthropogenic aerosols and greenhouse gases emitted between 1950s–1980s (Booth et al., 2012; Wang et al., 2016; Giannini and Kaplan, 2019; Douville et al., 2021). Declining rainfall trends ended by 1990 due to the growing influence of greenhouse gasses and reduced cooling effect of aerosol emissions, with a trend to wetter conditions emerging in the mid-1990s accompanied by more intense, but fewer precipitation events (Sanogo et al., 2015; Sylla et al., 2016; Kennedy et al., 2017; Barry et al., 2018; Bichet and Diedhiou, 2018a; Bichet and Diedhiou, 2018b; Thomas and Nigam, 2018). A shift to a later onset and end of the West African monsoon is also reported in West Africa and Sahel (*low confidence*) (Chen et al., 2021; Ranasinghe et al., 2021). Between 1981–2014 the Gulf of Guinea and the Sahel have experienced more intense precipitation events (Panthou et al., 2014; Bichet and Diedhiou, 2018a; Panthou et al., 2018) and the frequency of mesoscale storms has tripled (Taylor et al., 2017; Callo-Concha, 2018). Extreme heavy precipitation indices show increasing trends from 1981–2010 (Barry et al., 2018), increasing high flow events in large Sahelian rivers as well as small to mesoscale catchments leading to pluvial and riverine flooding (Douville et al., 2021). Meteorological, agricultural and hydrological drought in the region has increased in frequency since the 1950s (*medium confidence*) (Seneviratne et al., 2021).

Projections

West African rainfall projections show a gradient of precipitation decrease in the west and increase in the east (*medium confidence*) (Dosio et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Figure 9.14). This pattern is evident at 1.5°C of global warming and the magnitude of change increases at higher warming levels (Schleussner et al., 2016b; Kumi and Abiodun, 2018; Sylla et al., 2018) (Figure 9.16c). A reduction in length of the rainy season is projected over the western Sahel through delayed rainfall onset by 4 to 6 days at global warming levels of 1.5°C and 2°C (Kumi and Abiodun, 2018; Douville et al., 2021; Gutiérrez et al., 2021). Although there are uncertainties in rainfall projections over the Sahel (Klutse et al., 2018; Gutiérrez et al., 2021), CMIP6 models project monsoon rainfall amounts to increase by approximately 2.9% per degree of warming (Jin et al., 2020; Wang et al., 2020a), therefore, at higher levels of warming and towards the end of the century, a wetter monsoon is projected in the eastern Sahel (*medium confidence*).

The frequency and intensity of extremely heavy precipitation are projected to increase under mid- and high-emission scenarios (Sylla et al., 2015b; Diallo et al., 2016; Akinsanola and Zhou, 2019; Giorgi et al., 2019; Dosio et al., 2021; Li et al., 2021; Seneviratne et al., 2021) (Figure 9.16d). However, heavy rainfall statistics from global and regional climate models may be conservative as very-high-resolution, convection-permitting climate models simulate more intense rainfall than these models (Stratton et al., 2018; Berthou et al., 2019; Han et al., 2019; Kendon et al., 2019).

At 2°C global warming, West Africa is projected to experience a drier, more drought-prone and arid climate, especially in the last decades of the 21st century (Sylla et al., 2016; Zhao and Dai, 2016; Klutse et al., 2018). The duration of meteorological drought duration is projected to increase from approximately 2 months during 1950–2014 to approximately 4 months in the period 2050–2100 under RCP8.5 and SSP5–8.5 (Ukkola et al., 2020). Increased intensity of heavy precipitation events combined with increasing drought occurrences will substantially increase the cumulative hydroclimatic stress on populations in West Africa during the late 21st century (Giorgi et al., 2019).

9.5.4 Central Africa

9.5.4.1 Temperature

Observations

Mean annual temperature across Central Africa has increased by 0.75°C–1.2°C since 1960 (Aloysius et al., 2016; Gutiérrez et al., 2021). The number of hot days, heatwaves and heatwave days increased between 1979–2016 (Hu et al., 2019) and cold extremes have decreased (Aguilar et al., 2009; Seneviratne et al., 2021) (Figure 9.14). Uncertainties associated with the poor ground-based observation networks in the region and associated observational uncertainties (Section 9.5.1.1) result in an assessment of *medium confidence* in an increase in the number of heat extremes over the region.

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in Central Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average, respectively (Figure 9.16a). By the end of the century (2070–2099), warming of 2°C (RCP4.5) to 4°C (RCP8.5) is projected over the region (Aloysius et al., 2016; Fotso-Nguemo et al., 2017; Diedhiou et al., 2018; Mba et al., 2018; Tamoffo et al., 2019) and the number of days with maximum temperature exceeding 35°C is projected to increase by 150 days or more at GWL 4.4°C (Gutiérrez et al., 2021; Ranasinghe et al., 2021). According to CMIP6 and CORDEX models, the annual average number of days with maximum temperature exceeding 35°C will increase between 14–27 days at GWL 2°C and 33–59 days at GWL 3°C above the 61–63 days for 1995–2014 (Gutiérrez et al., 2021; Ranasinghe et al., 2021) (*high confidence*). The number of heatwave days is projected to increase and extreme heatwave events may last longer than 180 days at GWL 4.1°C (Dosio, 2017; Weber et al., 2018; Spinoni et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 6–8 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 7–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to 50–75 at GWL 1.6°C, 100–150 at GWL 2.5°C and 200–350 at GWL 4.4°C (Mora et al., 2017).

9.5.4.2 Precipitation

Observations

The severe lack of station data over the region leads to large uncertainty in the estimation of observed rainfall trends and *low confidence* in changes in extreme rainfall (Figure 9.13b) (Creese and Washington, 2018; Gutiérrez et al., 2021; Ranasinghe et al., 2021). There is some evidence of drying since the mid-20th century through decreased mean rainfall and increased precipitation deficits (Gutiérrez et al., 2021), as well as increases in meteorological, agricultural and ecological drought (*medium confidence*) (Seneviratne et al., 2021). However, there is spatial heterogeneity in annual rainfall trends between 1983–2010 ranging from –10 to +39 mm per year (Maidment et al., 2015), with a decline in mean seasonal April–June precipitation of –69 mm per year in most regions except in the northwest (Zhou et al., 2014; Hua et al., 2016; Klotter et al., 2018; Hu et al., 2019). Southern and eastern Central Africa were identified as drought hotspots between 1991–2010 (Spinoni et al., 2014).

Projections

Under low emission scenarios and at GWL 1.5 and GWL 2°C there is *low confidence* in projected mean rainfall change over the region (Figure 9.16c). At GWL 3°C and GWL 4.4°C an increased mean annual rainfall of 10–25% is projected by regional climate models (Coppola et al., 2014; Pinto et al., 2015) and the intensity of extreme precipitation will increase (*high confidence*) (Sylla et al., 2015a; Diallo et al., 2016; Dosio et al., 2019; Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021) (Figure 9.16c,d). This is projected to increase the likelihood of widespread flood occurrences before, during and after the mature monsoon season (Figure 9.14).

Convection permitting simulations (4.5 km spatial resolution) simulate increased dry spell length not apparent at coarser resolutions, suggesting drying in addition to more intense extreme rainfall (Stratton et al., 2018). Although reduced drought frequency is indicated in Figure 9.16e, the SPI metric does not account for the effect of increased temperature on drought (increased moisture deficit), and metrics that account for this indicate slightly increased drought frequency or no change (Spinoni et al., 2020). Therefore, there is *low confidence* in projected changes of drought frequency over the region (Figure 9.14).

9.5.5 East Africa

9.5.5.1 Temperature

Observations

Mean temperatures over the region have increased by 0.7°C–1°C from 1973 to 2013, depending on the season (Ayugi and Tan, 2018; Camberlin, 2018). Increases in TX and TN are evident across the region accompanied by significantly increasing trends of warm nights, warm days and warm spells (Russo et al., 2016; Gebrechorkos et al., 2019; Nashwan and Shahid, 2019). The greatest increases are found in northern and central regions.

Projections

At 1.5°C, 2°C and 3°C of global warming above pre-industrial levels, mean annual temperatures in East Africa are projected to be on average, 0.6°C, 1.1°C and 2.1°C warmer than the 1994–2005 average respectively (Figure 9.16a). Highest increases are projected over the northern and central parts of the region and the lowest increase over the coastal regions (Otieno and Anyah, 2013; Dosio, 2017). The magnitude and frequency of hot days are projected to increase from GWL 2°C and above with larger increases at higher GWLs (Dosio, 2017; Bathiany et al., 2018; Dosio et al., 2018; Kharin et al., 2018) (Figure 9.16a,b). At GWL 4.6°C a number of East African cities are projected to have an up to 2000-fold increase in exposure to dangerous heat (days >40.6 °C) compared to 1985–2005 including Blantyre-Limbe, Lusaka and Kampala, (Mora et al., 2017; Rohat et al., 2019). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 3–5 times more heatwaves in their lifetimes compared to people born in 1960; this exposure increases to 4–9 times more heatwaves at GWL 2.4°C (Thiery et al., 2021). The number of potentially lethal heat days per year is projected to increase from <50 during 1995–2005 to <50 at GWL 1.6°C, 50–120 at GWL 2.5°C and 150–350 at GWL 4.4°C with largest increases at the coast (Mora et al., 2017), highlighting the new emergence of dangerous heat conditions in these areas.

9.5.5.2 Precipitation

Observations

Over Equatorial East Africa the short rains (October–November–December) have shown a long-term wetting trend from the 1960s until present (Manatsa and Behera, 2013; Nicholson, 2015; Nicholson, 2017), which is linked with western Indian Ocean warming and a steady intensification of Indian Ocean Walker Cell (Liebmann et al., 2014; Nicholson, 2015).

In contrast, the long rainfall season (March-April-May) has experienced a long-term drying trend between 1986 and 2007, with rainfall declines in each of these months and a shortening of the wet season (Rowell et al., 2015; Wainwright et al., 2019). Unlike previous decades, since around 2000 the long rains have exhibited a significant relationship with the El Niño-Southern Oscillation (Park et al., 2020), as multiple droughts have occurred during recent La Niña events and when the western to central Pacific SST gradient was La Niña-like (Funk et al., 2015; Funk et al., 2018a). Wetter-than-average rainfall years within this long-term drying trend are often associated with a stronger amplitude of the Madden-Julian Oscillation (Vellinga and Milton, 2018).

In the northern, summer rainfall region (June–September), a decline in rainfall occurred in the 1960s and rainfall has remained relatively low, while interannual variability has increased since the late 1980s (Nicholson, 2017); the cause of this drying trend is uncertain.

Since 2005, drought frequency has doubled from once every six to once every three years and has become more severe during the long and summer rainfall seasons than during the short rainfall season (Ayana et al., 2016; Gebremeskel Haile et al., 2019). Several prolonged droughts have occurred predominantly within the arid and semi-arid parts of the region over the past three decades (Nicholson, 2017).

Projections

Higher mean annual rainfall, particularly in the eastern parts of east Africa are projected at GWL 1.5°C and 2°C by 25 CORDEX models (Nikulin et al., 2018; Osima et al., 2018). The additional 0.5°C of warming from 1.5°C increases average dry spell duration by between two and four days, except over southern Somalia where this is reduced by between two to three days (Hoegh-Guldberg et al., 2018; Nikulin et al., 2018; Osima et al., 2018; Weber et al., 2018).

During the short rainy season, a longer rainfall season (Gudoshava et al., 2020) and increased rainfall of up to over 100 mm on average is projected over the eastern horn of Africa and regions of high/complex topography at GWL 4.5° C (Dunning et al., 2018; Endris et al., 2019; Ogega et al., 2020).

During the long rainy season, there is *low confidence* in projected mean rainfall change (Gutiérrez et al., 2021). Although some studies report projected increased end of century rainfall (Otieno and Anyah, 2013; Kent et al., 2015), the mechanisms responsible for this are not well-understood and a recent regional model study has detected no significant change (Cook et al., 2020b). Projected wetting is opposite to the observed drying trends, giving rise to the 'East African rainfall paradox' (Rowell et al., 2015; Wainwright et al., 2019). In other parts of East Africa, no significant trend is evident (Ogega et al., 2020), agreement on the sign of change is low, and in some regions, CMIP5 and CORDEX data show opposite signs of change (Lyon et al., 2017; Lyon and Vigaud, 2017; Osima et al., 2018; Kendon et al., 2019; Ogega et al., 2020).

Heavy rainfall events are projected to increase over the region at global warming of 2°C and higher (*high confidence*) (Nikulin et al., 2018; Finney et al., 2020; Ogega et al., 2020; Li et al., 2021). Drought frequency, duration and intensity are projected to increase in Sudan, South Sudan, Somalia and Tanzania but decrease or not change over Kenya, Uganda and Ethiopian highlands (Liu et al., 2018c; Nguvava et al., 2019; Haile et al., 2020; Spinoni et al., 2020).

9.5.6 Southern Africa

9.5.6.1 Temperature

Observations

Mean annual temperatures over the region have increased by between 1.04°C and 1.44°C over the period 1961–2015 depending on the observational dataset (Gutiérrez et al., 2021) and in northern Botswana and Zimbabwe increasing 1.6°C–1.8°C between 1961–2010 (Engelbrecht et al 2015). The annual number of hot days have increased in southern Africa over the last four decades (Ceccherini et al., 2017; Kruger and Nxumalo, 2017b; Kruger and Nxumalo, 2017a) and there is increasing evidence of increased heat stress impacting agriculture and human health (Section 9.10.2). The occurrence of cold extremes, including frost days, have decreased (Kruger and Nxumalo, 2017b) (Figure 9.14).

Projections

At 1.5℃, 2℃ and 3°C of global warming above pre-industrial levels, mean annual temperatures in southern Africa are projected to be on average, 1.2℃, 2.3℃ and 3.3℃ warmer than the 1994–2005 average respectively (Figure 9.16a). The annual number of heatwaves is projected to increase by between 2–4 (GWL 1.5°C), 4–8 (GWL 2°C) and 8–12 (GWL 3°C) and hot and very hot days are *virtually certain* to increase under 1.5°C and 2°C of global warming (Engelbrecht et al., 2015; Russo et al., 2016; Dosio, 2017; Weber et al., 2018; Seneviratne et al., 2021). Cold days and cold extremes are projected to decrease under all emission scenarios with the strongest decreases associated with low mitigation (Iyakaremye et al., 2021). Children born in 2020, under a 1.5°C-compatible scenario will be exposed to 3–4 times more heatwaves in their lifetimes compared to people born in 1960, although in Angola this is 7–8 times; at GWL 2.4°C this exposure increases to 5–9 times more heatwaves (>10 times in Angola) (Thiery et al., 2021).

9.5.6.2 Precipitation

Observations

Mean annual rainfall has increased over parts of Namibia, Botswana and southern Angola during 1980–2015 by between 128 and 256 mm (Figure 9.13b). Since the 1960s decreasing precipitation trends have been detected over the South African winter rainfall region (*high confidence*) and the far eastern parts of South Africa (*low confidence*) (Engelbrecht et al., 2009; Kruger and Nxumalo, 2017b; Burls et al., 2019; Lakhraj-Govender and Grab, 2019; Gutiérrez et al., 2021; Ranasinghe et al., 2021). The frequency of dry spells and agricultural drought in the region has increased over the period 1961–2016 (Yuan et al., 2018; Seneviratne et al., 2021), the frequency of meteorological drought increased by between 2.5–3 events per decade since 1961 (Spinoni et al 2019) and the probability of the multi-year drought over the southwestern cape of South Africa increased by a factor of three in response to global warming (Otto et al., 2018). The number and intensity of extreme precipitation events have increased over the last century (Kruger and Nxumalo, 2017b; Ranasinghe et al., 2021; Sun et al., 2021), and in the Karoo region of southern South Africa, long-term station data show an increasing trend in annual rainfall of greater than 5 mm per decade over the period 1921–2015 (Kruger and Nxumalo, 2017b).

Projections

Mean annual rainfall in the summer rainfall region is projected to decrease by 10–20%, accompanied by an increase in the number of consecutive dry days during the rainy season under RCP8.5 (Kusangaya et al., 2014; Engelbrecht et al., 2015; Lazenby et al., 2018; Maúre et al., 2018; Spinoni et al., 2019). The western parts of the region are projected to become drier, with increasing drought frequency, intensity and duration *likely* under RCP8.5 (*high confidence*) (Engelbrecht et al., 2015; Liu et al., 2018b; Liu et al., 2018c; Ukkola et al., 2020) (Figures 9.16c,e and 9.14), including multi-year droughts (Zhao and Dai, 2016; Dosio, 2017).

Dryness in the summer rainfall region is expected to increase at 1.5°C and higher levels of global warming (Hoegh-Guldberg et al., 2018) and together with higher temperatures will enhance evaporation from the region's mega-dams and reduce soil-moisture content (Engelbrecht et al., 2015) (Section 9.7.1). Increases in drought frequency and duration are projected over large parts of southern Africa at GWL 1.5°C (Liu et al., 2018b; Liu et al., 2018c; Seneviratne et al., 2021) and unprecedented extreme droughts (compared to the 1981–2010 period) emerge at GWL 2°C (Spinoni et al., 2021). Meteorological drought duration is projected to increase from approximately 2 months during 1950–2014 to approximately 4 months in the mid-to-late-21st century future under RCP8.5 (Ukkola et al., 2020). Heavy precipitation in the southwestern region is projected to decrease (Donat et al., 2019) and increase in the eastern parts of southern Africa at all warming levels (Li et al., 2021; Seneviratne et al., 2021).

9.5.7 Tropical cyclones

There is limited evidence of an increased frequency of Category 5 tropical cyclones in the southwestern Indian Ocean (Fitchett et al., 2016; Ranasinghe et al., 2021; Seneviratne et al., 2021) and more frequent landfall of tropical cyclones over central to northern Mozambique (Malherbe et al., 2013; Muthige et al., 2018). There is a projected decrease in the number of tropical cyclones making landfall in the region at 1℃, 2℃ and 3℃ of global warming, however, they are projected to become more intense with higher wind speeds so when they do make landfall the impacts are expected to be high (*medium confidence*) (Malherbe et al., 2013; Muthige et al., 2018; Ranasinghe et al., 2021).

9.5.8 Glaciers

Total glacial area on Mount Kenya decreased by 121×10^3 m^2 (44%) during 2004–2016 (Prinz et al., 2016), Kilimanjaro from 4.8 km^2 in 1984 to 1.7 km^2 in 2011 (Cullen et al., 2013) and, in the Rwenzori Mountains, from ~2 km^2 in 1987 to ~1 km^2 in 2003 (Taylor et al., 2006). Declining glacial areas in East Africa are linked to rising air temperatures (Taylor et al., 2006; Hastenrath, 2010; Veettil and Kamp, 2019), and in the case of Kilimanjaro and Mount Kenya, declining precipitation and atmospheric moisture (Mölg et al., 2009a; Mölg et al., 2009b; Prinz et al., 2016; Veettil and Kamp, 2019).

Glacial ice cover is projected to disappear before 2030 on the Rwenzori Mountains (Taylor et al., 2006) and Mount Kenya (Prinz et al., 2018) and by 2040 on Kilimanjaro (Cullen et al., 2013). The loss of glaciers is expected to result in a loss in tourism revenues, especially in mountain tourism (Wang and Zhou, 2019).

9.5.9 Teleconnections and Large-Scale Drivers of African Climate Variability

The El Niño-Southern Oscillation (ENSO), Indian Ocean dipole (IOD) and southern annular mode (SAM) are the primary large-scale drivers of African seasonal and interannual climate variability. The diurnal temperature range tends to be greater during La Niña than El Niño in northeastern Africa (Hurrell et al., 2003; Donat et al., 2014a), and in southern Africa, the El Niño warming effect has been stronger for more recent times (1979–2016) compared to earlier period (1940–1978) (Lakhraj-Govender and Grab, 2019). In East Africa, ENSO and IOD exert an interannual control on particularly October–November–December (short rains) and June–July–August–September seasons. In southern Africa, El Niño is associated with negative rainfall and positive temperature anomalies with the opposite true for La Niña. The SAM exerts control on rainfall in the southwestern parts of the region and a positive SAM mode is often associated with lower seasonal rainfall in the region (Reason and Rouault, 2005). The SAM shows a systematic positive trend over the last five decades (Niang et al., 2014).

There is no clear indication that climate change will impact the frequencies of ENSO and IOD (Stevenson et al., 2012; Endris et al., 2019), although there is some indication that extreme ENSO events and extreme phases of the IOD, particularly the positive phase, may become more frequent with implications for extreme events associated with these features, such as drought (Collins et al., 2019; Cai et al., 2021; Seneviratne et al., 2021). Under high emission scenarios, a positive trend in SAM is projected to continue through the 21st century, however, under low emission scenarios, this trend is projected to be weak or even negative given the potential for ozone hole recovery (Arblaster et al., 2011).

9.5.10 African Marine Heatwaves

Marine heatwaves are periods of extreme warm sea surface temperature that persist for days to months and can extend up to thousands of kilometres (Hobday et al., 2016; Scannell et al., 2016), negatively impacting marine ecosystems (Section 9.6.1.4).

The number of marine heatwaves doubled in Mediterranean North Africa and along the Somalian and southern African coastlines from 1982–2016 (Frölicher et al., 2018; Laufkötter et al., 2020) (Oliver et al., 2018), *very likely* as a result of human-induced climate change (Seneviratne et al., 2021). Marine heatwave intensity has increased along the southern African coastline (Oliver et al., 2018). In the ecologically sensitive region west of southern Madagascar, the longest and most intense marine heatwave in the past 35 years was recorded during the austral summer of 2017 in the region, it lasted 48 days and reached a maximum intensity of 3.44°C above climatology (Mawren et al., 2021). Satellite-derived measurements of coastal marine heatwaves may under-report their intensity as measured against coastal *in situ* measurements (Schlegel et al., 2017).

Sea surface temperatures around Africa are projected to increase 0.5°C–1.3°C under GWL1.5 and 1.3°C–2.0°C under GWL3 (Figure 9.16f). Globally, 87% of observed MHWs have been attributed to anthropogenic forcing, and at GWL2.0, nearly all MHWs would be attributable to anthropogenic heating (Frölicher et al., 2018; Laufkötter et al., 2020). Increases in frequency, intensity, spatial extent and duration of marine heatwaves are projected for all coastal zones of Africa. At 1°C and 3.5°C of global warming, the probability of MHW days is between 4–15 times and 30–60 times higher compared to the preindustrial (1861–1880) 99th percentile probability, with highest increases over equatorial and sub-tropical coastal regions (Frölicher et al., 2018) (Figure 9.16). These events are expected to overwhelm the ability of marine organisms and ecosystems to adapt to these changes (Frölicher et al., 2018) (Sections 9.6.1). Reducing emissions and limiting warming to lower levels reduces risk to these systems (*high confidence*) (Hoegh-Guldberg et al., 2018).

[START BOX 9.2 HERE]

Box 9.2: Indigenous Knowledge and Local Knowledge

This box aims at mapping the diversity of indigenous and local knowledge systems in Africa and highlights the potential of this knowledge to enable sustainability and effective climate adaptation. This box builds on the framing of the IPCC system for which 'indigenous knowledge (IK) refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings' (IPCC, 2019b), while 'local knowledge (LK) refers to the understandings and skills developed by individuals and populations, specific to the place where they live' (IPCC, 2019b) (Cross-Chapter Box INDIG in Chapter 18).

Early warning systems and indicators of climate variability

In most African indigenous agrarian systems, local communities integrate IK to anticipate or respond to climate variability (Mafongoya et al., 2017). This holds potential for a more holistic response to climate change, as IK and LK approaches seek solutions that increase resilience to a wide range of shocks and community stresses (IPCC, 2019b). In Africa, IK and LK are exceptionally rich in ecosystem-specific knowledge, with the potential to enhance the management of natural hazards and climate variability (*high confidence*), but there is uncertainty about IK and LK for adaptation under future climate conditions.

Common indicators for the quality of the rain season for local communities in Africa include flower and fruit production of local trees (Nkomwa et al., 2014; Jiri et al., 2015; Kagunyu et al., 2016), insect, bird and animal behaviour and occurrence (Jiri et al., 2016; Mwaniki and Stevenson, 2017; Ebhuoma, 2020) and dry season temperatures (Kolawole et al., 2016; Okonya et al., 2017). Fulani herders in West Africa believe that when 'nests hang high on trees, then rains will be heavy; when nests hang low, rains will be scarce' (Roncoli et al., 2002). In South Africa, LK on weather forecasting is based on the hatching of insects, locust swarm movements and the arrival of migratory birds, which has enabled farmers to make adjustments to cropping practices (Muyambo et al., 2017; Tume et al., 2019). Most of these IK indicators apply to specific communities, and are used for short-term forecasting (e.g., event-specific predictions, such as a violent storm, and onset rain predictions) (Zuma-Netshiukhwi et al., 2013; Mutula et al., 2014). There is evidence of communities that rely heavily on IK and LK indicators to forecast seasonal variability across the continent (Kagunyu et al., 2016; Mwaniki and Stevenson, 2017; Tume et al., 2019). However, their accuracy is debatable, with evidence of both accuracy and inaccuracies due to age-old knowledge losing accuracy because of recent changes in weather conditions (Shaffer, 2014; Adjei and Kyerematen, 2018). There are also some limitations in the transferability of IK across geographical scales, as its understanding is framed by traditional beliefs and cultural practices, historical and social conditions of each community, which vary significantly across communities. This has direct implications for the adoption of IK and LK in national policy and planned adaptation by governments. However, in some parts of Africa, evidence of the integration of IK and LK and scientific-based weather forecasting is increasing (Jiri et al., 2016; Mapfumo et al., 2017; Williams et al., 2020).

IK and LK and climate adaptation

Communities across Africa have long histories of using IK and LK to cope with climate variability, reduce vulnerability and improve the capacity to cope with climate variability (Iloka Nnamdi, 2016; Mapfumo et al., 2017). The adaptation is mostly incremental, such as customary rainwater harvesting practices and planting ahead of rains (Ajibade and Eche, 2017; Makate, 2019), which are used to address the late-onset rains and rainfall variability. Although IK and LK adaptation practices implemented by African communities are incremental, such practices record higher evidence of climate risk reduction compared to practices influenced by other knowledge types (Williams et al., 2020). African communities have used IK and LK to cope, adapt to and manage climate hazards, mainly floods, wildfires, rainfall variability and droughts (see Table Box 9.2.1) (IPCC, 2018b; IPCC, 2019b).

Table Box 9.2.1: Selected studies where IK and LK have been used to cope with climate variability and climate change impacts in Africa.

Climate Hazard	Adaptation/Coping Strategy	Indigenous Group, Community, Country	Evidence
Floods	Use IK to predict floods (village elders acted as meteorologists) and use LK to prepare coping mechanisms (social capital); place valuable goods on higher ground, raise the floor level; leave the field uncultivated when facing flood/drought; indigenous earthen walls to protect homesteads from flooding; planting of culturally flood-immunising indigenous plants.	Coastal communities in Nigeria; Oshiwambo communities in the northern region of Namibia; Matabeleland and Mashonaland provinces in Zimbabwe; communities in Nyamwamba watershed, Uganda; subsistent farmers in Mount Oku and Mbaw, Cameroon; Akobo in South Sudan.	(Fabiyi and Oloukoi, 2013; Hooli, 2016; Lunga and Musarurwa, 2016; Bwambale et al., 2018; Tume et al., 2019)
Wildfires	Early burning to prevent the intensity of the late-season fires	Smallholders in Mutoko, Zimbabwe; Khwe and Mbukushu communities in Namibia	(Mugambiwa, 2018; Humphrey et al., 2021)
Rainfall variability	Change crop type (from maize to traditional millet and sorghum); no weeding; forecasting, rainwater harvesting; women perform rituals rainmaking, seed dressing and crop maintenance as adaptation measures; mulching	Communities in Accra, Ghana; small-scale farmers in Ngamiland in Botswana; Malawi; Zimbabwe; Women in Dikgale, South Africa, agropastoral smallholders in Ntungamo, Kamuli and Sembabule in Uganda.	(Codjoe et al., 2014; Nkomwa et al., 2014; Lunga and Musarurwa, 2016; Rankoana, 2016b; Mugambiwa, 2018; Mfitumukiza et al., 2020; Mogomotsi et al., 2020)
Droughts	Traditional drying of food for preservation (to consume during short	Communities in Accra, Ghana; Malawi; South Africa, Uganda; Smallholder	(Egeru, 2012; Gebresenbet and Kefale, 2012; Codjoe et al., 2014; Kamwendo and

	term droughts); harvesting wild fruits and vegetables; herd splitting by pastorals	farmers in Mutoko, Zimbabwe; Agro-pastoralists in Makueni, Kenya; Pastoralists in South Omo, Ethiopia	Kamwendo, 2014; Okoye and Oni, 2017; Mugambiwa, 2018)
Drought related water scarcity	Traditional rainwater harvesting to supplement both irrigation and domestic water; indigenous water bottle technology for irrigation.	Smallholder farmers in Beaufort, South Africa	(Ncube, 2018)

IK and LK and coping strategies in Table Box 9.2.1 are supportive measures that communities cannot solely rely upon, but which can be used to complement other adaptation options to increase community resilience.

African indigenous language and climate change adaptation

The diversity of African languages is crucial for climate adaptation. Africa has over 30% of the world's indigenous languages (Seti et al., 2016) which are exceptionally rich in ecosystem-specific knowledge on biodiversity, soil systems and water (Oyero, 2007; Mugambiwa, 2018). Taking into consideration the low level of literacy in Africa, especially among women and girls, indigenous languages hold great potential for more effective climate change communication and services that enable climate adaptation (Brooks et al., 2005; Ologeh et al., 2018; IPCC, 2019b). African traditional beliefs and cultural practices place great value on the natural environment, especially land as the dwelling place of the ancestors and source of livelihoods (Tarusarira, 2017) (see Section 9.12).

Limitations of African IK and LK in climate adaptation

Studies on IK and LK and climate change adaptation conducted in various African countries and across ecosystems indicate that indigenous environmental knowledge is negatively affected by several factors. Local farmers who depend on this knowledge system for their livelihoods hold the view that African governments do not support and promote it in policy development. Most government agricultural extension workers still consider IK as unscientific and unreliable (Seaman et al., 2014; Mafongoya et al., 2017). At the national level, there is a lack of recognition and inclusion of IK and LK in adaptation planning by African governments, partly because most of the IK and LK in African local communities remains undocumented, but also because IK and LK are inadequately captured in the literature (Ford et al., 2016; IPCC, 2019b). It is predominantly preserved in the memories of the elderly and is handed down orally or by demonstration from generation to generation. It gradually disappears due to memory gaps, and when those holding the knowledge die or refuse to pass it to another generation, the knowledge becomes extinct (Rankoana, 2016a). The way in which IK is transmitted, accessed and shared in most African societies is not smooth (IIED, 2015). IK is also threatened by urbanisation, which attracts rural migrants to urban areas where IK and LK use is limited (Fernández-Llamazares et al., 2015). Further, most African societies that use IK were once colonised, whereby the African indigenous ways of knowing were devalued and marginalised (Bolden et al., 2018). There are concerns about the effectiveness of both IK indicators and related adaptation responses by communities to predict and adapt to weather events under future climate conditions (Speranza et al., 2009; Shaffer, 2014; Hooli, 2016).

Figure Box 9.2.1: Indigenous earth walls *(hayit)* built by indigenous people in Akobo, Jonglei Region, South Sudan to protect their houses/ infrastructure from the worst flood in 25 years occurred in 2019. The wall is 1–2 m high. Photo credit, **Laurent-Charles Levesque**.

[END BOX 9.2 HERE]

9.6 Ecosystems

9.6.1 Observed Impacts of Climate Change on African Biodiversity and Ecosystem Services

9.6.1.1 Terrestrial Ecosystems

The overall continental trend is woody plant expansion, particularly in grasslands and savannas, with woody plant cover increasing at a rate of 2.4% per decade (Stevens et al., 2017; Axelsson and Hanan, 2018) (Figure 9.17). There is also increased grass cover in arid regions in southwestern Africa (Masubelele et al., 2014). There is *high agreement* that this is attributable to increased CO_2, warmer and wetter climates, declines in burned area and release from herbivore browsing pressure, but the relative importance of these interacting drivers remains uncertain (O'Connor et al., 2014; Stevens et al., 2016; García Criado et al., 2020). Woody encroachment is the dominant trend in the western and central Sahel, occurring over 24% of the region, driven primarily by shifts in rainfall timing and recovery from drought (Anchang et al., 2019; Brandt et al., 2019). Remote sensing studies demonstrate greening in southern Africa and forest expansion into water-limited savannas in Central and West Africa (Baccini et al., 2017; Aleman et al., 2018; Piao et al., 2020), with increases in precipitation and atmospheric CO_2 the likely determinants of change (Venter et al., 2018; Brandt et al., 2019; Zhang et al., 2019). These trends of greening and woody plant expansion stand in contrast to the desertification and contraction of vegetated areas highlighted in AR5 (Niang et al., 2014), but are based on multiple studies and longer time series of observations. Reported cases of desertification and vegetation loss, for example, in the Sahel, appear transitory and localised rather than widespread and permanent (Dardel et al., 2014; Pandit et al., 2018; Sterk and Stoorvogel, 2020).

Shifts in demography, geographic ranges and abundance of plants and animals consistent with expected impacts of climate change are evident across Africa. These include uphill contractions of elevational range limits of birds (Neate-Clegg et al., 2021), changes in species distributions previously reported in AR5 (Niang et al., 2014) and the death of many of the oldest and largest African Baobabs (Patrut et al., 2018). An increase in frequency and intensity of hot, dry weather after wildfires led to a long-term decline in plant biodiversity in Fynbos since the 1960s (Slingsby et al., 2017). Increasing temperatures may have contributed to the declining abundance and range size of South African birds (Milne et al., 2015), including Cape Rock-jumper (*Chaetops frenatus*) and Protea Canary (*Serinus leucopterus*), from increased risk of reproductive failure (Lee and Barnard, 2016; Oswald et al., 2020). For hot and dry regions (e.g., Kalahari), there is strong evidence increased temperatures are having chronic sublethal impacts, including reduced foraging efficiency and loss of body mass (du Plessis et al., 2012; Conradie et al., 2019), and are approaching species physiological limits, with heat extremes driving mass mortality events in birds and bats (McKechnie et al., 2021). Vegetation change linked to climate change and increasing atmospheric CO_2 has had an indirect impact on animals. Increased woody cover has decreased the occurrence of bird, reptile and mammal species that require grassy habitats (Péron and Altwegg, 2015; McCleery et al., 2018). Decreased fruit production linked to rising temperatures has decreased the body condition of fruit-dependent forest elephants by 11% from 2008–2018 (Bush et al., 2020).

There is *high agreement* that land use activities counteract or exacerbate climate-driven vegetation change (Aleman et al., 2017; Timm Hoffman et al., 2019). Decreased woody plant biomass in 11% of sub-Saharan Africa was attributed to land clearing for agriculture (Brandt et al., 2017; Ordway et al., 2017). Localised loss of tree cover in Miombo woodlands and 16.6±0.5 Mha of forest loss in the Congo basin between 2000-2014 was driven largely by forest clearing and drought mortality (McNicol et al., 2018; Tyukavina et al., 2018).

Vegetation changes interacting with climate and land use change have impacted fire regimes across Africa. The frequency of weather conducive for fire has increased in southern and West Africa and is expected to continue increasing in the 21st century under both RCP2.6 and RCP8.5 (Betts et al., 2015; Abatzoglou et al., 2019). Increased grass cover in arid regions introduced fire into regions where fuel was previously insufficient to allow fire spread, such as the arid Karoo in South Africa (du Toit et al., 2015; Strydom and Savage, 2016). In contrast, shrub encroachment, increased precipitation (Zubkova et al., 2019), vegetation fragmentation and cropland expansion have reduced fire activity in many African grasslands and savannas (Andela and van der Werf, 2014; Probert et al., 2019). These drivers are expected to negate the effect of increasing fire weather and ultimately lead to a reduction in the total burned area under RCP4.5 and RCP8.5 (Knorr et al., 2016; Moncrieff et al., 2016; Wu et al., 2016).

9.6.1.2 Vegetation Resilience

African ecosystems have a long evolutionary association with fire, large mammal herbivory and drought (Maurin et al., 2014; Charles-Dominique et al., 2016). The maintenance of biodiversity depends on natural disturbance regimes. Natural regrowth of savanna plant biomass in southern Africa compensated for biomass removal through human activities (McNicol et al., 2018), and rapid recovery occurred after the 2014-2016 extreme drought (Abbas et al., 2019). During the same drought event, browsing and mixed feeder herbivores were resilient, but grazers declined by approximately 60% and were highly dependent on drought refugia (Abraham et al., 2019). African tropical forests remained a carbon sink through the record drought and temperature experienced in the 2015–2016 El Niño, indicating resilience in the face of extreme environmental conditions (Bennett et al., 2021). This is likely due to the presence of drought-tolerant species and floristic and functional shifts in tree species assemblages (Fauset et al., 2012; Aguirre-Gutiérrez et al., 2019). This resilience indicates that there is the capacity to recover from disturbances and short-term change. But resilience has limits and beyond certain points, change can lead to irreversible shifts to different states (Figure 9.18).

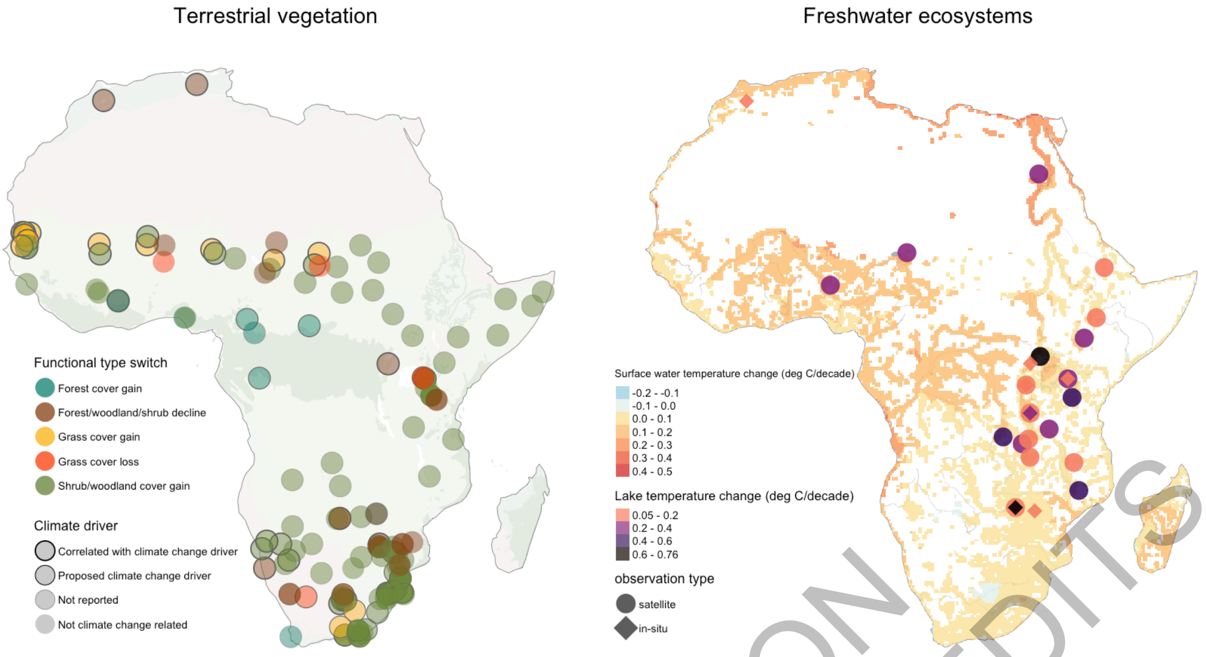


Figure 9.17: Widespread changes to African vegetation have been reported, especially increasing woody plant cover in many savannas and grasslands, with 37% of these changes proposed to be driven by anthropogenic climate change and increased CO_2. The warming of lakes and rivers has been detected across Africa and is attributed to climate change. Data on vegetation change was gathered from 156 studies published between 1989 and 2021. Climatic changes, mostly associated with changes in rainfall, are enhancing grass production in arid grasslands and savannas, and causing grass expansion into semi-desert regions with notable increases in the Sahel and southern Africa. Tropical forest expansion into mesic savannas is occurring on the fringes of the central African tropical forest. Interactions between land use, climate change and increasing atmospheric CO_2 concentrations are causing a widespread increase in woody plant cover encroachment in tropical savannas and grasslands. Some tree death and woody cover decline associated with climate and land use change have also been recorded across biomes. Of the reported changes to terrestrial vegetation, 24% were explicitly linked to climate change and a further 13% were proposed to be driven by climate change. In 48% of studies, no climate driver was mentioned and in 15% climate change was ruled out as the driver of change. Annual surface water temperatures in African lakes have warmed at a rate of 0.05°C–0.76°C per decade. Both satellite-based measures spanning 1985-2011 and *in situ* measurements spanning 1927-2014 agree on this warming trend. Other surface waters across Africa warmed from 1979-2018 at a rate of between 0.05°C and 0.5°C per decade (Woolway and Maberly, 2020). Vegetation change data were taken from a larger, global literature survey of existing databases supplemented with newer studies documenting changes in tree, shrub and grass cover linked to climate and land use change in natural and semi-natural areas (for further details 2.4.3.5 and Table 2.S.1 in Chapter 2, and see Supplementary Material Table SM 9.2 for Africa vegetation change data and Table SM 9.3 for studies reporting lake warming data).

9.6.1.3 Freshwater Ecosystems

Small climatic variations have large impacts on ecosystem function in Africa's freshwaters (Ndebele-Murisa, 2014; Ogutu-Ohwayo et al., 2016). Warming of water temperatures from 0.2°C to 3.2°C occurred in several lakes over 1927–2014 and has been attributed to anthropogenic climate change (Ogutu-Ohwayo et al., 2016); Figure 9.17). Increased temperature, changes in rainfall, and reduced wind speed altered the physical and chemical properties of inland water bodies, affecting water quality and productivity of algae, invertebrates and fish (*high confidence*). In deeper lakes, warmer surface waters and decreasing wind speeds reduced shallow waters mixing with nutrient-rich deeper waters, reducing biological productivity in the upper sunlit zone (Ndebele-Murisa, 2014; Saulnier-Talbot et al., 2014). In several lakes, climate change was identified as causing changes in insect emergence time (Dallas and Rivers-Moore, 2014) and in loss of fish habitats (Natugonza et al., 2015; Gownaris et al., 2016). This set of changes can harm human livelihoods, for example, from reduced fisheries productivity (Ndebele-Murisa, 2014; Ogutu-Ohwayo et al., 2016) (9.8.5) and reduced water supply and quality (Section 9.7.1).

9.6.1.4 Marine Ecosystems

Anthropogenic climate change is already negatively impacting Africa's marine biodiversity, ecosystem functioning and services by changing physical and chemical properties of seawater (increased temperature, salinity and acidification, and changes in oxygen concentration, ocean currents and vertical stratification) (*high confidence*) (Hoegh-Guldberg et al., 2014; Hoegh-Guldberg et al., 2018). Coastal ecosystems in West Africa are among the most vulnerable because of extensive low-lying deltas exposed to sea level rise, erosion, saltwater intrusion and flooding (Belhabib et al., 2016; UNEP, 2016b; Kifani et al., 2018). In southern Africa, shifting distributions of anchovy, sardine, hake, rock lobster and seabirds have been partly attributed to climate change (Crawford et al., 2015; van der Lingen and Hampton, 2018; Vizy et al., 2018), including southern shifts of 30 estuarine and marine fish species attributed to increased temperature and changes in water circulation from decreased river inflow (Augustyn et al., 2018). Warming sea surface temperatures inhibiting nutrient mixing reduced phytoplankton biomass in the western Indian Ocean by 20% since the 1960s, potentially reducing tuna catches (Roxy et al., 2016).

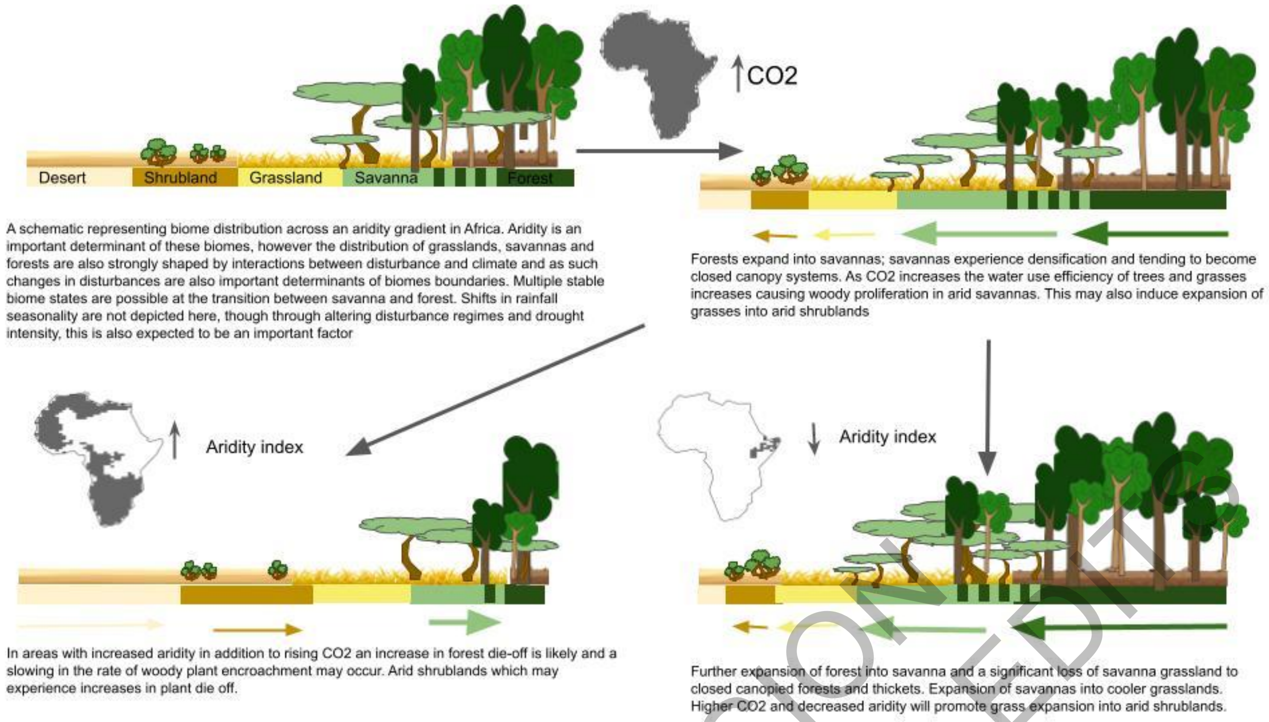
Mangroves, seagrasses and coral reefs support nursery habitats for fish, sequester carbon, trap sediment and provide shoreline protection (Ghermandi et al., 2019). Climate change is compromising these ecosystem services (*medium confidence*). Marine heatwaves associated with El Niño-Southern Oscillation (ENSO) events triggered massive coral bleaching and mortality over the past 20 years (Oliver et al., 2018). Mass coral bleaching in the western Indian Ocean occurred in 1998, 2005, 2010 and 2015/2016 with coral cover just 30–40% of 1998 levels by 2016 (Obura et al., 2017; Moustahfid et al., 2018). The northern Mozambique Channel has served as a refuge from climate change and biological reservoir for the entire coastal East African region (McClanahan et al., 2014; Hoegh-Guldberg et al., 2018). A southern shift of mangrove species has been observed in South Africa (Peer et al., 2018) with loss in total suitable coastal habitats for mangroves and shifts in the distribution of some species of mangroves and a gain for others (Record et al., 2013). Mangrove cover was reduced 48% in Mozambique in 2000 from tropical cyclone Eline, with 100% mortality of seaward mangroves dominated by *Rhizophora mucronata* (Macamo et al., 2016). Recovery of mangrove species was observed 14 years later in sheltered sites. There is *low confidence* these cyclone-induced impacts are attributable to climate change owing, in part, to a lack of reliable long-term data sets (Macamo et al., 2016). In West Africa, oil and gas extraction, deforestation, canalisation and de-silting of waterways have been the largest factors in mangrove destruction (Numbere, 2019).

9.6.2 Projected Risks of Climate Change for African Biodiversity and Ecosystem Services

9.6.2.1 Projected Biome Distribution

African biomes are projected to shift due to changes in atmospheric CO_2 concentrations and aridity (Figure 9.18). Grassland expansion into the desert, woody expansion into grasslands and forest expansion into savannas are projected for areas of reduced aridity, caused by reduced moisture stress from CO_2 fertilisation under medium (RCP4.5) and high (SRES A2) emissions scenarios (Heubes et al., 2011; Moncrieff et al., 2016). This greening trend may slow or reverse with continued temperature increase and/or in areas of increased aridity (Berdugo et al., 2020). The net impact of these effects on vegetation is highly uncertain (Trugman et al., 2018; Cook et al., 2020a; Martens et al., 2021). The maintenance or re-establishment of natural fire and large mammal herbivory processes can mitigate projected CO_2 and climate-driven changes (Scheiter and Savadogo, 2016; Stevens et al., 2016). Expansion of croplands and pastures will reduce ecosystem carbon storage in Africa, potentially reversing climate- and CO_2-driven greening in savannas (Aleman et al., 2018; Quesada et al., 2018).

Vegetation growth simulated by dynamic vegetation models is often highly sensitive to CO_2 fertilisation. These models project the African tropical forest carbon sink to be stable or strengthened under scenarios of future climate change (Huntingford et al., 2013; Martens et al., 2021). In contrast, statistical modelling suggests it has begun to decline and will weaken further, decreasing from current estimates of 0.66 tonnes of carbon removed from the atmosphere per hectare per year to 0.55 tonnes of carbon (Hubau et al., 2020). Increasing rainfall seasonality and aridity over central Africa (Haensler et al., 2013) threatens the massive carbon store in the Congo Basin's Cuvette Centrale peatlands, estimated at 30.6 billion tonnes (Dargie et al., 2019).



A schematic representing biome distribution across an aridity gradient in Africa. Aridity is an important determinant of these biomes, however the distribution of grasslands, savannas and forests are also strongly shaped by interactions between disturbance and climate and as such changes in disturbances are also important determinants of biomes boundaries. Multiple stable biome states are possible at the transition between savanna and forest. Shifts in rainfall seasonality are not depicted here, though through altering disturbance regimes and drought intensity, this is also expected to be an important factor

Forests expand into savannas; savannas experience densification and tending to become closed canopy systems. As CO2 increases the water use efficiency of trees and grasses increases causing woody proliferation in arid savannas. This may also induce expansion of grasses into arid shrublands

In areas with increased aridity in addition to rising CO2 an increase in forest die-off is likely and a slowing in the rate of woody plant encroachment may occur. Arid shrublands which may experience increases in plant die off.

Further expansion of forest into savanna and a significant loss of savanna grassland to closed canopied forests and thickets. Expansion of savannas into cooler grasslands. Higher CO2 and decreased aridity will promote grass expansion into arid shrublands.

Figure 9.18: Increases in atmospheric CO_2 and changes in aridity are projected to shift the geographic distribution of major biomes across Africa (*high confidence*). Arrows in the diagram indicate possible pathways of biome change from current conditions resulting from changes in CO_2 and aridity. Changes need not be gradual or linear and may occur rapidly if tipping points are crossed. Currently, widespread greening observed in Africa has been at least partially attributed to increasing atmospheric CO_2 concentrations. Future projected increases in aridity are expected to cause desertification in many regions, but it is highly uncertain how this will interact with the greening effect of CO_2. Inset maps show the projected geographical extent of changes in CO_2 concentrations and aridity. CO_2 is projected to increase globally under all future emission scenarios. Aridity index maps show projected change in aridity (calculated as annual precipitation/annual potential evapotranspiration) at around 4°C global warming relative to 1850–1900 (RCP8.5 in 2070–2099) from 34 CMIP5 models (Scheff et al., 2017). Shaded areas indicate regions where >75 % of models agree on the direction of change.

9.6.2.2 Terrestrial Biodiversity

Local extinction is when a species is extirpated from a local site. The magnitude and extent of local extinctions predicted across Africa increase substantially under all future global warming levels (*high confidence*) (Table 9.5; Figure 9.19). Above 2°C the risk of sudden disruption or loss of local biodiversity, increases and becomes more widespread, especially in Central, West and East Africa (Trisos et al., 2020).

Global extinction is when a species is extirpated from all areas. At 2°C global warming, 11.6% of African species (mean 11.6%, 95% CI 6.8–18.2%) assessed are at risk of global extinction, placing Africa second only to South America in the magnitude of projected biodiversity losses (Urban, 2015). At >2°C, 20% of North African mammals may lose all suitable climates (Soultan et al., 2019), and over half of the dwarf succulents in South African Karoo may lose >90% of their suitable habitat (Young et al., 2016). Among the thousands of species at risk, many are species of ecological, cultural and economic importance such as African wild dogs (Woodroffe et al., 2017) and Arabica Coffee (Moat et al., 2019).

With increasing warming, there is a lower likelihood species can migrate rapidly enough to track shifting climates, increasing global extinction risk and biodiversity loss across more of Africa (*high confidence*). Immigration of species from elsewhere may partly compensate for local extinctions and lead to local biodiversity gains in some regions (Newbold, 2018; Warren et al., 2018). However, more regions face net losses than net gains. At 1.5°C global warming, >46% of localities face net declines in vertebrate species richness of >10%, with net increases projected for less than 15% of localities (Barbet-Massin and Jetz, 2015; Newbold, 2018). At >2°C, 9% of species face complete range loss by 2100, regardless of their dispersal ability (Urban, 2015). With >4°C global warming, a net loss of >10% of vertebrate species richness is projected across 85% of Africa (Barbet-Massin and Jetz, 2015; Mokhatla et al., 2015; Newbold, 2018; Warren et al., 2018). Mountain top endemics and species in North and southern Africa are at risk due to disappearing cold climates (Milne et al., 2015; Garcia et al., 2016; Bentley et al., 2018; Soultan et al., 2019). For hot regions such as the Sahara, Congo Basin and Kalahari, no warmer-adapted species are available elsewhere to compensate for local extinctions, so the resilience of local biodiversity will depend entirely on the persistence of species (Burrows et al., 2014; Garcia et al., 2014). The capacity for species to avoid extinction through behavioural thermoregulation, plasticity or evolution is uncertain but will become increasingly *unlikely* under higher warming scenarios (Conradie et al., 2019).

Table 9.5: Risk of local extinction risk increases across Africa with increasing global warming.

Global Warming Level (relative to 1850-1900)	Taxa	% of species at a site at risk of local extinction	Extent across Africa (% of the land area of Africa)	Areas at risk	References
1.5°C	Plants, insects, vertebrates	>10%	>90%	Widespread. Hot and/or arid regions especially at risk, including Sahara, Sahel and Kalahari	Fig. 9.29b (Newbold, 2018; Warren et al., 2018)
>2°C	Plants, insects, vertebrates	>50%	18%	Widespread	(Newbold, 2018; Warren et al., 2018)
>4°C	Plants, insects, vertebrates	>50%	45-73%	Widespread. Higher uncertainty for central African tropical forests due to lower agreement between biodiversity models	Fig. 9.29c (Barbet-Massin and Jetz, 2015; Newbold, 2018; Warren et al., 2018)

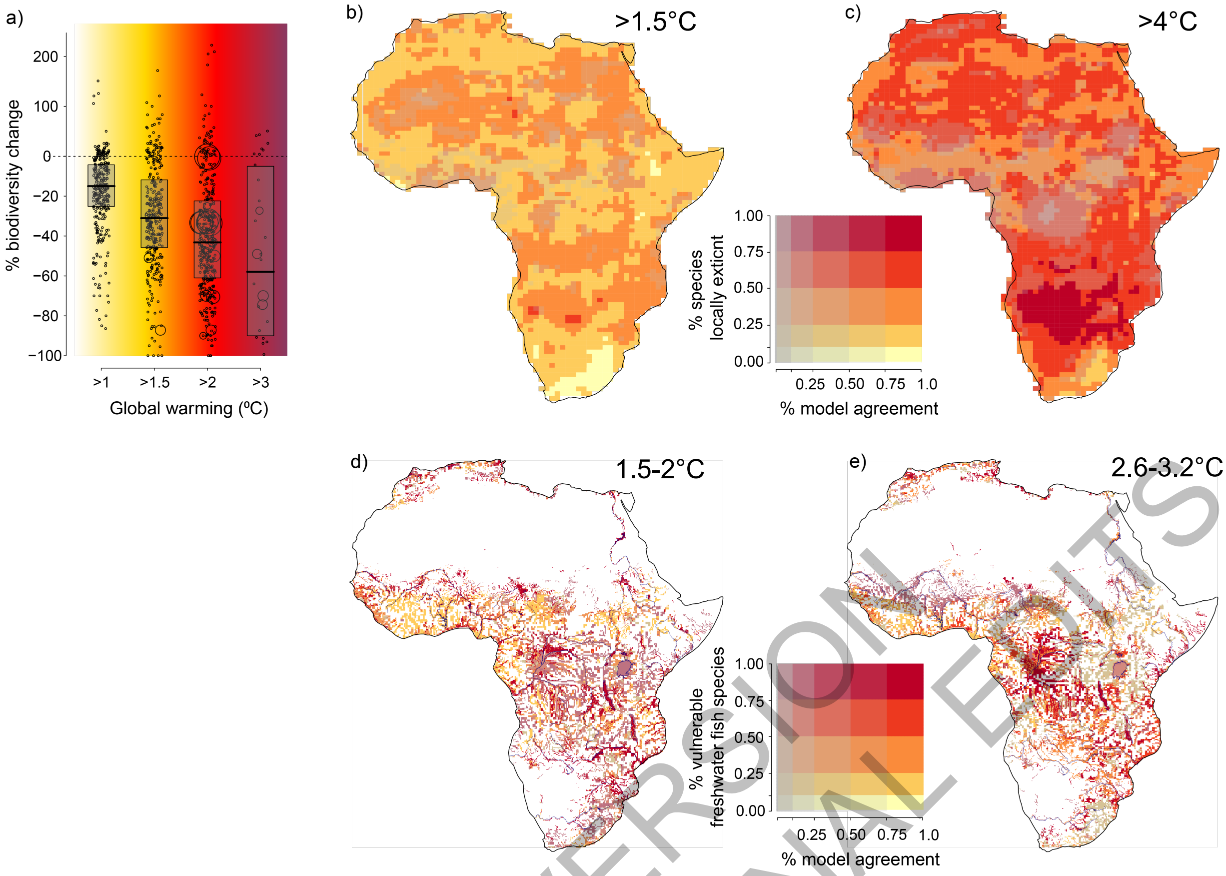


Figure 9.19: The loss of African biodiversity under future climate change is projected to be widespread and increasing substantially with every 0.5°C above the current (2001–2020) level of global warming (*high confidence*). (a) Projected biodiversity loss, quantified as percentage change in species abundance, range size or area of suitable habitat increases with increasing global warming levels (relative to 1850–1900). Above 1.5°C global warming, half of all assessed species are projected to lose >30% of their population, range size or area of suitable habitat, with losses increasing to >40% for >3°C. The 2001–2020 level of global warming is around 1°C higher than 1850–1900 (IPCC, 2021). Boxplots show the median (horizontal line), 50% quantiles (box), and points are studies of individual species or of multiple species (symbol size indicates the number of species in a study). (b–c) The mean projected local extinction of vertebrates, plants and insects within 100 km grid cells increases in severity and extent under increased global warming (relative to 1850–1900). Local extinction >10% is widespread by 1.5°C. Pixel colour shows the projected percentage of species undergoing local extinction and the agreement between multiple biodiversity models. (d–e) The mean projected increase in species of freshwater fish vulnerable to local extinction within 10 km grid cells for future global warming. Around a third of fish species are projected to be vulnerable to extinction by 2°C global warming. Pixel colour shows the projected percentage of species vulnerable to extinction and agreement between multiple vulnerability models. In (a), data were obtained from 22 peer-reviewed papers published since 2012 investigating the impacts of projected climate change on African biodiversity. When a paper provided impact projections for several time periods, climate change scenarios or for more than one species, each impact was recorded as an individual biodiversity impact projection, resulting in a database of 1,165 biodiversity impact projections. Data were initially collected by Manes et al. (2021) as part of a larger literature review for Cross-Chapter Paper 1 on Biodiversity Hotspots and then expanded to include areas outside of African priority conservation areas (see Supplementary Material Table SM 9.4). The literature review was limited to peer-reviewed publications that reported quantifiable risks to biodiversity, eliminating non-empirical studies. In (b–c), projections are based on intersecting current and future modelled species distributions at ~10 km spatial resolution from two recent global assessments of climate change impacts on terrestrial vertebrates (Newbold, 2018; Warren et al., 2018). In (d-e) projections are based on intersecting future species vulnerabilities from two recent assessments of climate change vulnerability of freshwater fish species (Nyboer et al., 2019; Barbarossa et al., 2021).

9.6.2.3 *Marine Ecosystems*

African coastal and marine ecosystems are highly vulnerable to climate change (*high confidence*). At 1.5°C of global warming, mangroves will be exposed to sedimentation and sea level rise, while seagrass ecosystems will be most affected by heat extremes (*high confidence*) (Hoegh-Guldberg et al., 2018) and turbidity (Wong et al., 2014). These risks will be amplified at 2°C and 3°C (*virtually certain*) (Hoegh-

Guldberg et al., 2018). Over 90% of East African coral reefs are projected to be destroyed by bleaching at 2°C of global warming (*very high confidence*) (Hoegh-Guldberg et al., 2018). At around 2.5°C global warming, an important reef-building coral (*Diploastrea heliopora*) in the central Red Sea is projected to stop growing altogether (Cantin et al., 2010). By 2.5°C, suitable habitat of >50% of species are projected to decline for coastal lobster in East and North Africa, with large declines for commercially important *J. lalandii* in southern Africa (Boavida-Portugal et al., 2018). More generally, tropical regions, especially exclusive economic zones in West Africa, are projected to lose large numbers of marine species and may experience sudden declines with extratropical regions having potential net increases as species track shifting temperatures poleward (García Molinos et al., 2016; Trisos et al., 2020).

9.6.2.4 Freshwater Ecosystems

Above 2°C global warming, the proportion of freshwater fish species vulnerable to climate change increases substantially (*high confidence*) (Figure 9.19). At 2°C, 36.4% of fish species are projected to be vulnerable to local or global extinction by 2100, increasing to 56.4% under 4°C warming (average of values from (Nyboer et al., 2019; Barbarossa et al., 2021) (Figure 9.19). Global warming reduces available habitat for freshwater species due to reduced precipitation and increased drought leading to increasing water temperatures above optimal physiological limits in floodplains, estuaries, wetlands, ephemeral pools, rivers and lakes (Dalu et al., 2017; Kalacska et al., 2017; Nyboer and Chapman, 2018). Along the Zambezi River, projected flow reductions could cause a 22% reduction in annual spawning habitat and depletion of food resources for fry and juvenile fish that could impede fish migration and reduce stocks (Kangalawe, 2017; Martínez-Capel et al., 2017; Tamatamah and Mwedzi, 2020). More aquatic species will have the capacity to cope with 2°C compared to 4°C global warming, with more negative effects on physiological performance at 4°C (Dallas, 2016; Pinceel et al., 2016; Zougmoré et al., 2016; Nyboer and Chapman, 2017; Ross-Gillespie et al., 2018). Endemic, specialised fish species will have a lower capacity to adjust to elevated water temperatures compared to hardier generalist fishes (McDonnell and Chapman, 2015; Nyboer and Chapman, 2017; Lapointe et al., 2018; Reizenberg et al., 2019). More work is needed to understand the risk for invertebrates (Dallas and Rivers-Moore, 2014; Cohen et al., 2016), and to understand the potential effects of reduced mixing of water and other climate risks on freshwater biodiversity.

9.6.2.5 Climate Change & Ecosystem Services

Direct human dependence on provisioning ecosystem services in Africa is high (Egoh et al., 2012; IPBES, 2018). For example, natural forests provided 21% of rural household income across 11 African countries (Angelsen et al., 2014) and wild-harvested foods (including fisheries) provide important nutrition to millions of Africans, including through important micronutrients and increased dietary diversity (Powell et al., 2013; Baudron et al., 2019a) (Sections 9.8.2.3 and 9.8.5)

Climate change has affected ecosystem services in Africa by reducing fish stocks, crop and livestock productivity and water provisioning due to heat and drought (see Sections 9.8.2.1, 9.8.2.2, 9.8.2.4 and 9.8.5.1). Woody encroachment is decreasing cattle production and water supply (Smit and Prins, 2015; Stafford et al., 2017), but can also provide forage for goat production, as well as resins, fuelwood and charcoal (Reed et al., 2015; Stafford et al., 2017; Charis et al., 2019). Local communities perceive climate change to have decreased crop and livestock productivity, reduced wild food availability and reduced forest resources across Africa (Onyekuru and Marchant, 2014) (see Sections 9.8.2.1, 9.8.2.2, 9.8.2.4 and 9.8.2.3).

With global warming >3°C, and with high population growth and agricultural expansion (SSP3, 2081–2100), 1.2 billion Africans are projected to be negatively affected by pollution of drinking water from reduced water quality regulation by ecosystems and 27 million people affected by reduced coastal protection by ecosystems (Chaplin-Kramer et al., 2019). The number of people affected reduces to 0.4 billion and 22 million under a sustainable development scenario with global warming below 2°C (SSP1, 2081–2100). The African tropical forest carbon sink has been more resilient than Amazonia to recent warming but may already have peaked, and this service is predicted to decline with further warming, reducing 14% by the 2030s (Hubau et al., 2020; Sullivan et al., 2020). This declining carbon storage may be offset by CO_2 fertilisation (*low confidence*) (Martens et al., 2021). Climate change is projected to shift the geographic distribution of important human and livestock disease vectors (see Section 9.8.2.4 and 9.10.2). Changes in rainfall seasonality compounded with land privatisation and population growth may adversely impact nomadic and semi-nomadic pastoralists who follow shifting patterns of greening vegetation (Van Der Ree et al., 2015).

9.6.2.6 Invasive Species

Invasive species threaten African ecosystems and livelihoods (Ranasinghe et al., 2021). For instance, economic impacts were estimated at USD 1 billion per year for smallholder maize farmers in East Africa (Pratt et al., 2017). Climate change is projected to change patterns of invasive species spread (*high confidence*). The area of suitable climate for *Lantana camara* is projected to contract (Taylor et al., 2012) and to expand for *Prosopis juliflora* (Sintayehu et al., 2020). Bioclimatic suitability for fall armyworm, a major threat to maize, is projected to decrease in Central Africa but expand in southern and West Africa (Zacarias, 2020), and to expand for coffee berry borer (*H. hampei*) in Uganda and around Mount Kenya (Jaramillo et al., 2011). Climate suitability for tephritid fruit flies is projected to decrease in central Africa (Hill et al., 2016). Increased water temperature is projected to favour invasive over local freshwater fish populations and shift the range of invasive aquatic plants in South Africa (Hoveka et al., 2016; Shelton et al., 2018). Alterations to lake and river connectivity are predicted to modify invasion pathways in Lake Tanganyika and water hyacinth coverage may increase with warmer waters in Lake Victoria (Masters and Norgrove, 2010; Plisnier et al., 2018).

9.6.3 Nature-Based Tourism in Africa

Nature-based tourism is important for African economies and jobs. Tourism contributed 8.5% of Africa's 2018 GDP (World Travel and Tourism Council, 2019a) with Wildlife tourism contributing a third of tourism revenue (USD 70.6 billion), supporting 8.8 million jobs (World Travel and Tourism Council, 2019b).

Climate change is already negatively affecting tourism in Africa (*high confidence*). The 2015–2018 Cape Town drought caused severe water restrictions, reducing tourist arrivals and spending with associated job losses (Dube et al., 2020). Anthropogenic climate change increased the likelihood of drought by a factor of five to six (Pascale et al., 2020). Extreme heat days have increased across South African national parks since the 1990s (van Wilgen et al., 2016). This reduces animal mobility, decreasing animal viewing opportunities (Dube and Nhamo, 2020). Tourists and employees also fear heat stress (Dube and Nhamo, 2020). Visitors to South Africa's national parks preferred to visit in cool-to-mild temperatures (Coldrey and Turpie, 2020). Extreme weather conditions disrupted tourist activities and damaged infrastructure at Victoria Falls, Hwange National Park, Kruger National Park and the Okavango Delta (Dube et al., 2018; Dube and Nhamo, 2018; Mushawemhuka et al., 2018; Dube and Nhamo, 2020). Rainfall variability and drought alters wildlife migrations, affecting tourist visits to the Serengeti (Kilungu et al., 2017). Reduced tourism decreases revenue for national park management (van Wilgen et al., 2016).

Future climate change is projected to further negatively affect nature-based tourism. Decreased snow and forest cover may reduce visits to Kilimanjaro National Park (Kilungu et al., 2019). Woody plant expansion in savanna and grasslands reduce tourist's game viewing experience and negatively impact conservation revenues (Gray Emma and Bond William, 2013; Arbieu et al., 2017). Visitation rates to South African national parks, based on mean monthly temperatures, are projected to decline 4% with 2°C global warming (Coldrey and Turpie, 2020). Sea level rise and increased intensity of storms is projected to reduce beach tourism due to beach erosion (Grant, 2015; Amusan and Olutola, 2017). Tourism in the Victoria Falls, Okavango and Chobe hydrological systems may be negatively affected by heat and increased variability of rainfall and river flow (Saarinen et al., 2012; Dube and Nhamo, 2019). Increased extreme heat will increase air turbulence and weight restrictions on aircraft, which could make air travel more uncomfortable and expensive to African destinations (Coffel and Horton, 2015; Dube and Nhamo, 2019).

9.6.3.1 Protected Areas and Climate Change

African protected areas store around 1.5% of global land ecosystem carbon stocks and support biodiversity (Gray et al., 2016; Melillo et al., 2016; Sala et al., 2018). They also support livelihoods and economies, such as through nature-based tourism and improved fisheries (Brockington and Wilkie, 2015; Mavah et al., 2018; Ban et al., 2019).

Climate change and land use change will interact to influence the effectiveness of African protected areas (*high confidence*). Species representation in the existing African protected area network is projected to decrease due to species range shifts for mammals, bats, birds and amphibians (Hole et al., 2009; Baker et al., 2015; Payne and Bro-Jørgensen, 2016; Smith et al., 2016; Phipps et al., 2017). Species ability to disperse between areas to track shifting climates is increasingly impaired by land transformation and fencing, which also impact seasonal wildlife migrations (Lovschal et al., 2017; Sloan et al., 2017). On land, only 0.5% of the African protected area network is connected through low-impact landscapes (Ward et al., 2020). Linear transport infrastructure (e.g., roads, railways, pipelines) and fencing from proposed 'development corridors' are projected to bisect over 400 protected areas and degrade around 1,800 more (Laurance et al., 2015). Climate change could increase human-wildlife conflict as resultant resource shortages cause communities to move into protected areas for harvesting or livestock grazing, or wildlife to move out of protected areas and into contact with people (Mukeka et al., 2018; Kupika et al., 2019; Hambira et al., 2020). See Section 9.1.4 for the role of land and ocean protected areas in climate change adaptation.

9.6.4 Ecosystem-Based Adaptation in Africa

Ecosystem-based adaptation (EbA) uses biodiversity and ecosystem services to assist people to adapt to climate change (Swanepoel and Sauka, 2019). Africa's Nationally Determined Contributions (NDCs) show 36% of adaptation actions identified by 52 countries are considered to be EbA (Figure 9.20).

EbA can reduce climate impacts and there is high agreement EbA can be more cost-effective than traditional grey infrastructure when a range of economic, social and environmental benefits are also accounted for (Table 9.6) (Baig et al., 2016; Emerton, 2017; Chausson et al., 2020). This is particularly relevant in Africa where climate vulnerabilities are strongly linked to natural resource-based livelihood practices and existing grey infrastructure levels are low in many regions (Dube et al., 2016; Reid et al., 2019). However, financial constraints limit EbA project implementation (Mumba et al., 2016; Swanepoel and Sauka, 2019).

Evidence for EbA in Africa is largely case study based and often anecdotal (Reid et al., 2018). There is *high agreement* that costs, challenges and negative outcomes of EbA interventions are still poorly understood (Reid, 2016; Chaplin-Kramer et al., 2019), despite limited evidence for the efficacy of context-specific applications at different scales (Doswald et al., 2014).

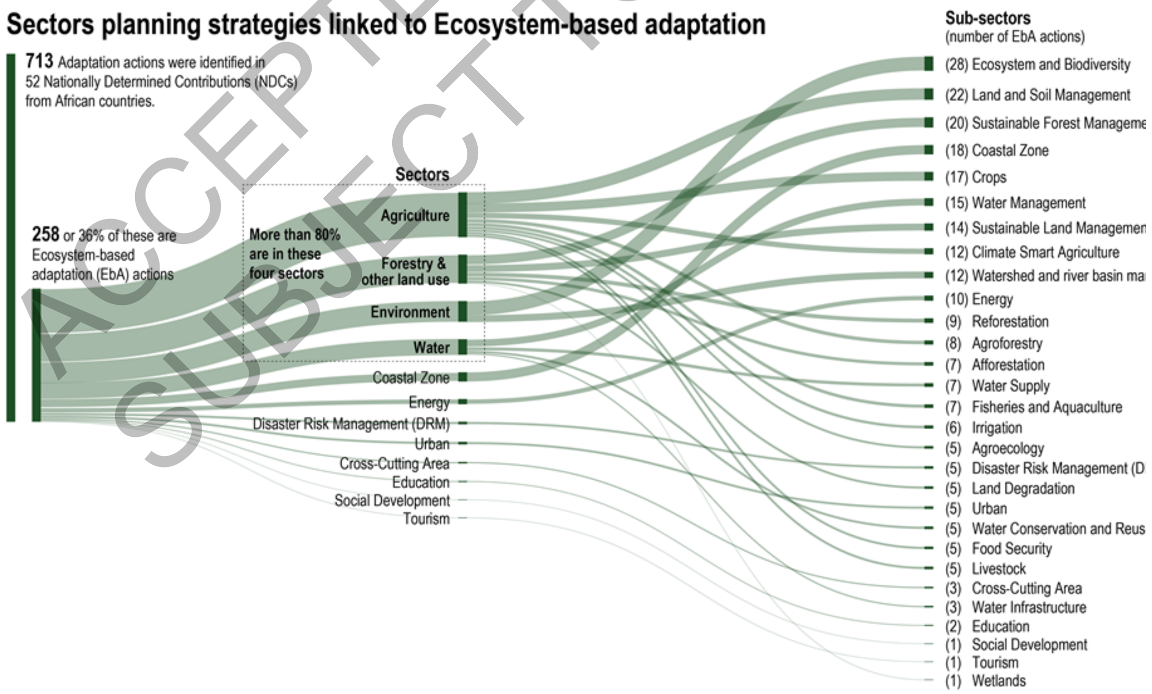


Figure 9.20: Over a third (36%) of all adaptation actions identified in the NDCs of 52 African countries are Ecosystem-based Adaptations (EbA). Of these actions ± 83% fall within the Agriculture, Land Use/Forestry, Environment and Water sectors. The EbA actions identified from the NDCs span 12 primary sectors and 29 sub-sectors.

Table 9.6: The beneficial outcomes of Ecosystem-based Adaptation (EbA) actions and assessed confidence in these outcomes. Assessment is provided for EbA options in the four most prevalent EbA sectors identified in the Nationally Determined Contributions of 52 African countries (Figure 9.20). See Chapter 2.6.3 and 3.6.2 of this report for further assessment of EbA approaches in terrestrial, freshwater and marine systems.

Sector	EbA Action(s)	Outcome(s)	Confidence	Source(s)
Agriculture	Conservation agriculture	Improved soil and water conservation	*High*	(Thierfelder et al., 2017)
		Improved agricultural productivity and drought resilience	*Medium*	(Pittelkow et al., 2015; Thierfelder et al., 2017; Adenle et al., 2019)
	Diversified crop varieties	Improved agricultural productivity and drought resilience	*High*	(Shiferaw et al., 2014; Tesfaye et al., 2016; Thierfelder et al., 2017)
Environment	Ecosystem protection and restoration	Carbon sequestration and storage	*High*	(Melillo et al., 2016; Griscom et al., 2017; FAO, 2018a)
		Stepping stones for species migrating due to climate change	*Medium*	(Beale et al., 2013; Roberts et al., 2020)
		Increased ecosystem resilience to disturbance	*High*	(Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; Roberts et al., 2017)
		Livelihood diversification opportunities from ecotourism, resource harvesting, and rangelands (among others)	*Medium*	(Lunga and Musarurwa, 2016; Bedelian and Ogutu, 2017; Agyeman, 2019; Kupika et al., 2019; Naidoo et al., 2019)
Forestry & Other Land Use	Restoration/ Reforestation Sustainable forestry and land management	Restoration of degraded ecosystems and enhanced carbon sequestration	*High*	(Mugwedi et al., 2018)
		Reducing pressure on forests for food and energy needs	*Medium*	(Peprah, 2017; Zegeye, 2018)
Water	Integrated catchment management	Improved flood attenuation capacity	*High*	(Bradshaw et al., 2007; Mwenge Kahinda et al., 2016; Rawlins et al., 2018)
		Improved resilience of freshwater ecosystems	*High*	(Ndebele-Murisa, 2014; Natugonza et al., 2015; Lowe et al., 2019; Tamatamah and Mwedzi, 2020)

9.6.4.1 Terrestrial Ecosystems

Improved ecosystem care and restoration are cost-effective for carbon sequestration while providing multiple environmental, social and economic co-benefits (Griscom et al., 2017; Shukla et al., 2019). Protecting and restoring natural forests and wetlands reduces flood risk across multiple African countries (Bradshaw et al., 2007). In Kenya, enclosures for rangeland regeneration diversified income sources, which could increase the adaptive capacity of local people (Mureithi et al., 2016; Wairore et al., 2016). Sustainable agroforestry in semi-arid regions provides income sources from fuelwood, fruit and timber and reduces exposure to drought, floods and erosion (Quandt et al., 2017). Forest protection in Zimbabwe maintains honey production during droughts, providing food supply options if crops fail (Lunga and Musarurwa, 2016). Community-based natural resource management in pastoral communities improved institutional governance outcomes through involving community members in decision-making, increasing the capacity of these communities to respond to climate change (Reid, 2014).

EbA can also increase ecological resilience. Re-introduction of fire and large mammals can restore ecosystem services, enhance adaptive capacity and benefit people by combatting woody encroachment, restoring grazing and increasing streamflow (Asner et al., 2016; Stafford et al., 2017; Cromsigt et al., 2018). Herbivores can also reduce fuel loads in areas facing increased fire risk (Hempson et al., 2017).

Protected areas can be ‘stepping stones’ that facilitate climate-induced species range shifts (Roberts et al., 2020), preserve medicinal plant diversity despite climate change (Kaky and Gilbert, 2017) and provide livelihood diversification opportunities (Table 9.6). Protecting 30% of sub-Saharan Africa’s land area could reduce the proportion of species at risk of extinction by around 60% in both low and high warming scenarios (Hannah et al., 2020). The role of protected areas in EbA can be strengthened by: (i) increasing coverage of diverse environments and high carbon storage ecosystems, (ii) habitat restoration, (iii) maintaining intact habitat, (iv) participatory, equitable conservation and adaptation strategies; (v) cooperation across borders and (vi) adequate monitoring (Gillson et al., 2013; Rannow et al., 2014; Midgley and Bond, 2015; Pecl et al., 2017; Dinerstein et al., 2019; Roberts et al., 2020).

[START BOX 9.3 HERE]

Box 9.3: Tree Planting in Africa

Due to widespread deforestation and forest degradation (Malhi et al., 2014), future scenarios to limit global warming include large-scale reforestation and afforestation (Griscom et al., 2017; Bastin et al., 2019). Africa has been targeted through the AFR100 (https://afr100.org) to plant ~1 million km^2 of trees by 2030 (Bond et al 2019). Maintaining existing indigenous forest and indigenous forest restoration is a win-win, maximising benefits to biodiversity, adaptation and mitigation (Griscom et al., 2017; Watson et al., 2018; Lewis et al., 2019) (*high confidence*).

Yet many areas targeted by AFR100 erroneously mark Africa’s open ecosystems (grasslands, savannas, shrublands) as degraded and suitable for afforestation (Figure Box 9.3.1) (Veldman et al., 2015; Bond et al., 2019) *(high confidence)*. These ecosystems are not degraded, they are ancient ecosystems that evolved in the presence of disturbances (fire/herbivory) (Maurin et al., 2014; Bond and Zaloumis, 2016; Charles-Dominique et al., 2016). Afforestation prioritises carbon sequestration at the cost of biodiversity and other ecosystem services (Veldman et al., 2015; Bond et al., 2019). Furthermore, it remains uncertain how much carbon can be sequestered as, compared to grassy ecosystems, afforestation can reduce belowground carbon stores and increase aboveground carbon loss to fire and drought (Yang et al., 2019; Wigley et al., 2020b; Nuñez et al., 2021). Thus, afforested areas may store less carbon than ecosystems they replace (Dass et al., 2018; Heilmayr et al., 2020). Afforestation would reduce livestock forage, eco-tourism potential and water availability (Gray Emma and Bond William, 2013; Anadón et al., 2014; Cao et al., 2016; Stafford et al., 2017; Du et al., 2021), and may reduce albedo thereby increasing warming (Baldocchi and Penuelas, 2019; Bright et al., 2015).

Exotic tree species are often selected for planting (e.g., *Pinus* spp or *Eucalyptus* spp), but in parts of Africa, they have become invasive (Zengeya, 2017; Witt et al., 2018), increasing fire hazards and decreasing biodiversity and water resources (Nuñez et al., 2021) *(high confidence)*. Negative impacts of afforestation on ecosystems are not restricted to plantations of exotic species; they extend to inappropriate planting of native forest species (Slingsby et al., 2020).

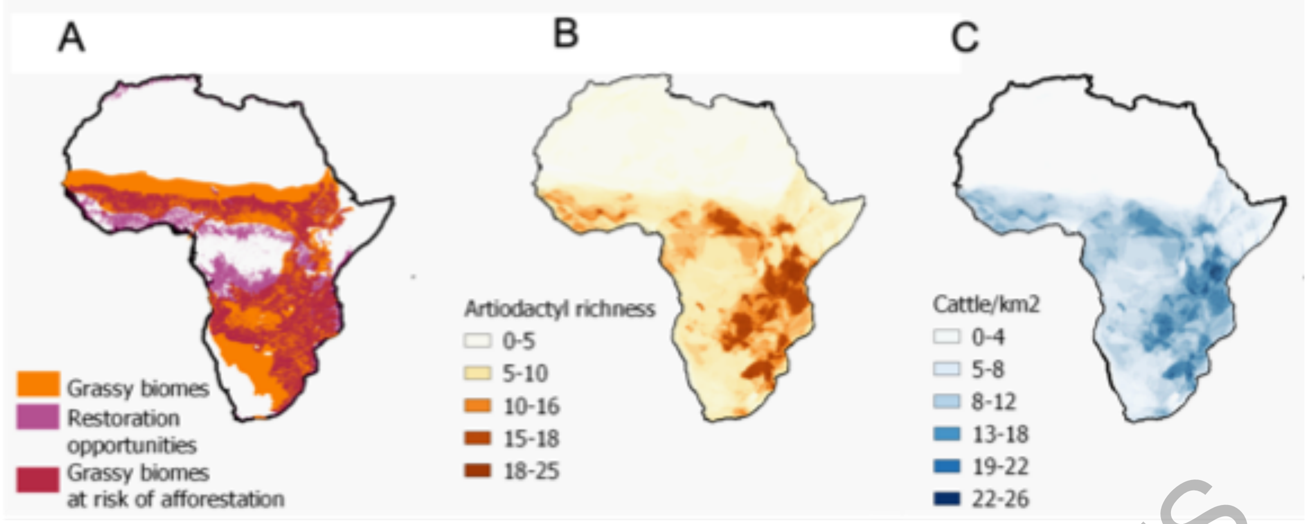


Figure Box 9.3.1: Proposed tree planting plans in Africa are focused on (a) non-forested ecosystems like savannas, grasslands and shrublands which (b) host uniquely adapted biodiversity and (c) offer important ecosystem services like grazing which supports subsistence and commercial agriculture. Figure adapted from (Bond et al., 2019).

[END BOX 9.3 HERE]

9.6.4.2 Freshwater Ecosystems

EbA can mitigate flooding and increase the resilience of freshwater ecosystems (Table 9.6). Adaptation in African freshwater ecosystems is heavily influenced by non-climate anthropogenic factors, including land use change, water abstraction and diversion, damming and overfishing (Dodds et al., 2013; Kimirei et al., 2020; UNESCO and UN-Water, 2020). Wetlands and riparian areas support biodiversity, act as natural filtration systems and serve as buffers to changes in the hydrological cycle, thereby increasing the resilience of freshwater ecosystems and the people that rely on them (Ndebele-Murisa, 2014; Musinguzi et al., 2015; Lowe et al., 2019). However, national adaptation programmes of action, national adaptation plans and national communications rarely consider the ecological stability of ecosystems safeguarding the very water resources they seek to preserve (Kolding et al., 2016). Some countries have mandated the protection of riparian zones, but implementation is low (Musinguzi et al., 2015; Muchuru and Nhamo, 2018). Protecting terrestrial areas surrounding Lake Tanganyika benefited fish diversity (Britton et al., 2017). Afforestation reduces water availability but forest restoration and removing invasive plant species can increase water flows in regions facing water insecurity from climate change (Chausson et al., 2020; Le Maitre et al., 2020). Regular, long-term monitoring of African freshwaters would improve understanding of responses to climate change. General principles for this type of monitoring were developed for Lake Tanganyika (Plisnier et al., 2018) and could be applied to develop harmonised, regional monitoring of African lakes, rivers and wetlands (Tamatamah and Mwedzi, 2020)

9.6.4.3 Marine and Coastal Ecosystems

Marine and coastal ecosystems such as mangroves, seagrass and coral reefs provide storm protection and food security for coastal communities (*high confidence*) (IPCC, 2019c). Restoring reef systems reduced wave height in Madagascar (Narayan et al., 2016), but there is limited evidence for the efficacy of coral reef restoration at large scales with increased warming (3.6.3). Populations at risk from storm surge and/or sea level rise coincide with areas of high coastal EbA potential from Mozambique to Somalia, and coastlines of the Gulf of Guinea, Gambia, Guinea-Bissau and Sierra Leone (Jones et al., 2020). Understanding hotspots of EbA potential is particularly important for West Africa with some of the highest levels of human dependence on marine ecosystems at high risk from climate change and large populations vulnerable to sea level rise (Selig et al., 2018; Trisos et al., 2020) (Sections 9.9.3.1 and 9.8.5.2).

Marine protected areas (MPAs) can yield multiple adaptation benefits, such as buffering species from extinction and increasing fish stocks, as well as storing large amounts of carbon (Edgar et al., 2014; Roberts et al., 2017; Lovelock and Duarte, 2019). However, this potential of MPAs will reach limits with increased warming (Roberts et al., 2017). For example, MPAs cannot prevent coral bleaching at scale and mass die-offs are well-described from MPAs following climate shocks (Bates et al., 2019; Bruno et al., 2019). Although prioritising MPA coverage of climate refugia, such as the northern Mozambique channel, may offer some increased resilience (McClanahan et al., 2014).

9.7 Water

Much of Africa experiences very high hydrological variability in all components of the water cycle, with important implications for people and ecosystems. Most of the continent's water is stored in groundwater (660,000 km^3), which is 20 times more than the water stored in the lakes and 100 times more than the annual renewable water resources (MacDonald et al., 2012). The accessible volume of groundwater via wells and springs is smaller than these estimates (Xu et al., 2019). Africa has 63 transboundary river basins (UNEP, 2010), 72 mapped transboundary aquifers (Nijsten et al., 2018) and 33 transboundary lakes (ILEC and UNEP, 2016), reflecting a highly water-connected and interdependent socio-ecological system across countries, extending also to the coastal areas of the continent (see Section 4.1, Figure 4.1).

9.7.1 Observed Impacts from Climate Variability and Climate Change

Climate impacts on water are occurring against a backdrop of increasing temperatures and changes in rainfall, with increased seasonal and interannual variability, droughts in some regions, and increased frequency of heavy rainfall events (see Section 9.5). In West Africa, declines in river flows have been attributed to declining rainfall and increasing temperature, drought frequency and water demand (Biao, 2017; Thompson et al., 2017; Descroix et al., 2018). In Central Africa, the Congo river demonstrates inter-decadal shifts but no long-term trend (Mahe et al., 2013; Alsdorf et al., 2016), however, recently observed falling water levels in its upper and middle reaches are attributed to climate change (von Lossow, 2017).

A review of river flow and lake level changes in 82 basins in eastern and southern Africa regions for 1970–2010 showed mixed trends: 51% had decreasing trends ranging from 10–49% and 11% increasing trends ranging from 7–60% (Schäfer et al., 2015). However, in southern Africa as a whole, river flows have mostly decreased *(high confidence)* (Dallas and Rivers-Moore, 2014). In East Africa, large rivers such as the Tana show increasing flow (1941–2016) related to increased rainfall in the highlands, with little influence of flow regulation by a series of dams (Langat et al., 2017). The Nile river basin has been experiencing a mainly increasing rainfall trend upstream and decreasing trend downstream (Onyutha et al., 2016). The observed changes are driven by a complex coupling of changes in climate, land use and water demand.

Observed climate changes in Africa (see Section 9.5) have led to changes in river flow and runoff (Dallas and Rivers-Moore, 2014; Wolski et al., 2014) and high fluctuations in lake levels *(high confidence*) (Natugonza et al., 2016; Ogutu-Ohwayo et al., 2016; Gownaris et al., 2018). Shallow lakes respond dramatically to hydrological changes, for example, Lake Chilwa has dried up completely nine times in the last century (Wilson, 2014), while Lake Chad shrunk by 90% between 1963 and 2000 (Gao et al., 2011). However, recent analyses indicate that Lake Chad's water levels have been stable since 2000 due to infilling from groundwater resources (Buma et al., 2018; Pham-Duc et al., 2020). Other factors such as deforestation and increased water use in upstream tributaries also contribute to lake shrinking (Mvula et al., 2014). Water levels in Kenya's mostly shallow rift lakes have been rising since 2010, with some exceeding historical record high levels (Schagerl and Renaut, 2016; Olago et al., 2021). The recent 10-year rising trend is partly attributed to increased rainfall and changing land uses (Onywere and John M. Mironga, 2012; Olago et al., 2021). Changes in water level fluctuations of 13 African lakes have been positively correlated with primary and overall production (Gownaris et al., 2018), and will have important consequences for freshwater ecosystems and related ecosystem goods and services (see Sections 9.6.1.3 and 9.8.5). Other effects of observed climate changes in Africa include higher episodic groundwater recharge, particularly in drylands, from heavy rainfall events that are in some cases related to El Niño-Southern Oscillation and the Indian Ocean Dipole (Taylor et al., 2013; Fischer and Knutti, 2016; Cuthbert et al., 2019; Kotchoni et al., 2019; Myhre et al., 2019), reduced soil moisture, more frequent and intense floods, more persistent and frequent droughts (Douville et al., 2021) and the steady decline and projected disappearance by 2040 of African tropical glaciers (see Section 9.5.9).

The mixed-signal in river flow trends (increase/decrease/no-change) across Africa mirrors the results seen globally for runoff and streamflow (see Section 4.2.3 in Chapter 4). Hydrological extremes are, however, of increasing concern. There has been an increase in drought frequency, severity and spatial extent in recent decades. From 1900–2013, Africa suffered the largest number of drought events globally and registered the second largest number of people affected after Asia (Masih et al., 2014). The likelihood of recent severe climate conditions such as the multi-year Cape Town Drought has increased to due to human-induced climate change (Otto et al., 2018; Pascale et al., 2020) (see Box 9.4), and regional and urban floods (Yuan et al., 2018; Tiitmamer, 2020) and droughts (Funk et al., 2018b; Siderius et al., 2018; Uhe et al., 2018) are expected to increase.

However, between 2010–2020 more people across Africa have been impacted by floods (e.g., related to Cyclone Idai in March 2019) compared to droughts (Lumbroso, 2020). Coastal cities are vulnerable to floods related to rainfall and sea level rise (Musa et al., 2014), as exemplified by the flood disasters experienced in the Niger delta in 2012 which displaced more than 3 million people and destroyed schools, clinics, markets and electricity installations (Amadi and Ogonor, 2015). From 2000–2015, the proportion of people exposed to floods grew by 20–24%, mostly in Africa and Asia, and these numbers will increase under climate change (Tellman et al., 2021). Sectoral impacts from flooding within Africa and globally are further elaborated on in Sections 9.8.2 and 9.8.5.1, Table 9.3 and Section 4.3 in Chapter 4.

[START BOX 9.4 HERE]

Box 9.4: African Cities Facing Water Scarcity

Many African cities will face increasing water scarcity under climate change (Grasham et al., 2019). The Cape Town and Dodoma cases illustrate challenges for both surface and groundwater supply and what adaptation responses have been employed.

The Cape Town Drought (2015-2018)

The Cape Town drought illustrates how a highly diverse African city and its citizens responded to protracted and unanticipated water scarcity. Anthropogenic climate change made the drought five to six times more *likely* (Pascale et al., 2020; Doblas-Reyes et al., 2021). After three consecutive years of low precipitation, Cape Town braced for a 'Day Zero' where large portions of the city would lose water supply (Cole et al., 2021a). The risk of day zero was anticipated to cascade to affect risks to health, economic output and security (Simpson et al., 2021b). The case study highlights the importance of communication, budgetary flexibility, robust financial buffers and insurance mechanisms, disaster planning, intergovernmental cooperation, nature-based solutions, infrastructure transformations and equitable access for climate adaptation in African cities facing water scarcity.

A substantial media campaign was launched to inform residents about the severity of the drought and urge water conservation (Booysen et al., 2019; Hellberg, 2019; Ouweneel et al., 2020). Together with stringent demand management through higher water tariffs, this communication campaign played an important role in reducing consumption from 540 to 280 litres per household per day (Booysen et al., 2019; Simpson et al., 2019a). Revenue from water sales contributes 14% of Cape Town's total revenue, making it the third-largest source of 'own' revenue for the city (Simpson et al., 2019b). However, with an unprecedented reduction in water use, the municipal budget was undermined (Simpson et al., 2020b). Collecting less revenue created a financial shock as the city struggled to recover operating finance, even while new capital requirements were needed for the development of expensive new water supply projects (Simpson et al., 2019b). This financial shock was compounded by the economic stress of poor agricultural and tourism performance brought about by the drought (Shepherd, 2019; Simpson et al., 2021b). As wealthy residents invested in private, off-grid water supplies, the risk of reduced municipal revenue collections from newly off-grid households aggregated with the risk of reduced tourism, increasing the risk to the reputation of the incumbent administration (Simpson et al., 2021b). This demonstrates how a population cohort with a high response capability to water scarcity can reduce risk while simultaneously increasing risks to the municipality and its capacity to provide water to vulnerable residents (Simpson et al., 2020b). Given that city populations in Africa pay 5–7 times more for water than the average price paid in the United States or Europe (Adamu and Ndi, 2017; Lwasa et al., 2018), municipal finance needs to delink operating revenue from potential climate shocks (see Box 8.6 in Chapter 8).

The drought led the municipality to consider a broader diversity of water supply options, including groundwater (CoCT, 2019), developing city-scale slow-onset disaster planning (Cole et al., 2021a) and building an enhanced 'relationship with water' (CoCT, 2019; Madonsela et al., 2019). This shift in approach is displayed in the recognition of nature-based solutions as a priority in water resilience-building efforts (Rodina, 2019) and is signalled in Cape Town's Water Strategy which aims to become a 'water sensitive city' that makes 'optimal use of stormwater and urban waterways for flood control, aquifer recharge, water reuse and recreation' (CoCT, 2019).

The drought required cooperation between multiple spheres of government, and the management of a broad range of stakeholders and political entities (Nhamo and Agyepong Adelaide, 2019; Cole et al., 2021a). The case highlights how a lack of coordination between essential organs of state and political entities can reduce response efficacy (Rodina, 2019). Despite significant investments in water security by public and private entities, one-quarter of Cape Town's population remains in persistent conditions of water stress, emphasising the challenge and importance of inclusive solutions that address the persistent social and economic stressors which affect vulnerability to water scarcity (Enqvist and Ziervogel, 2019).

Sustaining intensive groundwater use in a dryland city under climate change: Dodoma, Tanzania

Since 1954, the Makutapora wellfield in semi-arid, central Tanzania has supplied safe water to the city of Dodoma. Substantial rises in wellfield pumping and population growth have increased freshwater demand in Dodoma and dependence upon the Makutapora Wellfield, currently the sole perennial source of piped water to the city. Yet, there is high uncertainty of groundwater recharge rates (Nkotagu, 1996; Taylor et al., 2013) which rely on intense seasonal rainfall associated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) modes of climate variability (e.g., 2 to 7 years) to contribute disproportionately to recharge (Taylor et al., 2013; Kolusu et al., 2019).

Defining a sustainable pumping rate for the Makutapora wellfield is complicated by the variable and episodic nature of groundwater replenishment in this dryland environment. For example, groundwater recharge during the 1997/1998 El Niño event, the strongest El Niño event of the 20th century, accounted for nearly 20% of all of the recharge received from 1955–2010 (Taylor et al., 2013), highlighting the vital role interannual groundwater storage plays in enabling adaptation to climate variability and change in drylands. The disproportionate contribution of intense seasonal rainfalls to the replenishment of the Makutapora wellfield, consistent with observations from across sub-Saharan Africa (Cuthbert et al., 2019), suggests that groundwater in drylands are currently naturally resilient to climate change. However, it remains unclear whether climate change will strengthen or weaken the influence of ENSO and IOD on rainfall (Brown et al., 2020) and thereby affect the predictability of groundwater recharge.

As freshwater demand in Tanzania's rapidly growing capital is projected to increase substantially in the coming decades, questions remain as to whether the capacity of the Makutapora wellfield can meet some or all of this demand. Nature-based solutions to improve the resilience of wellfield abstraction to increased pumpage and climate change include Managed Aquifer Recharge (MAR). The sharing of general lessons learned from other cities in dryland Africa employing MAR, such as Windhoek in Namibia (Murray et al., 2018), could prove invaluable.

[END BOX 9.4 HERE]

9.7.2 Projected Risks and Vulnerability

9.7.2.1 Projected Risks

By 2050, up to 921 million additional people in Africa could be exposed to climate change-related water stress, while up to 459 million could experience reduced exposure (Dickerson et al., 2021). This large variance in numbers and direction of change is related to uncertainties in climate models and non-climate factors like population growth and water withdrawals (Dickerson et al., 2021). The baseline for most of the projected risks presented here is 1971–2000.

In West Africa, significant spatial variability in river flow is projected in the upper reaches of several rivers, with no clear pattern overall (Roudier et al., 2014) and large uncertainties in estimations of change in runoff (Roudier et al., 2014; Bodian et al., 2018). In some higher altitude regions, like the Niger Inland Delta in West Africa, river flows and water levels are expected to increase (*medium confidence*) (Aich et al., 2014; Thompson et al., 2017). In the Lower Niger Basin, combined average annual rainfall and erosivity for all the climatic models in all scenario shows increasing rainfall amounts are projected to result in an increasing average change in rainfall-runoff erosivity of about 14%, 19% and 24% for the 2030s, 2050s and 2070s, with concomitant increase in soil loss of 12%, 19% and 21% (Amanambu et al., 2019). In the Volta River system, increasing wet season river flows (+36% by 2090s) and Volta lake outflow (+5% by 2090s) are anticipated under RCP8.5 (*medium confidence*) (Awotwi A et al., 2015; Jin et al., 2018). In the Volta River basin, compared to 1976–2005, drought events are projected to increase by 1.2 events per decade at around 2°C to 1.6 events per decade at around 2.5°C global warming, and drought area extent is projected to increase by 24% to 34% (Oguntunde et al., 2017). In Central Africa, runoff in the Congo River system may increase by up to 50% (RCP8.5), especially in the wet season, enhancing flood risks in the entire Congo basin, particularly in the central and western parts (CSC, 2013). Average river flows are expected to increase in most parts of Central Africa, with expected increases in total potential hydropower production (Ludwig et al., 2013).

In North Africa, in the upper White Nile basin, Olaka et al. (2019) project a 25% and 5 to 10% (RCP4.5) increase in the intensification of future annual rainfall in the eastern and western parts of the Lake Victoria Basin, respectively, with corresponding variability in future river discharge ranging from 5 to 26%. In the upper Blue Nile basin, models also indicate up to 15% increase in runoffs in wet-season and up to −24% decreasing in dry-season 2021–2040 (RCP8.5) (Ayele et al., 2016; Siam and Eltahir, 2017; Meresa and Gatachew, 2018). The increase of precipitation in wet-season indicates a higher possibility of flash floods while decreased runoffs in dry-season further intensify existing shortage of irrigation water demand (Ayele et al., 2016; Siam and Eltahir, 2017; Meresa and Gatachew, 2018). The annual flow and revenues from hydropower production and irrigated agriculture of the Blue Nile River at Khartoum are projected to increase under maximum but are expected to decrease under minimum and median projected changes in streamflow for 2041–2070 and 2071–2100, respectively (Tariku et al., 2021). The Middle Draa valley in Morocco is expected to experience more severe droughts and the estimation of the water balance suggests a lack of supply in the future (Karmaoui et al., 2016).

In East Africa, Liwenga et al. (2015) show that it will *likely* be warmer and wetter in the Great Ruaha River region and with increasing seasonal variation and extremes towards the end of the century. A similar observation is made for the River Pangani, with mean river flow being about 10% higher in the 2050s relative to the 1980–1999 period, associated with a 16–18% increase in rainfall in its upper catchment (Kishiwa et al., 2018). However, at more local scales, the projections cover a range of slight declines to significant increases in mean annual rainfall amounts (Gulacha and Mulungu, 2017). In the Tana River basin in Kenya, water yield is projected to increase progressively under RCP4.5 and RCP8.5 relative to the baseline period 1983–2011 but is characterised by distinct spatial heterogeneity (Muthuwatta et al., 2018).

In southern Africa, reductions in rainfall over the Limpopo and Zambezi river basins under 1.5°C and 2°C global warming could have adverse impacts on hydropower generation, irrigation, tourism, agriculture and ecosystems (Figure Box 9.5.1) (Maúre et al., 2018), although model projections of strong early summer drying trends remain uncertain (Munday and Washington, 2019).

Changes in the amplitude, timing and frequency of extreme events such as droughts and floods will continue to affect lake levels, rates of river discharge and runoff and groundwater recharge (*high confidence*) (Gownaris et al., 2016; Darko et al., 2019), but with disparate effects at regional, basin and sub-basin scales, and at seasonal, annual and longer timescales. The increased frequency of extreme rainfall events under climate change (Myhre et al., 2019) is projected to amplify groundwater recharge in drylands (Jasechko and Taylor, 2015; Cuthbert et al., 2019). However, declining trends in rainfall and snowfall in some areas of North Africa (Donat et al., 2014b) are projected to continue in a warming world (Seif-Ennasr et al., 2016), restricting groundwater recharge from meltwater flows, exacerbating the salinisation and depletion of groundwater (Hamed et al., 2018) and increasing the risk of reduced soil moisture (Petrova et al., 2018) in this region where groundwater abstraction is greatest (Wada et al., 2014).

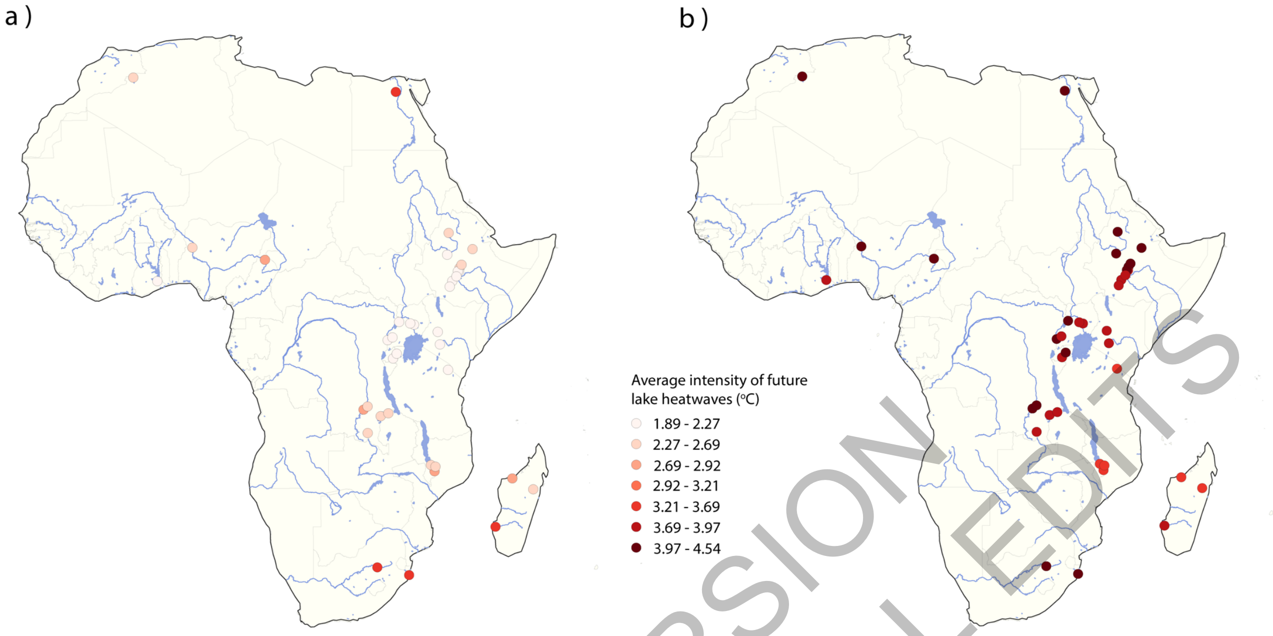


Figure 9.21: Climate change is projected to increase the intensity of lake heatwaves across Africa. Projected increases in average intensity of lake heatwaves (°C) under (a) 1.8°C global warming (RCP2.6 in 2070–2099) and (b) 4.2°C global warming (RCP8.5 in 2070–2099). Each lake is represented by a point. Data were extracted from (Woolway et al., 2021).

Lake surface temperatures across Africa are expected to rise in tandem with increasing global warming. Lake heatwaves, periods of extreme warm lake surface water temperature, are projected to become hotter and longer (Figure 9.21), with heatwaves more than 300 days per year in many lakes for global warming of 4.2°C (Woolway et al., 2021). Lake warming is expected to have adverse consequences for aquatic biodiversity, habitats, water quality and disruption of current lake physical processes and circulation patterns (Kraemer et al., 2021).

9.7.2.2 Vulnerability

Climate change is projected to reduce water availability and increase the extent of water scarcity (Mekonnen and Hoekstra, 2016), particularly in southern and North Africa, while other regions will be more affected by increased hydrological variability over temporally short to interannual timescales (see Section 9.6.2). African countries are considered to be particularly at risk due to their underlying vulnerabilities (IPCC, 2014; UNESCO and UN-Water, 2020), yet the continents' water resources are still inadequately quantified and modelled (Müller Schmied et al., 2016; Reinecke et al., 2019), constraining sustainable management practices (Cuthbert et al., 2019; Hughes, 2019).

Hydrological fluctuations are associated with drought, flood and cyclone events which have had multi-sector impacts (Siderius et al., 2021) (see Sections 4.3 and 4.5 in Chapter 4), including: reduced crop production (D'Odorico et al., 2018), migration and displacement (Siam and Eltahir, 2017; IDMC, 2018), food insecurity and extensive livestock deaths (Nhamo et al., 2018), electricity outages (Gannon et al., 2018), increased incidence of cholera (Olago et al., 2007; Sorensen et al., 2015; Houéménou et al., 2020) and increased groundwater abstraction amplifying the risk from sea level rise of saline intrusion (Hamed et al., 2018; Ouhamdouch et al., 2019).

The literature shows significant gender-differentiated vulnerability and intersectional vulnerability to climate change impacts on water in Africa (Fleifel et al., 2019; Grasham et al., 2019; Mackinnon et al., 2019; Dickin et al., 2020; Lund Schlamovitz and Becker, 2020), although studies are generally lacking in northern Africa (Daoud, 2021). Women and girls are in most cases more impacted than men/boys by customary water practices as adult females are the primary water collectors (46% in Liberia to 90% in Cote d'Ivoire), while more female than male children are associated with water collection (62% compared with 38%, respectively) (Graham et al., 2016). Women and girls face barriers toward accessing basic sanitation and hygiene resources, and 71% of studies reported a negative health outcome, reflecting a water-gender-health nexus (Pouramin et al., 2020). These differential vulnerabilities are crucial for informing adaptation, but are still relatively under-researched, more so for the urban poor than rural communities (Grasham et al., 2019; Mackinnon et al., 2019; Lund Schlamovitz and Becker, 2020).

9.7.3 Water Adaptation Options and their Feasibility

9.7.3.1 Reducing Risk through a Systems Approach to Water Resources Planning and Management

An integrated systems and risk-based approach to the design and management of water resources at scale is generally accepted as a practical and viable way of underpinning the resilience of water systems to climate change and human pressures (Duffy, 2012; García et al., 2014). Such approaches confer multiple benefits to nature and society at scale and enhance efficiency gains through technology and management improvements, but their full implementation has not yet been realised (Weinzierl and Schilling, 2013; McDonald et al., 2014; UN Environment, 2019). Drylands are particularly singled out as ignored areas that require Integrated Water Resource Management approaches (Stringer et al., 2021) (Section 9.3.1). Appropriate nature-based solutions that are applicable at scale should be identified and strongly embedded in these approaches to deliver multiple benefits while maintaining the integrity of ecosystems and biodiversity (UN Environment, 2019) (see Sections 9.6.4, 9.8.5, and Box 4.6). Furthermore, adaptation options are often influenced or constrained by institutions, regulation, availability, distribution, price and technologies (McCarl et al., 2016). Thus, institutional capacity to manage complex water supply systems under rapidly increasing demand and climate change stress is critical in achieving water security for African cities, particularly as cities become more dependent on alternative and distant water sources (Padowski et al., 2016).

9.7.3.2 Adopting Nexus Lenses

The water-energy-food (WEF) nexus explicitly recognises the strong interdependencies of these three sectors and their high levels of exposure to climate change (Zografos et al., 2014; Dottori et al., 2018) (see Box 9.5). With increasing societal demands on more variable water resources under climate change, an intensification of WEF competition and trade-offs are projected (D'Odorico et al., 2018; Dottori et al., 2018). Other interacting factors, for example, the increasing number of transnational investments in land resources can lead to localised increased competition for water resources (Messerli et al., 2014; Breu et al., 2016; Chiarelli et al., 2016). Understanding such nexus inter-linkages can help characterise risks to water resource security, identify co-benefits and clarify the range of multi-sectoral actors involved in and affected by development decisions (Kyriakarakos et al., 2020). Major barriers and entry points for greater integration include coordination of horizontal policy and integration of climate change adaptation actions (England et al., 2018), capturing the scarcity values of water and energy embedded in food/energy products (Allan et al., 2015), and inclusion of community-based organisations such as water resource user associations (Villamayor-Tomas et al., 2015) and agricultural cooperatives (Kyriakarakos et al., 2020).

[START BOX 9.5 HERE]

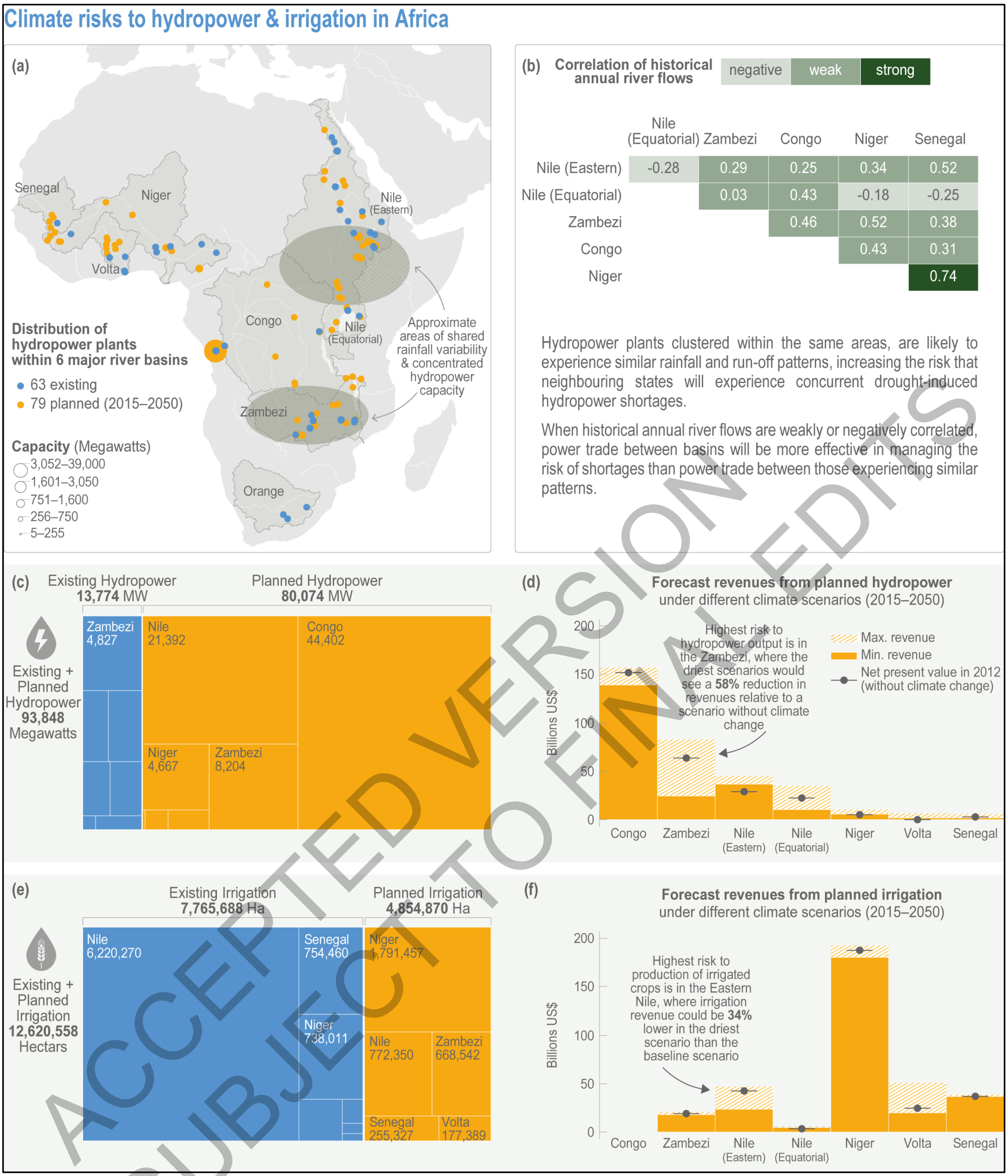
Box 9.5: Water-Energy-Food Nexus

The water-energy-food (WEF) nexus explicitly recognises the strong interdependencies of these three sectors and their high levels of exposure to climate change. Risks can be transmitted from one WEF sector to the other two with cascading risks to human health, cities and infrastructure (Conway et al., 2015; Mpandeli et al., 2018; Nhamo et al., 2018; Yang and Wi, 2018; Ding et al., 2019; Simpson et al., 2021b). For example, increasing demand for water for agricultural and energy production is driving an increasing competition over water resources between food and energy industries which, among other effects, compromises the nutritional needs of local populations (Zografos et al., 2014; Dottori et al., 2018). Drought events, such as in southern

Africa during the 2015/16 El Niño, have been associated with major multi-sector impacts on food security (over 40 million food-insecure people and extensive livestock deaths) and reduced energy security through disruption to hydropower generation (associated in Zambia with the lowest rate of real economic growth in over 15 years)(Nhamo et al., 2018). The WEF nexus of the Nile and Zambezi river basins, which include many of Africa's largest existing hydropower dams, have received the most attention. In these two regions where socioeconomic development is already driving up demand, projections indicate that water scarcity may be exacerbated by drying (Munday and Washington, 2019) and increased flow variability (Siam and Eltahir, 2017). However, for Africa more widely, very few studies fully integrate all three WEF nexus sectors and rarely include an explicit focus on climate change.

In Africa, the climate risks that the water, energy and food sectors will face in the future are heavily influenced by the infrastructure decisions that governments make in the near term. The African Union's Programme for Infrastructure Development (PIDA), along with other national energy plans (jointly referred to as PIDA+), aim to increase hydropower capacity nearly six-fold, irrigation capacity by over 60% and hydropower storage capacity by over 80% in major African river basins (Cervigni et al., 2015). The vast majority of hydropower additions would occur in the Congo, Nile, Zambezi and Niger river basins, and the majority of the irrigation capacity additions would occur in the Niger, Nile and Zambezi River basins (Huber-Lee et al., 2015) (Figure Box 9.5.1).

Climate change risk to the productivity of this rapidly expanding hydropower and irrigation infrastructure compound the overall WEF nexus risk. Future levels of rainfall, evaporation and runoff will have a substantial impact on hydropower and irrigation production. Climate models disagree on whether climates will become wetter or dryer in each river basin. Cervigni et al. (2015) modelled revenues from the sale of hydroelectricity and irrigated crops in major African river basins under different climate scenarios between 2015 and 2050 (Figure Box 9.5.1). The study found that hydropower revenues in the driest climate scenarios could be 58% lower in the Zambezi River basin, 30% lower in the Orange basin and 7% lower in the Congo basin relative to a scenario with current climate conditions. Hydropower revenues in the wettest climate scenario could be more than 20% higher in the Zambezi River basin and 50% higher in the Orange basin. The biggest risk to the production of irrigated crops is in the eastern Nile where irrigation revenue could be 34% lower in the driest scenario and 11% higher in the wettest than in a scenario without climate change (Cervigni et al., 2015).



	Nile (Equatorial)	Zambezi	Congo	Niger	Senegal
Nile (Eastern)	-0.28	0.29	0.25	0.34	0.52
Nile (Equatorial)		0.03	0.43	-0.18	-0.25
Zambezi			0.46	0.52	0.38
Congo				0.43	0.31
Niger					0.74

Hydropower plants clustered within the same areas, are likely to experience similar rainfall and run-off patterns, increasing the risk that neighbouring states will experience concurrent drought-induced hydropower shortages.

When historical annual river flows are weakly or negatively correlated, power trade between basins will be more effective in managing the risk of shortages than power trade between those experiencing similar patterns.

Figure Box 9.5.1: Climate risks to hydropower and irrigation in Africa. The map shows the location and size of existing (blue) and planned (red) hydropower plants in African governments' infrastructure expansion plans, 2015–2050. The bar graphs show the forecast revenues for hydropower and irrigation infrastructure from 2015-2050 in each river basin. Hydropower revenues refer to net present value of hydroelectricity produced in each river basin over the period, and irrigation revenues refer to the crop revenues per hectare for each crop multiplied by the number of hectares of each crop across the basin. Dark blue dots show forecasted revenues from 2015–2050 of existing irrigation and hydropower in major African river basins in a scenario without further climate change (i.e., based on historical data). Red dots show how hydropower and irrigation revenues are expected to increase as new hydropower and irrigation infrastructure is added in a scenario without climate change. Blue and green bars illustrate the range of forecasted revenue from 2015–2050 from new and existing hydropower and irrigation under 121 different climate futures. In river basins with a wide range of potential outcomes, such as the eastern Nile and Zambezi River, there is significant uncertainty around revenue forecasts based on historical trends. All figures are estimates of the net present value of revenues, using a discount rate of 3%, and are in 2012 USD billions. The 121 potential climate futures were derived using different General Circulation Models (GCMs), Representative Concentration Pathways (RCPs), and downscaling methods. IPCC AR4 and AR5 provided data from 22 and 23 GCMs, respectively. These were evaluated across two or three emissions pathways, including RCP4.5 and RCP8.5. The Bias Corrected Spatial Disaggregation (BCSD) method of downscaling was then used to derive 99 potential climate futures. An additional 22 climate futures (11 GCMs driven by the RCP4.5 and RCP8.5 emissions pathways) were produced using the Empirical Statistical Downscaling Methods developed at the Climate Systems Analysis Group at the University of Cape Town.. Data sourced from (Cervigni et al., 2015).

Studies have used the river basin as a unit of analysis and adopted sophisticated techniques to assess and present trade-offs between competing uses. For example, Yang and Wi (2018) consider the WEF nexus in the Great Ruaha tributary of the Rufiji River in Tanzania motivated by an observed decrease in streamflow during the dry season in the 1990s, but without an explicit focus on climate. Yang and Wi (2018) show sensitivity of water availability for irrigated crop production to warming, and sensitivity of hydropower generation and ecosystem health to changes in precipitation and dam development. Understanding of WEF nexus interlinkages can help characterise risks and identify entry points and the relevant institutional levels for cross-sectoral climate change adaptation actions (England et al., 2018). An integrated response can be enhanced through the inclusion of community-based organisations, such as water resource user associations and the wide range of other multi-sectoral actors involved in and affected by development decisions. Capturing the scarcity values of water and energy embedded in food and other products can help identify the co-benefits and costs of integrated adaptation (Allan et al., 2015).

[END BOX 9.5 HERE]

9.7.3.3 Climate-Proofing Water Infrastructure

While natural variability in the hydrological cycle has always been considered by water resources planners and engineers (Müller Schmied et al., 2016; Muller, 2018), many countries will have to take into consideration the range of historically unprecedented extremes expected in the future. Increasingly, the provision of urban water security is dependent on the functioning of complex bulk water infrastructure systems consisting of dams, inter-basin transfers, pipelines, pump stations, water treatment plants and distribution networks (McDonald et al., 2014). Risk-based studies on the potential climate change risks for water security show that there are benefits when risks are reduced at the tails of the distribution - floods and droughts—even if there is little benefit in terms of changes in the mean (Arndt et al., 2019). When risk is taken into account in an integrated (national) bulk water infrastructure supply system, the overall impact of climate change on the average availability of water to meet current and future demands is significantly reduced (Cullis et al., 2015). Further, stemming leakages and enhancing efficiency through technology and management improvements is important in building climate-resilient water conveyance systems (UN Environment, 2019). African cities could leap-frog through the development phases to achieve a water sensitive city ideal, reaping benefits such as improved liveability, reduced flooding impacts, safe water and overall lower net energy requirements and avoid making the mistakes developed countries' cities have made (Fisher-Jeffes et al., 2017) (Brodnik et al., 2018). However, the challenge of large proportions of the population lacking access to even basic water supply and sanitation infrastructure (Armitage et al., 2014) must be simultaneously and effectively addressed, particularly in light of other major exacerbating factors like the COVID-19 pandemic (Section 9.11.5).

9.7.3.4 Decision Support Tools for Managing Complex Water Systems

Many studies in Africa use the river basin as a unit of analysis at scale and adopt sophisticated model-based techniques to assess climate change impacts on hydrology under different climate and development scenarios, thereby presenting trade-offs between competing uses such as hydropower generation, irrigation and ecosystem requirements (Yang and Wi, 2018; Ahmed, 2020) (Section 9.12.1). However, longer (multi-decadal) hydrological datasets and model improvements are required (Taye et al., 2015), and models should incorporate the quantification of the wider benefits, risks and political opportunities arising from reservoir development to better inform decision-makers to achieve a higher level of (transboundary) cooperation (Digna et al., 2016; Nijsten et al., 2018). Collaboration between scientists and policy-makers to address the complexity of decision-making under uncertainty (Steynor et al., 2016) (Pienaar and Hughes, 2017), coupled with community involvement in participatory scenario development and participatory GIS to aid in collaborative planning that is context-specific (Muhati et al., 2018; Álvarez Larrain and McCall, 2019) are powerful tools for more beneficial adaptive and resilience building actions.

9.7.3.5 Other Adaptation Options

Climate change is projected to increase dependence upon groundwater withdrawals in most parts of Africa as an adaptive strategy to amplified variability in precipitation and surface water resources, highlighting the need for conjunctive surface-groundwater management and rainwater harvesting (Cobbing and Hiller, 2019; Taylor et al., 2019). Alternative water supply options such as desalination, managed aquifer recharge, stormwater harvesting and re-use (direct and indirect, potable and non-potable), all require significant amounts of energy and are complex to operate and maintain. A failure to provide a source of reliable energy and the capacity to implement, maintain, and operate these systems is a significant contributor to water scarcity risks in Africa (Muller and Wright, 2016). Soft adaptation options include increasing water use efficiency, chaning agricultural practices, more appropriate water pricing (Olmstead, 2014) and enhancing capacity to tackle groundwater overexploitation (Kuper et al., 2016), among others (see Section 9.10.2.4; Sections 4.6 and 4.7 in Chapter 4).

9.7.3.6 Mainstreaming Gender Across all Adaptation Options

Gender is important in building resilience and adaptation pathways to global environmental change (Ravera et al., 2016). It is well-established that women, in most societies, have accumulated considerable knowledge about water resources, including location, quality and storage methods because they are primarily responsible for the management of water for household water supply, sanitation and health, and for productive uses in subsistence agriculture (UN-Water, 2006). As gender-differentiated relationships are complex, adaptation should take into account intersectional differences such as homeownership, employment and age (Harris et al., 2016), educational, infrastructural and programmatic interventions (Pouramin et al., 2020), aspects of protection and safety (Mackinnon et al., 2019), barriers to adaptation and gendered differences in the choice of adaptation measures (Mersha and Van Laerhoven, 2016), the complex power dynamics of existing social and political relations (Djoudi et al., 2016; Rao et al., 2017) and inclusion and empowerment of women in the management of environmental resources (Makina and Moyo, 2016). Incorporation of gender and water inequities into climate change adaptation would have a significant impact on achieving the SDGs (particularly 1,3,4, 5 and 6), while failure to incorporate gender will undermine adaptation efforts (Bunce and Ford, 2015; Fleifel et al., 2019; Pouramin et al., 2020).

9.8 Food Systems

Ideally, a systems approach (Ericksen, 2008; Rosenzweig et al., 2020) could be used to assess how global environmental changes affect the food sector in Africa, emphasising the complex interactions that exist within the components of the food supply system, including its enabling socioeconomic and biophysical environment (Ingram, 2011; Foran et al., 2014; Tendall et al., 2015), and how food is connected to other critical systems such as energy, water and transportation (Albrecht et al., 2018) (see Box 9.5). Production will not be the only aspect of food security that is impacted by climate change. Processing, storage, distribution and consumption will also be affected. Access to healthy and adequate food in the face of climate change requires resilience across these components of the food system (Adenle et al., 2017). However, most studies on climate change impacts on food in Africa are heavily focused on production only. A significant knowledge gap, therefore, exists around the complex ways in which climate change will interact with broader components of African food systems, and strategies for making these systems more resilient, particularly in a context of rapid population growth and urbanisation across the continent (Adenle et al., 2017; Schmitt Olabisi et al., 2018).

9.8.1 Vulnerability to Observed and Projected Impacts from Climate Change

Agricultural activities are mainly rainfed and subsistence across Africa. The dominant farming system is mixed cereal-livestock (Thornton and Herrero, 2015; Nematchoua et al., 2019), with pastoral systems in East Africa, and commercial livestock and crop systems also representing a significant proportion of the food system in southern Africa (Thornton and Herrero, 2015). Many African regions are vulnerable to food insecurity, facing dwindling food production, food access, stocks and income due to low adaptive capacity (Evariste et al., 2018; Fuller et al., 2018; Bang et al., 2019; Gebre and Rahut, 2021).

Across regions with food systems highly vulnerable to climate change, female farmers, cocoa farmers, pastoralists, plantain farmers, coastal zone communities, rural households and forest communities in central Africa indicate higher vulnerability (Chia et al., 2016; Schut et al., 2016; Nematchoua et al., 2019). Their vulnerability is multidimensional and affected by low adaptive capacity, location, livelihood system, socioeconomic status, gender, age and ethnicity (Perez et al., 2015; Weston et al., 2015; Gebre and Rahut, 2021) (see also Box 9.1).

Across Africa, including West Africa, adverse climate conditions for agricultural and pastoral livelihoods have contributed to rural-to-urban migration patterns and migration among African regions (see Box 9.8) (Baudoin et al., 2014; Abbas, 2017; Gemenne and Blocher, 2017b). Rural to urban migration may increase vulnerability of migrants through exposure to additional risks, including food insecurity (Amadi and Ogonor, 2015; Abbas, 2017). In general, West African countries are characterised by the poor adaptive capacity of rural households (Douxchamps et al., 2015; Dumenu and Obeng, 2016).

In North Africa, livelihoods and economies are strongly dependent on agriculture. Pressure on water demand due to climate change and variability is threatening income, development processes and food security in the region (*high confidence*) (Mohmmed et al., 2018; Khedr, 2019). Increased temperatures and droughts have enhanced the vulnerability of the irrigation sector (Verner et al., 2018; İlseven et al., 2019), and the combined effect of these hazards negatively affects crop and animal production (Mohmmed et al., 2018; Verner et al., 2018). For example, dairy farms in Tunisia are experiencing warmer temperatures above the thermoneutral zone of cows for more than 5 months each year, reducing production efficiency and resulting in significant economic losses (Amamou et al., 2018).

Non-climatic stressors aggravate food insecurity in many parts of the continent, including lack of access to production inputs and land, lack of education and limited income sources, with adverse climate impacts on agriculture reducing education attainment for children (Evariste et al., 2018; Fuller et al., 2018) (Section 9.11.1.2). Geographic and social isolation is another type of social vulnerability, especially for pastoralist communities in East and southern Africa (Sonwa et al., 2017; Basupi et al., 2019). Rural communities often have poor transport networks, limited access to markets or information and fewer livelihood alternatives, and are less able to be informed of risks or be assisted in the event of extreme climate events (Sonwa et al., 2017; Basupi et al., 2019).

Extreme climate events have been key drivers in rising acute food insecurity and malnutrition of millions of people requiring humanitarian assistance in Africa (*high confidence*). Between 2015 and 2019, an estimated 45.1 million people in the Horn of Africa and 62 million people in eastern and southern Africa required humanitarian assistance due to climate-related food emergencies. Children and pregnant women experience disproportionately greater adverse health and nutrition impacts (*very high confidence*) (Gebremeskel Haile et al., 2019) (see Chapter 7, Section 7.2.4).

Future climate warming will *likely* have a substantial impact on food security in Africa and is anticipated to coincide with low adaptive capacity as climate change intensifies anthropogenic stressors, as 85% of Africa's poor live in rural areas and mostly depend on agriculture for their livelihoods (Adams, 2018; Mahmood et al., 2019). This highlights the need to prioritise innovative measures for reducing vulnerabilities in Africa food systems (Fuller et al., 2018; Mahmood et al., 2019).

Climate change impacts could increase the global number of people at risk of hunger in 2050 by 8 million people under a scenario of sustainable development (SSP1) and 80 million people under a scenario of reduced international cooperation and low environmental protection (SSP3), with populations concentrated in sub-Saharan Africa, South Asia and Central America (see Chapter 5, Sections 5.2.2, 5.4.2 and 5.4.3). Global climate impacts on food availability are expected to lead to higher food prices, increasing the risk of hunger for people in African countries, and slow progress towards eradicating child undernutrition and malnutrition in all its forms (see Chapter 7, Section 7.4).

9.8.2 Observed Impacts and Projected Risks to Crops and Livestock

9.8.2.1 Observed Impacts and Projected Risks for Staple Crops

Climate change is already negatively impacting crop production and slowing productivity growth in Africa (*high confidence*) (Iizumi et al., 2018; Ray et al., 2019; Sultan et al., 2019; Ortiz-Bobea et al., 2021). Climate change has reduced total agricultural productivity growth in Africa by 34% since 1961, more than in any other region (Ortiz-Bobea et al., 2021), more than in any other region. Maize yields have decreased 5.8% and wheat yields 2.3%, on average, in sub-Saharan Africa due to climate change in the period 1974–2008 (Ray et al., 2019). Overall, climate change has decreased food total calories across all crops in sub-Saharan Africa by 1.4% on average compared to a no climate change counterfactual since 1970, with up to 10% reductions in Ghana and Zimbabwe (Ray et al., 2019).

Farmers perceive a wide variety of climate threats to crop production including droughts, precipitation variability, a delayed onset and overall reductions in early growing season rainfall and excess heat (Rankoana, 2016a; Elum et al., 2017; Kichamu et al., 2017; Alvar-Beltrán et al., 2020). Farmers attribute these perceived changes as a major driver of yield losses (Ayanlade and Jegede, 2016) (see Section 9.4.5). Over half of surveyed farmers in West Africa perceive increases in crop pests and diseases as due to climate change as the range and seasonality of many pests and diseases change under warming (Callo-Concha, 2018),. Pests and diseases contribute between 10–35% yield losses for wheat, rice, maize, potato and soybean in sub-Saharan Africa (Savary et al., 2019). Recent locust outbreaks in 2019 in East Africa have been linked to climate conditions caused in part by ocean warming (Wang et al., 2020b) (see Box 5.8 in Chapter 5).

Future climate change may increase insect pest-driven losses in Africa for maize, rice and wheat: Compared to 1950–2000, losses may increase by up to 50% at 2°C of global warming (Deutsch et al., 2018). However, many challenges remain in modelling pest and disease under climate change with additional research needed expanding the range of crops and diseases studied (Newbery et al., 2016).

Agriculture in Africa is especially vulnerable to future climate change in part because 90–95% of African food production is rainfed (Adams, 2018). Maize, rice, wheat and soybean yields in tropical regions (20S-20N) are projected to decrease approximately 5% per °C of global warming in a multi-model ensemble (Rosenzweig et al., 2014; Franke et al., 2020). Dryland agricultural areas are especially sensitive to changes in rainfall. For example, without adaptation, substantial yield declines are projected for staple crops in North Africa (Figure 9.3). A recent meta-analysis of 56 studies indicates that, compared to 1995–2005, economic welfare in the agriculture sector in North Africa is projected to decline 5% for 2°C global warming and 20% for 3°C global warming, and in sub-Saharan Africa by 5% (2°C) and 10% (3°C) (Moore et al., 2017a), both more pessimistic than previous economic estimates.

A synthesis of projected staple crop impacts across 35 studies for nearly 1040 locations and cases shows on average decreases in crop yields with increasing global warming across staple crops in Africa, including when accounting for CO_2 increases and adaptation measures. For example for maize in West Africa, compared to 2005 yield levels, median projected yields decrease 9% at 1.5°C global warming and 41% at 4°C, without adaptation (Figure 9.22). However, uncertainties in projected impacts across crops and regions are driven by uncertainties in crop responses to increasing CO_2 and adaptation response, especially for maize in East Africa and wheat in North Africa and East Africa (Figure 9.22) (Hasegawa et al., 2021).

There is also growing evidence that climate change is *likely* beginning to outpace adaptation in agricultural systems in parts of Africa (Rippke et al., 2016). For example, despite the use of adjusted sowing dates and existing heat-tolerant varieties, Sudan's domestic production share of wheat may decrease from 16.0% to 4.5–12.2% by 2050 under RCP8.5 (2.4°C global warming) (Iizumi et al., 2021).

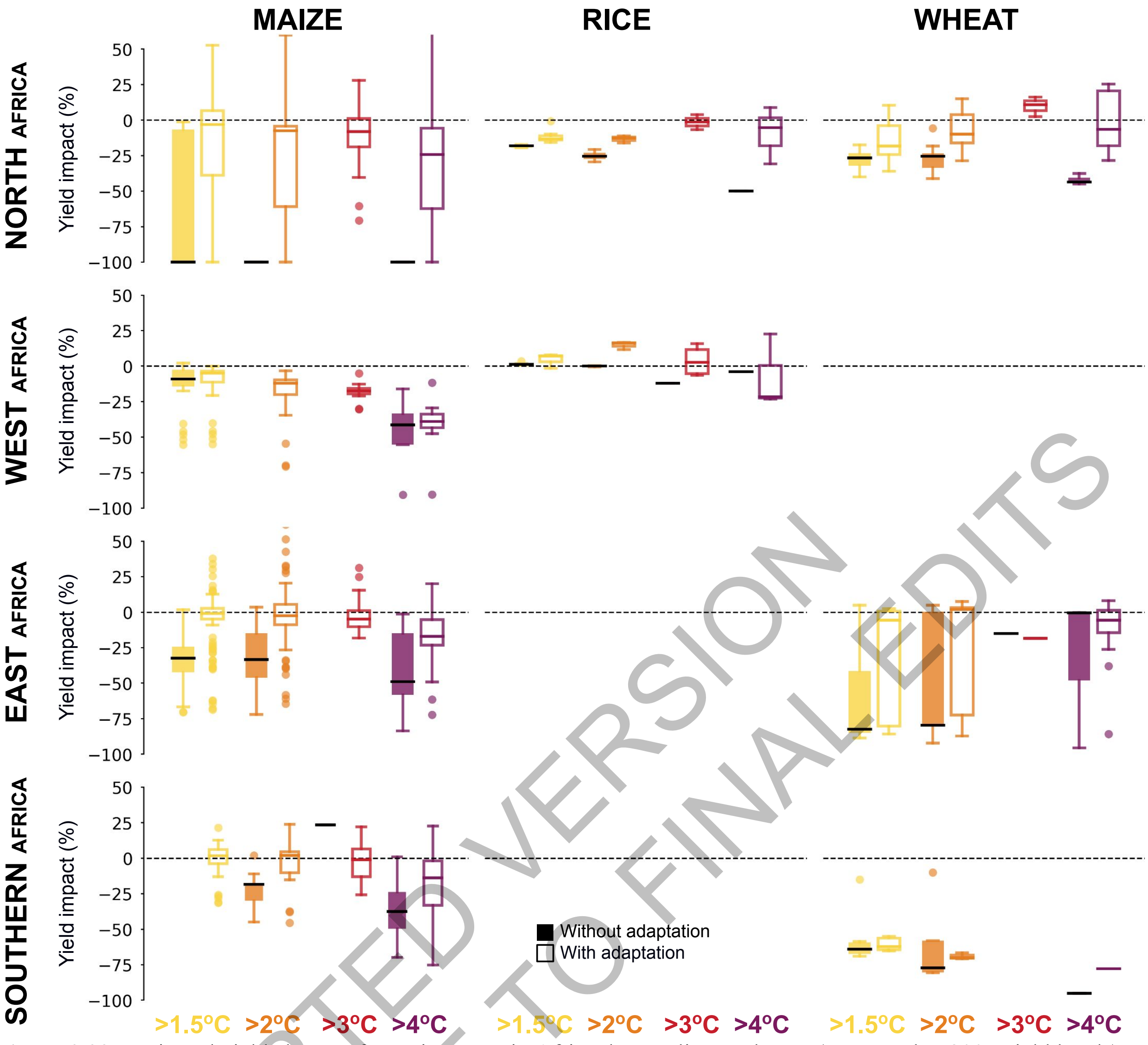


Figure 9.22: Projected yield changes for major crops in Africa due to climate change (compared to 2005 yield levels). Impacts are binned into global warming levels above pre-industrial global mean temperature (1850–1900). Boxplots show a synthesis of projected staple crop impacts, with and without adaptation measures (e.g. planting date, cultivar, tillage or irrigation). On average crop yields are projected to decrease with increasing global warming across staple crops in Africa. The overall adaptation potential to offset yield losses across Africa for rice, maize and wheat reduces with increasing global warming. On average, in projections including adaptation options and yield losses, in the median case, are reduced from –33% to –10% of 2005 levels at 2°C of global warming and from –46% to –23% at 4°C. Data are a synthesis across 35 studies for nearly 1040 locations and cases of projected impacts for regions of Africa for maize, rice and wheat (Hasegawa et al., 2021) (Supplementary Material Table SM 9.5).

Elevated CO_2 concentrations in the atmosphere might mitigate some or all climate-driven losses (Swann et al., 2016; Durand et al., 2018), but there is considerable uncertainty around the CO_2 response (Deryng et al., 2016; Toreti et al., 2020), especially when nutrients such as nitrogen and phosphorus are limiting crop growth. Additional Free-Air Carbon dioxide Enrichment (FACE) experiments are needed in the tropics, particularly on the African continent, to better understand the impacts of increased CO_2 concentrations on the productivity of crops and cultivars grown in Africa under additional temperature impacts and water and nutrient limitations (Ainsworth and Long, 2021). Warming and elevated CO_2 may also change the nutritional content of some crops. By 2050 under RCP8.5 (2.4°C global warming), overall wheat yields and grain protein content may decrease by 10% and 15%, respectively, in North and East Africa, and by over 15% in southern Africa (Asseng et al., 2019). See Chapter 5 for more details on CO_2 impacts and uncertainties.

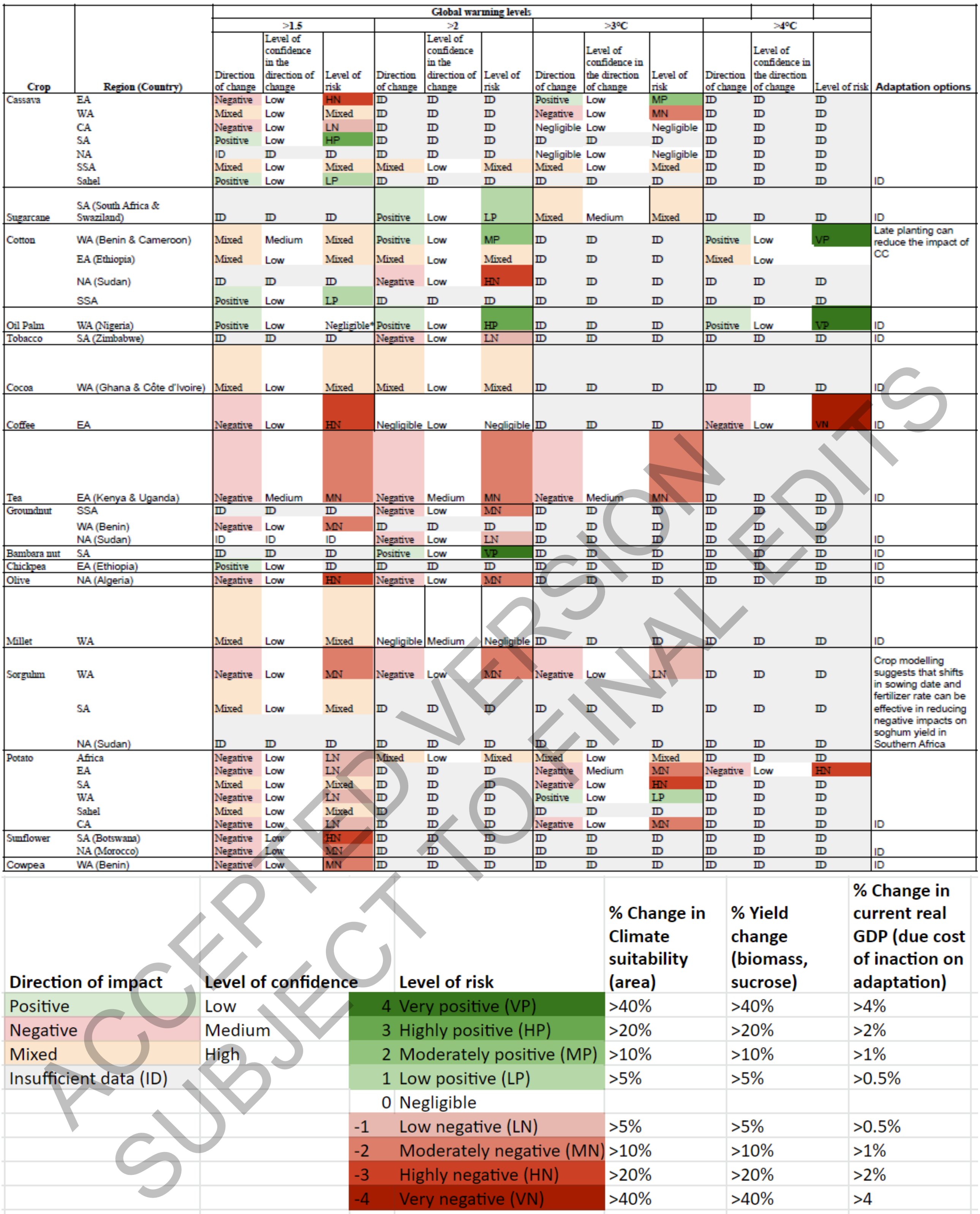
9.8.2.2 Observed Impacts and Projected Risks on Regional Cash Crops and Food Crops

Few studies have attributed changes in yields of cash crops and other regionally important food crops in Africa to anthropogenic climate change, but recent research suggests yields of cash crops in Africa have already been impacted by climate change, in both a negative and positive manner (Falco et al., 2012; Traore et al., 2013; Ray et al., 2019). For example, between the period 1974–2008, sugarcane yields decreased on average by 3.9% and 5.1% in sub-Saharan Africa and North Africa, respectively, due to climate change, while sorghum yields increased 0.7%, and cassava yield increased 1.7% in sub-Saharan Africa and 18% in North Africa (Ray et al., 2019).

There are also limited studies for assessing projected climate change impacts on important cash crops and food crops other than maize, rice and wheat (Jarvis et al., 2012; Schroth et al., 2016; Awoye et al., 2017). These studies often represent changes at specific sites in a country or assess changes in the yield and/or suitability for cultivating a specific crop across a larger geographic area. Climate change is projected to have overall positive impacts on sugarcane and Bambara nuts in southern Africa, oil palm in Nigeria and chickpea in Ethiopia (*low confidence*) (Figure 9.23).

Climate change is projected to reduce sorghum yields in West Africa (Figure 9.23). For example, across the West African Sahel savanna sorghum yields are projected to decline on average 2% at 1.5°C and 5% at 2°C global warming (Faye et al., 2018). For coffee and tea in eastern Africa, olives in Algeria and sunflower in Botswana and Morocco, we find studies indicating mostly negative impacts on production systems. For example, in Kenya, compared to 2000, optimal habitat for tea production is projected to decrease in area by 27% with yields declining 10% for global warming of 1.8–1.9°C, although yield declines may be reduced at higher levels of warming (Beringer et al., 2020; Jayasinghe and Kumar, 2020; Rigden et al., 2020). Suitable area for tea production may reduce by half in Uganda (Eitzinger et al., 2011; Läderach et al., 2013). In East Africa, the coffee-growing area is projected to shift up in elevation with suitability decreasing 10–30% between 1.5–2°C of global warming (Bunn et al., 2015; Ovalle-Rivera et al., 2015).

For all other crops, there is at least one study that finds low to highly negative impacts for one or several warming levels (Figure 9.23). Mixed results on the direction of change often occur when several contrasting sites with varying baseline climates are studied, and when a study considers the full range of climate scenarios. For example, there are mixed results on the direction of change for impacts of 1.5°C global warming on cassava, cotton, cocoa and millet in West Africa (*low confidence*) (Figure 9.23). In general, there is limited evidence in the direction of change, due to single studies being available for most crop-country combinations (Knox et al., 2010; Chemura et al., 2013; Asaminew et al., 2017; Bouregaa, 2019). Occasionally, two studies agree on the direction and magnitude of change, for example, for potatoes in East Africa, yields are projected to decrease by 11–17% with 3°C of warming (Fleisher et al., 2010; Tatsumi et al., 2011).



Crop	Region (Country)	Global warming levels >1.5 Direction of change	>1.5 Level of confidence in the direction of change	>1.5 Level of risk	>2 Direction of change	>2 Level of confidence in the direction of change	>2 Level of risk	>3°C Direction of change	>3°C Level of confidence in the direction of change	>3°C Level of risk	>4°C Direction of change	>4°C Level of confidence in the direction of change	>4°C Level of risk	Adaptation options
Cassava	EA	Negative	Low	HN	ID	ID	ID	Positive	Low	MP	ID	ID	ID	ID
	WA	Mixed	Low	Mixed	ID	ID	ID	Negative	Low	MN	ID	ID	ID	
	CA	Negative	Low	LN	ID	ID	ID	Negligible	Low	Negligible	ID	ID	ID	
	SA	Positive	Low	HP	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA	ID	ID	ID	ID	ID	ID	Negligible	Low	Negligible	ID	ID	ID	
	SSA	Mixed	Low	Mixed	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	
	Sahel	Positive	Low	LP	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Sugarcane	SA (South Africa & Swaziland)	ID	ID	ID	Positive	Low	LP	Mixed	Medium	Mixed	ID	ID	ID	ID
Cotton	WA (Benin & Cameroon)	Mixed	Medium	Mixed	Positive	Low	MP	ID	ID	ID	Positive	Low	VP	Late planting can reduce the impact of CC
	EA (Ethiopia)	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	Mixed	Low		
	NA (Sudan)	ID	ID	ID	Negative	Low	HN	ID	ID	ID	ID	ID	ID	
	SSA	Positive	Low	LP	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Oil Palm	WA (Nigeria)	Positive	Low	Negligible*	Positive	Low	HP	ID	ID	ID	Positive	Low	VP	ID
Tobacco	SA (Zimbabwe)	ID	ID	ID	Negative	Low	LN	ID	ID	ID	ID	ID	ID	ID
Cocoa	WA (Ghana & Côte d'Ivoire)	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID
Coffee	EA	Negative	Low	HN	Negligible	Low	Negligible	ID	ID	ID	Negative	Low	VN	ID
Tea	EA (Kenya & Uganda)	Negative	Medium	MN	Negative	Medium	MN	Negative	Medium	MN	ID	ID	ID	ID
Groundnut	SSA	ID	ID	ID	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID
	WA (Benin)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA (Sudan)	ID	ID	ID	Negative	Low	LN	ID	ID	ID	ID	ID	ID	
Bambara nut	SA	ID	ID	ID	Positive	Low	VP	ID	ID	ID	ID	ID	ID	ID
Chickpea	EA (Ethiopia)	Positive	Low	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
Olive	NA (Algeria)	Negative	Low	HN	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID
Millet	WA	Mixed	Low	Mixed	Negligible	Medium	Negligible	ID	ID	ID	ID	ID	ID	ID
Sorguhm	WA	Negative	Low	MN	Negative	Low	MN	Negative	Low	LN	ID	ID	ID	Crop modelling suggests that shifts in sowing date and fertilizer rate can be effective in reducing negative impacts on soghum yield in Southern Africa
	SA	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	NA (Sudan)	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Potato	Africa	Negative	Low	LN	Mixed	Low	Mixed	Mixed	Low	Mixed	ID	ID	ID	ID
	EA	Negative	Low	LN	ID	ID	ID	Negative	Medium	MN	Negative	Low	HN	
	SA	Mixed	Low	Mixed	ID	ID	ID	Negative	Low	HN	ID	ID	ID	
	WA	Negative	Low	LN	ID	ID	ID	Positive	Low	LP	ID	ID	ID	
	Sahel	Mixed	Low	Mixed	ID	ID	ID	ID	ID	ID	ID	ID	ID	
	CA	Negative	Low	LN	ID	ID	ID	Negative	Low	MN	ID	ID	ID	
Sunflower	SA (Botswana)	Negative	Low	HN	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID
	NA (Morocco)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	
Cowpea	WA (Benin)	Negative	Low	MN	ID	ID	ID	ID	ID	ID	ID	ID	ID	ID

Direction of impact	Level of confidence	Level of risk	% Change in Climate suitability (area)	% Yield change (biomass, sucrose)	% Change in current real GDP (due cost of inaction on adaptation)
Positive	Low	4 Very positive (VP)	>40%	>40%	>4%
Negative	Medium	3 Highly positive (HP)	>20%	>20%	>2%
Mixed	High	2 Moderately positive (MP)	>10%	>10%	>1%
Insufficient data (ID)		1 Low positive (LP)	>5%	>5%	>0.5%
		0 Negligible			
		-1 Low negative (LN)	>5%	>5%	>0.5%
		-2 Moderately negative (MN)	>10%	>10%	>1%
		-3 Highly negative (HN)	>20%	>20%	>2%
		-4 Very negative (VN)	>40%	>40%	>4

Figure 9.23: Projected risks at increasing global warming levels for regionally important cash and food crops in Africa. Insufficient data (ID) indicates there were limited to no published studies that have quantified projected climate change impacts or adaptation options for specific crops under different warming levels (see Supplementary Material Table SM 9.6).

9.8.2.3 Observed Impacts and Projected Risks for Wild-Harvested Food

Wild-harvested foods (e.g., fruits, vegetables and insects) provide dietary diversification and for many people in Africa, wild-harvested food plants may provide a livelihood and/or nutritional safety net when other sources of food fail, such as during drought (Sunderland et al., 2013; Shumsky et al., 2014; Wunder et al., 2014; Baudron et al., 2019b). In Zimbabwe, during lean times, consumption of wild fruits increases, as does their sale to generate income for additional food expenses in poor, rural households (Mithöfer and Waibel, 2004). In Zambia, Mali and Tanzania, household surveys indicate that forest products including wild foods can play an important role in reducing household vulnerability to climate shocks by providing alternative sources of food and income during droughts and floods (Robledo et al., 2012). In the Parklands of West Africa, wild trees are a significant source of wild foods and are thus a place where one might expect wild plant foods to make an important contribution to diets and nutrition (Boedecker et al., 2014; Leßmeister et al., 2015). Non-timber forest products are consumed by an estimated 43% of all households in Burkina Faso (FAO, 2019), and wild vegetables accounted for about 50% of total vegetable consumption in southeastern Burkina Faso (Mertz et al., 2001).

The focus of projected climate change impacts has been almost exclusively on agricultural production, yet climate change could have substantial impacts on the distribution and availability of wild-harvested food plants in Africa (Wessels et al., 2021). Non-cultivated species in Africa are vulnerable to current and future climate changes, with widespread changes in woody plant cover already observed (see Section 9.6.1.1). Evidence about the impacts of climate change on individual wild food species is less consistent. Communities in the Kalahari (Crate and Nuttall, 2016) and Zimbabwe (Sango and Godwell, 2015) report growing scarcity of wild foods (such as wild meat and fruit) perceived to be, at least in part, due to drought and climate change. Shea tree (*Vitellaria paradoxa*) nuts provide fats and oils for the diets of many rural populations in West Africa. In Burkina Faso, global warming of 3°C is projected to reduce area of suitable habitat for the Shea tree by 14% (Dimobe et al., 2020). In southern Africa, 40% of native, wild-harvested food plant species are projected to decrease in geographic range extent at 1.7°C global warming with range reductions for 66% of species projected for 3.5°C (Wessels et al., 2021).

9.8.2.4 Observed Impacts and Projected Risks on Livestock

Livestock systems in Africa are already being affected by changes in climate through increased precipitation variability decreasing fodder availability (Sloat et al., 2018; Stanimirova et al., 2019). More than twice as many countries in Africa have experienced increases in precipitation variability in the last century than decreases (Sloat et al., 2018). Fodder availability is also being impacted by Woody Plant Encroachment—the increase in shrub and tree cover—which has increased by 10% on subsistence grazing lands and 20% on economically important grazing lands in South Africa in the last 60 years (Stevens et al., 2016), and is driven in part by climatic factors (see Section 9.6.1.1). Increased temperature and precipitation have contributed to the expanding range, especially in East and southern Africa, of several ixodid tick species which carry economically important livestock diseases (Nyangiwe et al., 2018).

Pastoralists in Africa perceive the climate as already changing and report more erratic and reduced rainfall, prolonged and more frequent droughts and a rise in temperature (Sanogo et al., 2017; Kimaro et al., 2018). They also report reduced milk production, increased deaths and disease outbreaks in their herds due to malnutrition and starvation resulting from the shortages in forage and water (Kimaro et al., 2018). Additional research is required to attribute precipitation variability to anthropogenic forcing (see Section 9.3), and to evaluate the relative contributions of climate change and management to disease vector extent.

Future climate change will have compounding impacts on livestock, including negative impacts on fodder availability and quality, availability of drinking water, direct heat stress and the prevalence of livestock diseases (Nardone et al., 2010; Rojas-Downing et al., 2017; Godde et al., 2021). Climate change is projected to negatively affect fodder availability (Briske, 2017) because overall rangeland net primary productivity (NPP) by 2050 is projected to decrease 42% under RCP4.5 (2°C global warming) and 46% under RCP8.5 (2.4°C global warming) for western sub-Saharan Africa, compared to a 2000 baseline (Boone et al., 2018). NPP is also projected to decline by 37% in southern Africa, 32% in North Africa and 5% in both East Africa and Central Africa by 2050 under RCP8.5 (2.4°C global warming) (Boone et al., 2018). For example, in Zimbabwe by 2040–2070, net revenues from livestock production, compared to a 2011 survey, are projected to decline by 8–32% under RCP4.5 for 2°C and 11–43% under RCP8.5 for 2.7°C global warming due to a decline in fodder availability (Descheemaeker et al., 2018). The available literature does not comprehensively capture the economic implications of climate-related impacts on livestock production across Africa.

Fodder quality, critical for animal health and weight gain, is at risk from climate change as increases in temperature, elevated CO_2 and water stress have been shown to reduce dry matter digestibility and nitrogen content for C_3 grasses (Augustine et al., 2018), tropical C_4 grasses (Habermann et al., 2019) and fodder crops such as Lucerne/Alfalfa (Polley et al., 2013; Thivierge et al., 2016).

Climate change is projected to threaten water availability for livestock. Droughts in Africa have become more intense, frequent and widespread in the last 50 years (Masih et al., 2014), and progressive increase in droughts between three- and twenty-fold under climate change up to 3°C of warming are projected for most of Africa (9.5). In the Klela basin in Mali by 2050, groundwater recharge is projected to decline by 49% and groundwater storage by 24% under RCP8.5 (2.4°C global warming) compared to the 2006 baseline (Toure et al., 2017). Water availability for livestock during drought is a major concern for many African pastoralists including but not limited to those in Zimbabwe (Dzavo et al., 2019) and Nigeria (Ayanlade and Ojebisi, 2019). Increased livestock mortality and livestock price shocks have been associated with droughts in Africa, as well as being a potential pathway for climate-related conflict (Catley et al., 2014; Maystadt and Ecker, 2014) (see Box 9.9).

Heat stress may already be the largest factor impacting livestock production in many regions in Africa (El-Tarabany et al., 2017; Pragna et al., 2018), as the combination of high temperatures and high relative humidity can be dangerous for livestock and has already decreased dairy production in Tunisia (Amamou et al., 2018). Climate change is projected to increase heat stress for all types of livestock, especially in the tropics (Lallo et al., 2018) (Figure 9.24). More studies quantifying the impact of heat stress on other types of livestock production loss are needed in Africa (Rahimi et al., 2021).

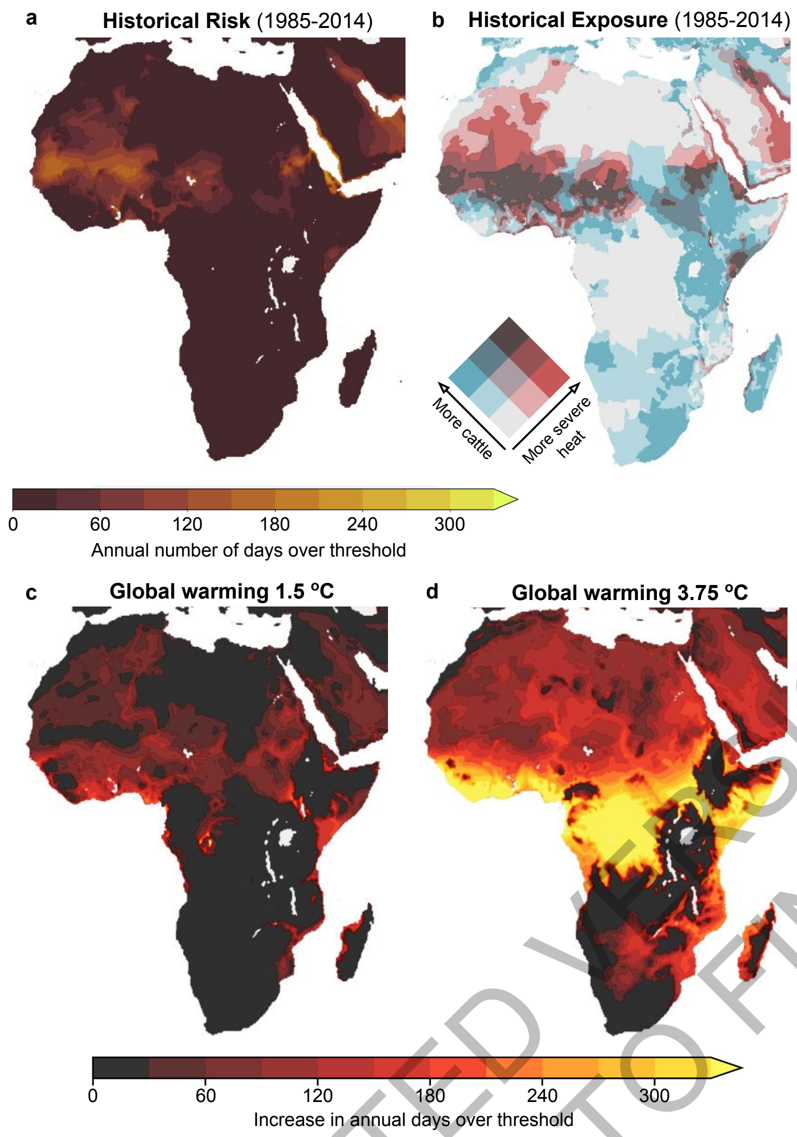


Figure 9.24: Severe heat stress duration for cattle in Africa is projected to increase with increased global warming. (a) Number of days per year with severe heat stress in the historical climate (1985-2014). (b) Historical cattle exposure to severe heat. (Cattle density fromGilbert et al., 2018) . (c and d) Increase in the number of days per year with severe heat stress for global warming of 1.5C and 3.75C above pre-industrial levels (1850-2100). Severe heat stress for cattle is projected to become much more extensive in the future in Africa at increased global warming levels. Strong mitigation would substantially limit the spatial extent and the duration of cattle heat stress across Africa. Heat stress is estimated using THI (Temperature Humidity Index) with a value greater than 79 considered the onset of severe heat stress (Livestock Weather Safety Index) (Lallo et al., 2018). Global warming of 1.5°C used scenario SSP1–2.6 and global warming of 3.75°C used SSP5–8.5, both for 2070–2099 (12 climate models fromO'Neill et al., 2016; Tebaldi et al., 2021) .

Climate change will impact livestock disease prevalence primarily through changes in vector dynamics or range (Abdela and Jilo, 2016; Semenza and Suk, 2018). African Rift Valley Fever (RVF) and Trypanosomiasis are positively associated with extreme climate events (droughts and ENSO) (Bett et al., 2017) and are projected to expand in range under climate change (Kimaro et al., 2017; Mweya et al., 2017). More quantitative estimates of projected risk from diseases are needed.

9.8.3 Adapting to Climate Variability and Change

Agricultural and livelihood diversification are strategies used by African households to cope with climate change, enabling them to spread risks and adjust to shifting climate conditions (Thierfelder et al., 2017; Thornton et al., 2018). This includes adjusting cropping choices, planting times, or size, type and location of planted areas (Altieri et al., 2015; Nyagumbo et al., 2017; Dayamba et al., 2018). In southern Africa, changes in planting dates provide farmers with greater yield stability in uncertain climate conditions (Nyagumbo et al., 2017). In Ghana, farmers are changing planting schedules and using early maturing varieties to cope with late-onset and early cessation of the rainy season (Antwi-Agyei et al., 2014; Bawakyillenuo et al., 2016).

The use of drought-tolerant crop varieties is another adaptation available to African farmers (Hove and Gweme, 2018; Choko et al., 2019). Adoption, however, is hindered by lack of information and training, availability or affordability of seed, inadequate labelling and packaging size for seed supplies and financial constraints (Fisher et al., 2015). Moreover, drought-tolerant varieties do not address changing temperature regimes (Guan et al., 2017).

Crop diversification enhances crop productivity and resilience and reduces vulnerability in smallholder farming systems (McCord et al., 2015; Mulwa and Visser, 2020). In Tanzania, diversified crop portfolios are associated with greater food security and dietary quality (Brüssow et al., 2017). In Kenya, levels of crop diversity are higher in villages affected by frequent droughts, which are the main cause of crop failure (Bozzola and Smale, 2020). They also help control pest outbreaks, which may become more frequent and severe under increased climate variability and extreme events (Schroth and Ruf, 2014). High farming diversity enables households to better meet food needs, but only up to a certain level of diversity (Waha et al., 2018), and the viability of and benefits from mixed-farming are highly context-dependent (Thornton and Herrero, 2015; Weindl et al., 2015).

Agroecological and conservation agriculture practices, such as intercropping, integration of legumes, mulching and incorporation of crop residues, are associated with household food security and improved health status (Nyantakyi-Frimpong et al., 2017; Shikuku et al., 2017). These practices can enhance the benefits of other adaptations, such as planting drought- and heat-tolerant or improved varieties, although effects vary across soil types, geographical zones and social groups (Makate et al., 2019; Mutenje et al., 2019). Non-climatic variables, such as financial resources, access to information and technology, level of education, land security and gender dynamics affect feasibility and adoption (Makate et al., 2019; Mutenje et al., 2019).

To mitigate growing water stress, countries like Tanzania, Uganda, Rwanda and Ethiopia are striving to improve irrigation efficiency (McCarl et al., 2015; Connolly-Boutin and Smit, 2016; Herrero et al., 2016). The feasibility and effectiveness of this adaptation depend on biophysical and socioeconomic conditions (Amamou et al., 2018; Harmanny and Malek, 2019; Schilling et al., 2020). Irrigation is unaffordable for many smallholder farmers and only covers a negligible proportion of the total cultivated area. Nonetheless, in some regions of West Africa, small-scale irrigation, including the digging of ditches, holes and depressions to collect rainwater (Makondo and Thomas, 2018), is widely adopted and promoted to support national food security (Dowd-Uribe et al., 2018).

African farmers are also diversifying their income sources to offset reduced yields or crop losses by shifting labour resources to off-farm work, or by migrating seasonally or longer-term (Kangalawe et al., 2017; Hove and Gweme, 2018). Off-farm activities provide financial resources that rural households need to cope with extreme climate variability (Hamed et al., 2018; Rouabhi et al., 2019). However, in some cases, these off-farm activities can be maladaptive at larger scales, such as when households turn to charcoal production which contributes to deforestation (Egeru, 2016). Whether off-farm activities constitute maladaptation depends on whether resources are available to upgrade skills or support investments that make a new business more lucrative. Without such resources, this option may lead to impoverishment (see Box 5.8 on AFOLU in Chapter 5).

Smallholder farmers' responses tend to address short-term shocks or stresses by deploying coping responses (e.g., selling labour, reducing consumption and temporary migration), rather than longer-term sustainable adaptations (Ziervogel and Parnell, 2014; Jiri et al., 2017). This is partly due to institutional barriers (e.g., markets, credit, infrastructure and information) and resource requirements that are unaffordable to smallholder farmers (Pauline et al., 2017). There is a need for policies that strengthen natural, financial, human and social capitals, the latter being key to household and community resilience, especially where government services may be limited (Mutabazi et al., 2015; Alemayehu and Bewket, 2017). There is evidence that collective action, local organizations and climate information are associated with higher food security, and that institutional interventions are needed to ensure scaling up of adaptations (Thornton et al., 2018).

A range of options is considered potentially effective in reducing future climate change risk, including plant breeding, crop diversification alongside livestock, mixed planting, intercrops, crop rotation and integrated crop-livestock systems (Thornton and Herrero, 2014; Cunningham et al., 2015; Himanen et al., 2016; Farrell et al., 2018; Snowdon et al., 2021) (Chapter 5, Sections 5.4.4 and 5.14.1). However, adaptation limits for crops in Africa are increasingly reached for global warming above 2°C (*high confidence*), and in tropical Africa may already be reached at current levels of global warming (*low confidence*).

Global warming beyond 2℃ will place nearly all of sub-Saharan Africa cropland substantially outside of its historical Safe Climate Zone (Kummu et al., 2021) and may exponentially increase the cost of adaptation and residual damage for major crops (Iizumi et al., 2020). Without accounting for CO_2 increases, global-scale studies employing ensembles of gridded crop models for 2°C of global warming find that for adaptation using genetic cultivar change in most of Africa net losses are projected, even with adaptation up to 2℃ of global warming for rice, maize, soybean, and wheat (Minoli et al., 2019; Zabel et al., 2021), although model uncertainty is still high (Müller et al., 2021). In contrast, when accounting for CO_2 increases, applying new genetics for rice under warming is projected to fully counteract all climate change-induced losses in Africa up to 3.5°C of global warming, except in West Africa (van Oort and Zwart, 2018).

However, compared to temperate regions, risks of adaptation shortfalls – that is climate change impacts even after adaptation – are generally greater for current agricultural conditions across much of Africa (tropical, arid and semi-arid) (Sun et al., 2019). The overall adaptation potential to offset yield losses across Africa for rice, maize, and wheat wheat reduces with increasing global warming. On average, in projections including adaptation options, yield losses, in the median case, are reduced from –33% to –10% of 2005 levels at 2°C of global warming and from –46% to –23% at 4°C, but estimates vary widely (Hasegawa et al., 2021) (Figure 9.22). Across Africa, the risks of no available genetic varieties of maize for growing season adaptation are higher for East Africa and southern Africa than for Central or West Africa (Zabel et al., 2021). To keep pace with expected rates of climate change, crop breeding, development and adoption must accelerate to meet the challenge (Challinor et al., 2016). Regional modelling has shown very little efficacy for late sowing, intensification of seeding density and fertilizers, water harvesting and other measures for cereals in West Africa at 2℃ of global warming (Sultan and Gaetani, 2016; Guan et al., 2017). Historical climate change adaptation by crop migration has been shown in some cases (Sloat et al., 2020) but poses risks to biodiversity and water resources and this option may be limited for maize in Africa by suitable climate shifting completely across national borders and available land at the edges of the continent (Franke et al., 2021). More research is required to evaluate the potential effectiveness and limits of adaptation options in African agriculture under future climate change (see Chapter 5, Section 5.4.4 for more details)

9.8.4 Climate Information Services and Insurance for Agriculture Adaptation

In addition to adaptation in crop, soil and water management, the combination of (i) Climate Information Services (CIS), (ii) institutional capacity building and (iii) strategic financial investment can help African food producers adapt to projected climate risks (Carter et al., 2015; Surminski et al., 2016; Scott et al., 2017; Cinner et al., 2018; Diouf et al., 2019; Hansen et al., 2019a). There is growing evidence of farmers' use of weather and climate information, especially at the short- and medium-time horizon (Carr et al., 2016; Singh et al., 2018). Digital services can contribute to the sustainable intensification of food production globally (Duncombe, 2018; Klerkx et al., 2019). This points to the need for the scientific and development communities to better understand the conditions that enable widespread adoption in Africa.

Although climate services have the potential to strengthen farmers' resilience, barriers to accessibility, affordability and utilisation remain (Krell et al., 2021). Often the information offered is not consistent with what farmers need to know and how they access and process information (Meadow et al., 2015; Singh et al., 2018). Production of salient and credible climate information is hindered by the limited availability of and access to weather and climate data (Coulibaly et al., 2017; Hansen et al., 2019a). The existing weather infrastructure remains suboptimal to enable the development of reliable early warning systems (Africa Adaptation Initiative, 2018; Krell et al., 2021). Of the 1,017 land-based observational networks in the world, only 10% are in Africa, and 54% of Africa's surface weather stations cannot capture data accurately (Africa Adaptation Initiative, 2018; World Bank, 2020d).

Advances in remote sensing and climate analysis tools have allowed the development of weather index insurance products as a potential adaptation option, with Malawi and Ethiopia being early testbeds (Tadesse et al., 2015). These pilot projects were initially sponsored by NGOs, but in the last decade, the private sector has become more active in this sector. The Ghana Agricultural Insurance Pool (GAIP) and Agriculture and Climate Risk Enterprise (ACRE) in Kenya, Tanzania and Rwanda are examples. Despite the potential for weather index insurance, uptake by smallholder farmers in Africa remains constrained by several factors. These include the failure to capture actual crop loss as in traditional crop insurance products, as well as the inability of poor farmers to pay premiums (Elum et al., 2017; Weber, 2019). Weather index insurance could be part of a wider portfolio of risk mitigation services offered to farmers (Tadesse et al., 2015; Weber, 2019). Strategic partnerships between key players (e.g., credit institutions, policymakers, meteorologists, farmer associations, extension services, NGOs) are needed to develop better products and build capacity among smallholder farmers to engage more beneficially with weather index insurance (Singh et al., 2018; Tesfaye et al., 2019).

9.8.5 Marine and Inland Fisheries

9.8.5.1 Observed Impacts of Climate Variability and Change on Marine and Inland Fisheries

Marine and freshwater fisheries provide 19.3% of animal protein intake (Chan et al., 2019) and support the livelihoods of 12.3 million people (de Graaf and Garibaldi, 2015) across Africa. Estimates suggest that fish provides ~30% of the continent's population (approximately 200 million people) with their main source of animal protein and key micronutrients (Obiero et al., 2019). Although marine fisheries account for >50 % of total capture fishery production (Obiero et al., 2019), 2.9 million tonnes of fish are harvested annually from inland water bodies constituting the highest per-capita inland fishery production of any continent (2.56 kg / year / person) (Harrod et al., 2018a; Funge-Smith and Bennett, 2019).

Climate change poses a significant threat to marine and freshwater fisheries and aquaculture in Africa (Blasiak et al., 2017; Harrod et al., 2018a). Severe (>30%) coral bleaching has impacted ~80% of major reef areas in the western Indian Ocean and Red Sea along Africa's eastern coast (Hughes et al., 2018). Biological effects (e.g., changes in primary production, fish distribution) have also occurred (Hidalgo et al., 2018). Range shifts in marine fish species can exacerbate boundary conflicts among fisher communities (Penney et al., 2017; Belhabib et al., 2019). Changes in fish distribution and reductions in catch across inland fisheries are associated with climatic variability by fishing communities (Okpara et al., 2017b; Lowe et al., 2019; Muringai et al., 2019b). Floods and reduced river flow reduces fish catches (Kolding et al., 2019), which scale positively with discharge rates in rivers across Africa (McIntyre et al., 2016). Warming air and water temperatures have altered water stratification patterns in African lakes causing reductions in or redistirbutions of primary productivity and leading to reduced fish biomass (Section 9.6.1.3). Such changes, partially explain reduced fish catches in Lake Tanganyika (Cohen et al., 2016). In some regions, water scarcity has resulted in conflict within and among food production sectors (pastoralists, fishers and farmers) in this region (Okpara et al., 2017b). Small-scale and artisanal fisher communities are ill-equipped to adapt to climate impacts because there are few financially-accessible alternative livelihoods (Belhabib et al., 2016; Ndhlovu and Saito, 2017).

9.8.5.2 Projected Risks of Climate Change to Fisheries

At 4.3°C global warming, maximum catch potential (MCP) from marine fisheries in African Exclusive Economic Zones (EEZs) would decrease by 12–69% by the end of the 21st century relative to recent decades (1986–2005) whereas maintaining warming levels below 1.6°C would decrease MCP by 3–41% (Cheung William et al., 2016) (Figure 9.25). However, by mid-century under 2°C global warming, MCP would decrease by 10 to >30% on the western coast of South Africa, the Horn of Africa and West Africa, indicating these regions could be at risk to declines in MCP earlier in the century than other parts of Africa (Cheung et al., 2016) (Figure 9.25). Declining fish harvests due to sea temperature rise could leave 1.2–70 (median 11.1) million people in Africa vulnerable to deficiencies in iron, and up to 188 million to vitamin A and 285 million to vitamin B_{12} and omega-3 fatty acids by mid-century under 1.7°C global warming (Golden et al., 2016). Maire et al. (2021) assessed the nutritional vulnerabilities of African countries to climate change and overfishing, and found that the four most vulnerable countries ranked on a scale from 0 (low vulnerability) to 100 (high vulnerability) were Mozambique (87), Madagascar (76), Tanzania (61) and Sierra Leone (58). Coral reef habitat in East Africa is projected to decrease, resulting in negative impacts on demersal fish stocks and invertebrates (Hoegh-Guldberg et al., 2018). Central, West and East Africa appear to be at the greatest nutritional risk from sea temperature rise, leading to reduced catch in coastal waters (Golden et al., 2016) (Figure 9.25). In North Africa, a rise in water temperatures is expected to impact the phenology and migratory patterns of large pelagic species (e.g., bluefin tuna, *Thunnus thynnus*) (Hidalgo et al., 2018). Increased sea surface temperatures have been associated with increases in spring and summer upwelling intensity reducing the abundance and larval survival of small pelagic fishes and shellfish in West Africa (Bakun et al., 2015; Tiedemann et al., 2017; Atindana et al., 2020). Ocean warming, acidification and hypoxia are predicted to affect the early life history stages of several marine food species, including fish and crustaceans (Kifani et al., 2018). Climate warming is projected to impact water temperature and horizontal and vertical mixing on the southern Benguela ecosystem, with marked negative effects on the biomass of several important fishery resources by 2050 amplified under 2.5°C compared to 1.7°C global warming (Ortega-Cisneros et al., 2018).

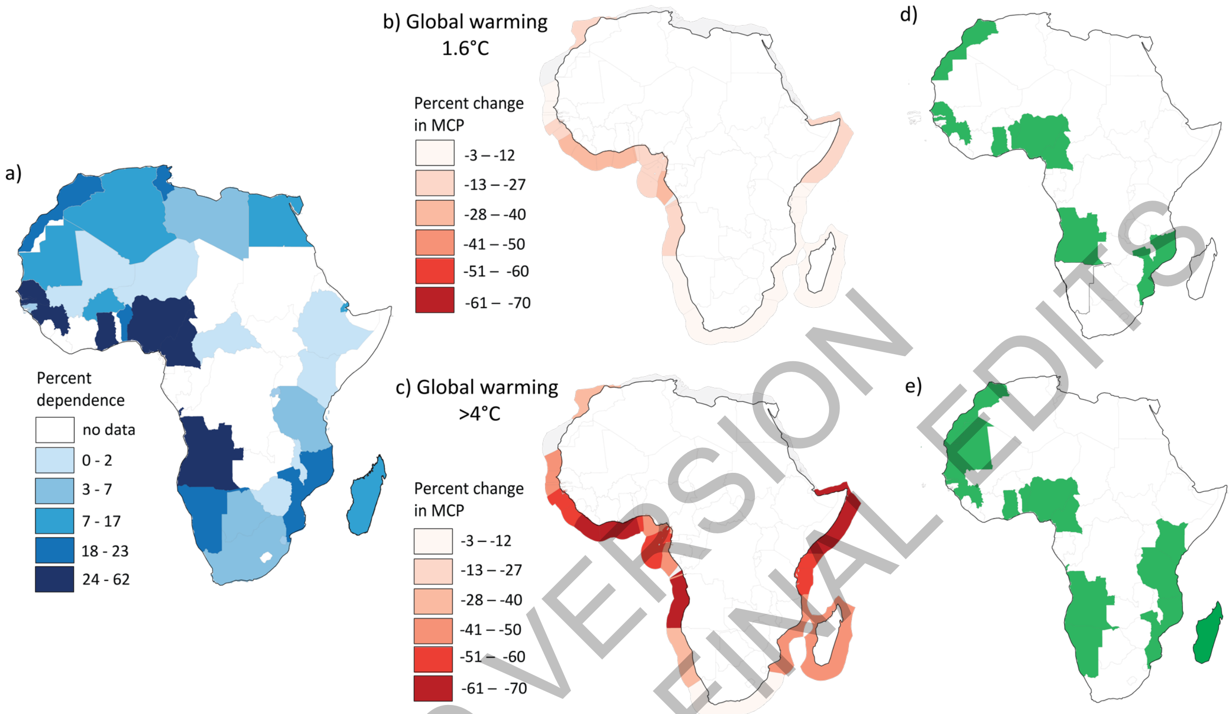
For inland fisheries, 55–68% of commercially harvested fish species will be vulnerable to extinction under 2.5°C global warming by the end of the 21st century (2071–2100) compared to 77–97% under 4.4°C global warming (Figure 9.26). This will increase the number of countries that are at food security risk due to fishery species declines from 10 to 13 (Figure 9.26). Other recent analyses suggest that African countries with the highest inland fisheries production have low- to mid-range projected climate risk (2.4°C–2.6°C local temperature increase compared to other regions with 2.7°C–3.3°C increase by end of centruy) based on a 3.9°C global warming scenario (Harrod et al., 2018b). In regions where inland fishery production is derived primarily from lakes, there is a lower likelihood of reduced catch, especially where precipitation is projected to increase (e.g., African Great Lakes region) (Harrod et al., 2018b). Regions reliant on rivers and floodplains (e.g., Zambezi and Niger basins) are more *likely* to experience downturns in catch, as hydrological dynamics may be altered (Harrod et al., 2018b). Projections suggest that opportunistic species that do well in modified systems (Escalera-vázquez et al., 2017) and small pelagic fishes will remain important components to inland fishery food systems (Kolding et al., 2016; Gownaris et al., 2018; Kolding et al., 2019). Climate adaptation responses that rely on freshwater resources (e.g., hydroelectric power generation, agricultural irrigation) represent threats to inland fisheries (Cowx et al., 2018; Harrod et al., 2018c), by changing flow regimes, reducing water levels, and increasing runoff of pesticides and nutrients (Harrod et al., 2018c).

For both marine and freshwater fisheries, climate-related extreme weather events and flooding may drive the loss of fishing days, cause damage and loss to fishing gear, endanger the lives of fishers and block transportation from damaged roads (Muringai et al., 2021). Fish processing via weather-dependent techniques such as sun drying may be hampered, causing post-harvest losses (Akintola and Fakoya, 2017; Chan et al., 2019).

9.8.5.3 Current and Future Adaptation Responses for Fisheries

Patterns of vulnerability and adaptive capacity are highly context-dependent and vary within and among fishing communities in coastal and riparian areas (Ndhlovu and Saito, 2017; Lowe et al., 2019; D'agata et al., 2020). Interventions that integrate scientific knowledge and fishers' local knowledge while focusing on vulnerable groups are more *likely* to be more successful (Musinguzi et al., 2018; Muringai et al., 2019b). Infrastructure improvements (e.g., storage facilities, processing technologies, transport systems) could reduce post-harvest losses and improve food safety (Chan et al., 2019). Fisher safety can be aided by early warning of severe weather conditions (Thiery et al., 2017), enhanced through communication via mass media and mobile phones (Thiery et al., 2017; Kiwanuka-Tondo et al., 2019). Although changing fishing gears and shifting target species are important adaptation options for artisanal fishers, many have instead expanded their fishing range or increased effort (Musinguzi et al., 2015; Belhabib et al., 2016). Adapting to the impacts of climate change on marine fisheries productivity requires management reforms accounting for shifting productivity and species distributions, such as increasing marine protected areas, strengthening regional trade networks, and increasing the investment and innovation in climate-resilient aquaculture production (Golden et al., 2021). This could yield higher catch and profits in the future relative to today in

50% of African countries with marine territories under 2°C global warming and in 35% under 4.3°C global warming (Free et al., 2020). For inland fisheries, opportunities for adaptation include better integration of inland fisheries into management plans from other sectors (e.g., hydropower and irrigation) (Harrod et al., 2018c; Cowx and Ogutu-Ohwayo, 2019; McCartney et al., 2019). There is growing interest in enhancing the supply of freshwater fishery production from small water bodies and reservoirs in dryland regions of sub-Saharan Africa (Kolding et al., 2016).



Percent dependence on marine foods for nutrition

Projected percent change in maximum catch potential (MCP) of marine fisheries

Countries with high overlap of dependence and future threat to fisheries from climate change

Figure 9.25: Climate change risk to nutrition and catch potential from Marine Fisheries: Panels comparing countries current percent dependence on marine foods for nutrition compared with projected change in maximum catch potential (MCP) from marine fisheries. (a) The percentage of animal sources foods consumed that originate from a marine environment. Countries with higher dependence are indicated by darker shades of blue (Golden et al., 2016). (b–c) Projected percent change in maximum catch potential (MCP) of marine fisheries under 1.6°C global warming (b) and >4°C global warming (c) from recent past (1986–2005) to end of 21st century (2081-2100) in countries' Exclusive Economic Zones (EEZs)(Cheung William et al., 2016). Darker red indicates greater percent reduction [negative values]. (d–e) Countries (in green) that have overlap between high nutritional dependence and high reduction in MCP under two warming scenarios.

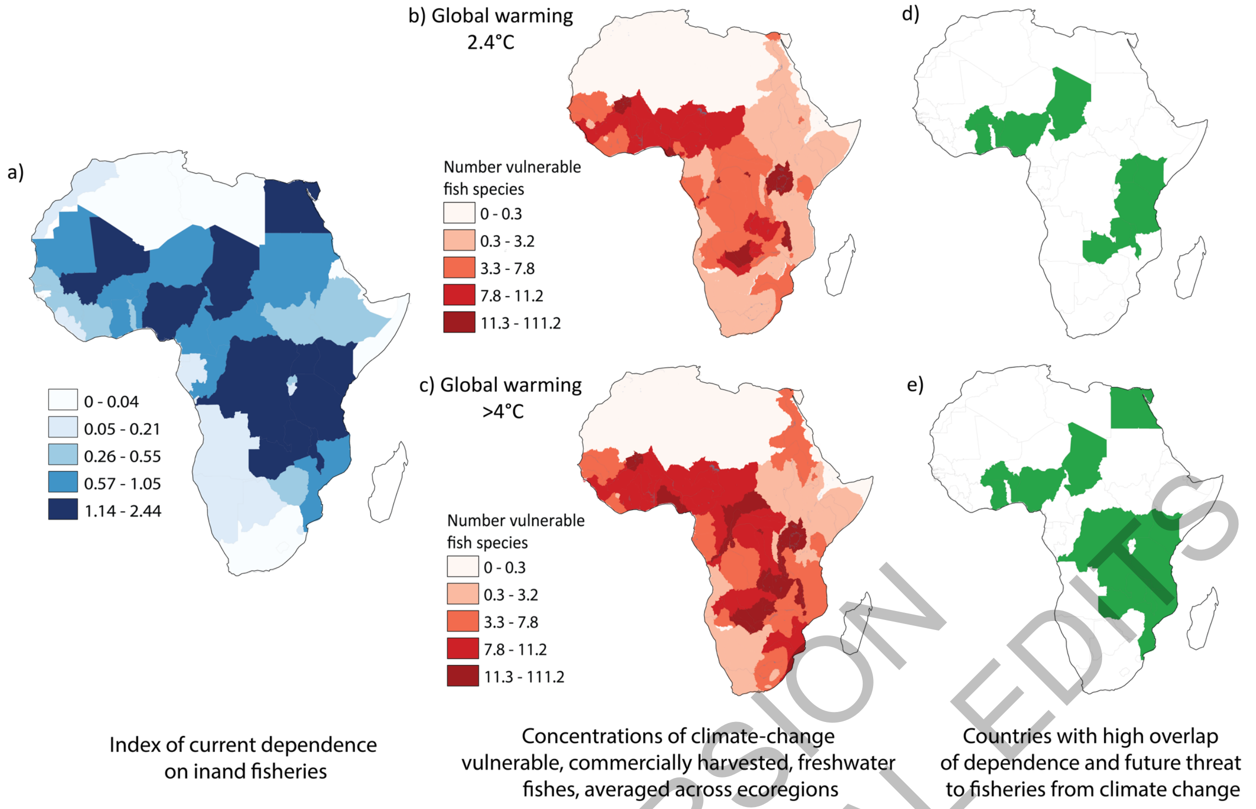


Figure 9.26: Climate change risk to Freshwater Fisheries: Panels comparing countries current dependence on inland fisheries compared with climate change vulnerability of important fishery species. (a) Countries' reliance on inland fisheries was estimated by catch (total, tonnes) (FAO, 2018b; Fluet-Chouinard et al., 2018), per capita catch (kg/person/year) (FAO, 2018b), percent reliance on fish for micronutrients, and percent consumption per household (Golden et al., 2016). Z-scores of each metric were averaged for each country to create a composite index describing 'current dependence on freshwater fish' for each country with darker blue colours indicating higher dependence. (b–c) Projected concentrations (numbers) of vulnerable freshwater fishery species averaged within freshwater ecoregions under >2°C global warming (b) and >4°C global warming (c) estimated from recent past (1961–1992) to the end of the 21st century (2071 to 2100) (Nyboer et al., 2019). Numbers of vulnerable fish species translate to an average of 55–68% vulnerable at >2°C and 77–97% vulnerable at <4°C global warming. Darker reds indicate higher concentrations of vulnerable fish species. (d–e) Countries (in green) that have an overlap between high dependence on freshwater fish and high concentrations of fishery species that are vulnerable to climate change under two warming scenarios

9.9 Human Settlements and Infrastructure

This section assesses climate impacts, risks and adaptation options for human settlements comprising human populations and infrastructure such as buildings, roads and energy across Africa.

9.9.1 Urbanisation, Population and Development Trends

Africa is the most rapidly urbanising region in the world, with an annual urban population growth rate of 3.6% for 2005–2015 (UN-Habitat, 2016). About 57% of the population currently lives in rural areas, the proprotion of the population living in urban areas is projectted to exceed 60% by 2050 (UNDESA, 2019b) (UN-Habitat, 2016). Much of the rapid rate of urbanisation has resulted from the growth of small towns and intermediary cities (African Development Bank et al., 2016).

Approximately 59% of sub-Saharan Africa's urban population resides in informal settlements (in some cities up to 80%), and the population in informal settlements is expected to increase (*very high confidence*) (Taylor and Peter, 2014; UN-Habitat, 2014; UN-Habitat, 2016; UNDP, 2019). These urbanisation trends are compounding the increasing exposure to climate hazards, particularly floods and heatwaves (*high confidence*) (Dodman et al., 2015).

Globally, the highest rates of population growth and urbanisation are taking place in Africa's coastal zones (*high confidence*) (Merkens et al., 2016). Coastal urban populations account for 25–29% of the total population in West, North and southern Africa (OECD/SWAC, 2020). Accounting for a continuing young population, stagnant economies and migration to regional growth centres, projections indicate that the low-lying coastal zone population of sub-Saharan Africa could increase by 175% (2030) and 625% (2060) relative to 24 million in 2000 (Neumann et al., 2015).

Climate-related displacement is widespread in Africa, with increased migration to urban areas in sub-Saharan Africa linked to decreased rainfall in rural areas, increasing urbanisation and affecting household vulnerability (see Box 9.9). Much of this growth can occur in informal settlements which are growing due to both climatic and non-climatic drivers, and which often house temporary migrants, including internally displaced people. Such informal settlements are located in areas exposed to climate change and variability and are exposed to floods, landslides, sea level rise and storm surges in low-lying coastal areas, or alongside rivers that frequently overflow, thereby exacerbating existing vulnerabilities (Satterthwaite et al., 2020).

Sub-Saharan Africa's large infrastructure deficit (quantity, quality and access) with respect to road transport, electricity, water supply and sanitation places the region at the lowest of all developing regions (AfDB, 2018a; Calderon et al., 2018). Adequate infrastructure to support Africa's rapidly growing population is important to raise living standards and productivity in informal settlements (AfDB, 2018b; UN Environment, 2019). Yet planned infrastructure developments, including those related to African Union's Programme for Infrastructure Development (PIDA), along with other energy plans, and China's Belt and Road Initiative (BRI), may increase or decrease both climate change mitigation and adaptation depending on whether infrastructure planning integrates current and future climate change risks (Cervigni et al., 2015; Addaney, 2020) (see Box 9.5).

9.9.2 Observed Impacts on Human Settlements and Infrastructure

African human settlements are particularly exposed to floods (pluvial and fluvial), droughts and heat waves. Other climate hazards are sea level rise and storm surges in coastal areas, tropical cyclones and convective storms. This sub-section provides an assessment of observed impacts and risks from climate hazards in different sub-regions to underscore the relevance of climate-sensitive planning and actions to advance social and economic development, and reduce the loss and damage of property, assets and critical infrastructure.

9.9.2.1 Observed Impacts on Human Settlements

The spatial distribution of climate hazards and observed impacts in terms of total people affected (displaced persons and deaths) during 2010–2020 is shown in Figure 9.27. From 2000–2019 , floods and droughts accounted for 80% and 16%, respectively, of the 337 million affected persons, and a further 32% and 46%, respectively, of 46,078 deaths from natural disasters in Africa (CRED, 2019). Flooding is a major hazard across Africa (Kundzewicz et al., 2014; Douglas, 2017) and is increasing (Zevenbergen et al., 2016; Elboshy et al., 2019). An increase in extreme poverty and up to a 35% decrease in consumption has been associated with exposure to flood shocks (Azzarri and Signorelli, 2020). Globally, only sub-Saharan Africa has recorded increasing rates of flood mortality since the 1990s (Tellman et al., 2021). Economic opportunities, transportation of goods and services, and mobility and access to essential services, including health and education, are greatly hindered by flooding (Gannon et al., 2018). Severe impacts from tropical cyclone landfalls have been recorded in East and southeastern Africa (Rapolaki and Reason, 2018; Cambaza et al., 2019; Chatiza, 2019; Hope, 2019). Cyclones Idai and Kenneth in early 2019 caused flooding of districts in Mozambique, Zimbabwe and Malawi, with substantial loss and damage to infrastructure in the energy, transport, water supply, communication services, housing, health and education sectors, particularly in Mozambique (Figure 9.27; see also Cross-Chapter Box DISASTER in Chapter 4) (Warren, 2019; Dube et al., 2021; Phiri et al., 2021).

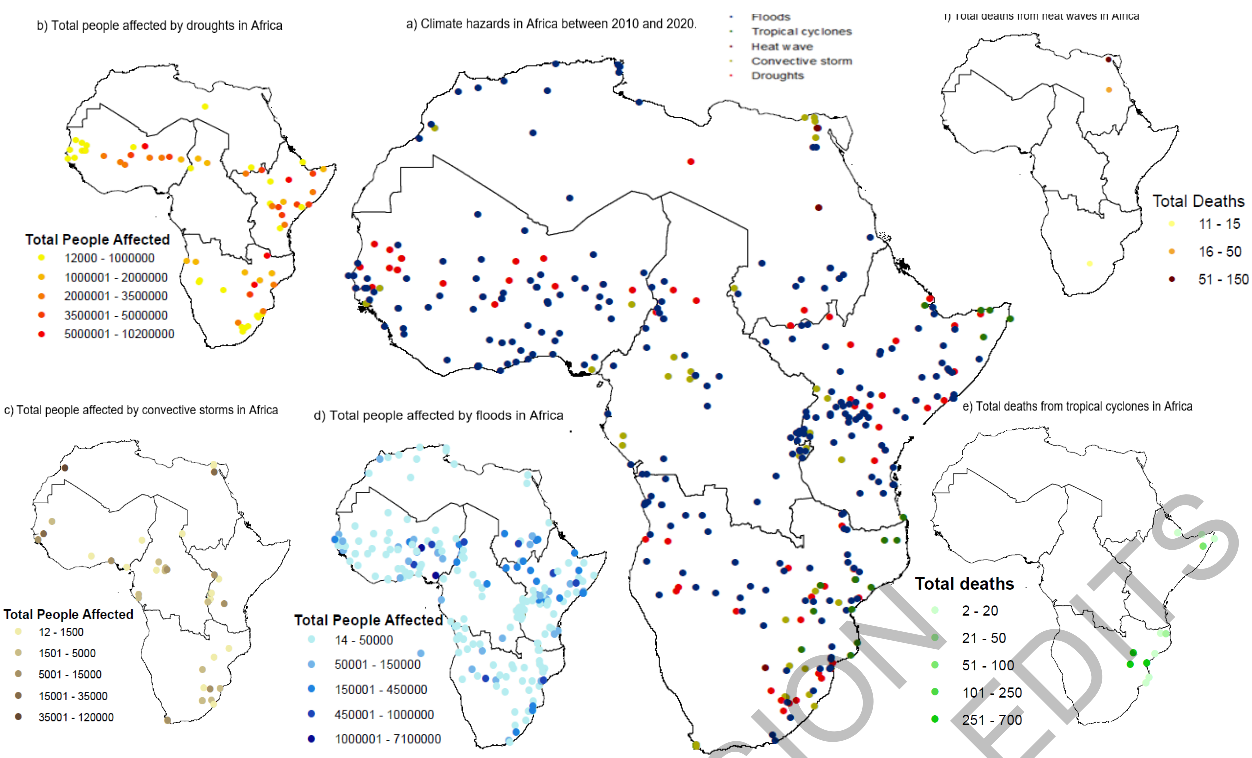


Figure 9.27: From 2010–2020, over 166 million people were reported to be affected by climate hazards across Africa. Maps show (a) location of all reported climate hazards, (b) people affected by droughts, (c) people affected by convective storms, (d) people affected by floods, (e) total deaths from tropical cyclones, and (f) total deaths from heat waves. Source (EMDAT and CRED, 2020). Note, although extreme weather damage databases under report heatwaves (which is indicated in panel (f) by very few deaths), the region has experienced a number of heatwaves and will be affected disproportionately by them in the future under climate change (Harrington and Otto, 2020).

Table 9.7: Case studies of climate hazard impacts and risks to selected human settlements in Africa

Hazard	Country/City	Impact on Human Settlement and Infrastructure	Source
Sea level rise and storm surge	Egypt (North Africa)	December 2010, January 2011, and October 2015: Storm surge of 1.2 m above MSL (typical of the Nile Delta coast: 0.4–0.5 m). Coastal flooding and damage to some coastal structures. Moderate flooding of the Nile Delta lowlands. Alexandria city: Flooding generated by heavy rainfall (2015). Increased turbidity of water sources affected efficiency of water treatment plants leading to reduction of water supplies affecting public health systems. Potable water supply affected by saltwater intrusion. Coastal erosion and property damage.	(Kloos and Baumert, 2015; Abutaleb et al., 2018) (Eldeberky Y, 2015; Yehia et al., 2017)
Drought	Southern Africa	**El Niño Drought 2015–2016**: Western Cape Region Affected 8.6 million people. Losses: >USD 2.2 billion. Power generation reduced by 75% at Kariba dam (Zambia) in 2016, and the Cahora Bassa dam (Mozambique) reduced to 34% of its capacity with widespread impact on electricity supplies across southern Africa.	(Davis-Reddy et al., 2017; Spalding-Fecher et al., 2017) (Brooks, 2019)
	Somalia (East Africa)	**Somalia drought 2016-2017**: 926,000 newly displaced persons reported (Nov. 2016–Oct. 2017). 40% of total drought-related displacements accommodated in Mogadishu, Baidoa, Kismayo; 60% hosted in other secondary cities. Increased population density and overcrowding in Somalia's urban areas. Explosion of new shelters and tents for displaced persons within and in outskirts of cities. In Mogadishu, 34% of new settlements developed within six months.	(Government of Somalia, 2018)
Flooding	Malawi (East Africa)	**Floods 2019**: Approximately 975,600 people affected, 672 injured, 60 persons killed, and 86,976 people displaced. 288,371 houses	(Government of Malawi, 2019)

		damaged. 129 bridges and 68 culverts destroyed. 1841 km of road network estimated at USD 36.1 million destroyed. Total cost of damage and losses: housing sector - USD 106.9 million, energy - USD 3.1 million; water and sanitation - USD 6.4 million; transport - USD 37.0 million. Total cost of destroyed physical assets – USD 157.7 million. Damage and Losses in Blantyre city: housing sector - USD 29.87 million, energy sector - USD 0.38 million and transport sector - USD 1.72 million.	
Tropical cyclone	Mozambique, Zimbabwe and Malawi (Southern Africa)	**Cyclones Idai and Kenneth 2019:** Severe flooding of districts in Mozambique, Zimbabwe, and Malawi; 233,900 houses completely destroyed or damaged in Mozambique. Cyclone Kenneth - about 40,000 houses and 19 health facilities destroyed. Cyclone Idai - destroyed or damaged 1,345 km of transmission lines, 10,216 km of distribution lines, two 90MW generation plants, 30 sub-stations and 4,000 transformers, resulting in estimated damage of USD 133.5 million and loss of USD 47.9 million in the energy sector in Mozambique. 602 and 299 people killed in Mozambique and Zimbabwe respectively; Affected persons - about 1.5 million in Mozambique and 270,000 in Zimbabwe. In Beira (Mozambique) - 60% of city was inundated, 70% of houses damaged or totally destroyed, mostly in the poorest neighbourhood, and 90% of the city's power grid affected. Huge losses and damages to infrastructures in the energy, transport, water supply, communication services, housing, health and education sector were also recorded.	(Cambaza et al., 2019; Chatiza, 2019; Government of Mozambique, 2019; Hope, 2019; Lequechane et al., 2020; Phiri et al., 2021) (Enenkel et al., 2020)
Landslide	Freetown (West Africa)	**August 2017**: At least 500 persons killed and over 600 persons declared missing, >3,000 residents rendered homeless; 349 houses destroyed. Damage to health facilities and educational buildings. Economic cost of landslide and flood: USD 31.6 million.	(Cui et al., 2019) (World Bank, 2017b)
	Uganda (East Africa)	Slopes of Mt. Elgon (2010): More than 350 deaths and 500,000 persons needed to be relocated	(Croitoru et al., 2019)

From 2005–2020, flood-induced damage over Africa was estimated at over USD 4.4 billion, with eastern and western Africa being the most affected regions (EMDAT and CRED, 2020). Total damages in four West African countries (Benin, Cote d'Ivoire, Senegal and Togo) in 2017 were estimated at USD 850 million for pluvial floods and USD 555 million for fluvial floods (Croitoru et al., 2019). Unprecedented economic loss, in terms of goods and properties, estimated by the Nigerian insurance industry at USD 200 million resulted from floods in Lagos in 2011 (Adelekan, 2016). In southern Africa, the highest costs were incurred from flood losses during the period 2000-2015 (UNEP-FI, 2019b; Simpson, 2020).

Business disruptions from climate impacts have implications for deepening poverty (Adelekan and Fregene, 2015). Small and medium enterprises (SMEs) employ 60–90% of workers in many African countries and contribute 40% or more to the GDP in Ghana, Kenya, Nigeria, Zimbabwe, South Africa and Tanzania (Muriithi, 2017). The viability of businesses and economic well-being of large populations employed in SMEs is severely affected by climate hazards as reported for local wind storms in Ibadan (Adelekan, 2012), El Niño-related flooding (Nairobi), drought-induced water supply disruption (Gaborone) and power outages (Lusaka) (Gannon et al., 2018). High water demand due to high rates of urbanisation and population growth, coupled with drought, reduce groundwater levels in cities (e.g., Bouake, Harare, Tripoli, Niamey) and increase saltwater intrusion into groundwater in coastal areas, reducing water availability and water security, particularly for poorer populations not connected to municipal water networks (Aswad et al., 2019; Claon et al., 2020).

Evidence of the impact of heat waves in urban Africa in the current climate is sparse, due in part to low reporting and monitoring (Engelbrecht et al., 2015; Harrington and Otto, 2020). Knowledge is also limited on the interaction of climate change, urban growth and the urban heat island effect in Africa (Chapman et al., 2017). In North Africa, the present day number of high heat-stress nights is around 10 times larger in urban than rural areas (Fischer et al., 2012).

9.9.2.2 Observed Impacts to Road and Energy Infrastructure

The highest transport infrastructure exposures are from floods (Koks et al., 2019), with potentially severe consequences for food security (Fanzo et al., 2018), communication and the economy of affected regions (*high confidence*) (Koks et al., 2019). Eight of the twenty countries with the highest expected annual damages to road and rail assets, relative to the country's GDP, are located in East, West and Central Africa (Koks et al., 2019). Transport impacts compound climate impacts, such as heat stress and air pollution linked to vehicle emissions in Dar es Salaam (Ndetto and Matzarakis, 2014).

African economies that rely primarily on hydropower for electricity generation are particularly sensitive to climate variability (Brooks, 2019). This sensitivity was already felt during the 2015/16 El Niño, in which Malawi, Tanzania, Zambia and Zimbabwe all experienced widespread and prolonged load shedding due to low rainfall. The impact was felt throughout the economy and reflected in reduced GDP growth in Zambia (Conway et al., 2017).

9.9.3 Observed Vulnerabilities of Human Settlements to Climate Risks

Urban vulnerabilities and exposure to climate change are increasing (*medium to high confidence*) and are influenced by patterns of urban settlement and housing characteristics (Satterthwaite, 2017; Godsmark et al., 2019; Williams et al., 2019a). About 70% of African cities are highly vulnerable to climate shocks of which small- and medium-sized towns and cities are more at risk (Verisk Maplecroft, 2018). Flooding was perceived as the most prominent water risk in 75% of 36 sampled cities across African sub-regions, while drought-related water scarcity was indicated as very important/important in 66.7% of cities (OECD, 2021). Almost one-third of African cities with populations of 300,000 or more are located in areas of high exposure to at least one natural hazard, including floods (12%) and droughts (20–25%) (Gu et al., 2015). The coastal cities of East, West and North Africa are particularly vulnerable to the effects of rising sea levels (Abutaleb et al., 2018; IPCC, 2019a).

Globally, sub-Saharan Africa has the largest population living in extreme poverty that are exposed to high flood risk (~71 million people or 55% of global total) (Rentschler and Salhab, 2020). Poverty is a significant factor of flood-induced displacement in Africa, where even small flood exposure can lead to high numbers of displacement (Kakinuma et al., 2020). Africa's large population of urban poor and marginalised groups and informal sector workers, further contribute to high vulnerability to extreme weather and climate change in many settlements (*high confidence*) (Adelekan and Fregene, 2015; IPCC, 2019a; UNDP, 2019).

Other non-climatic stressors which exacerbate vulnerabilities, especially in urban areas, include poor socioeconomic development, weak municipal governance, poor resource and institutional capacities, together with multi-dimensional, location-specific inequalities (*high confidence*) (Dodman et al., 2017; Satterthwaite, 2017).

9.9.4 Projected Risks for Human Settlements and Infrastructure

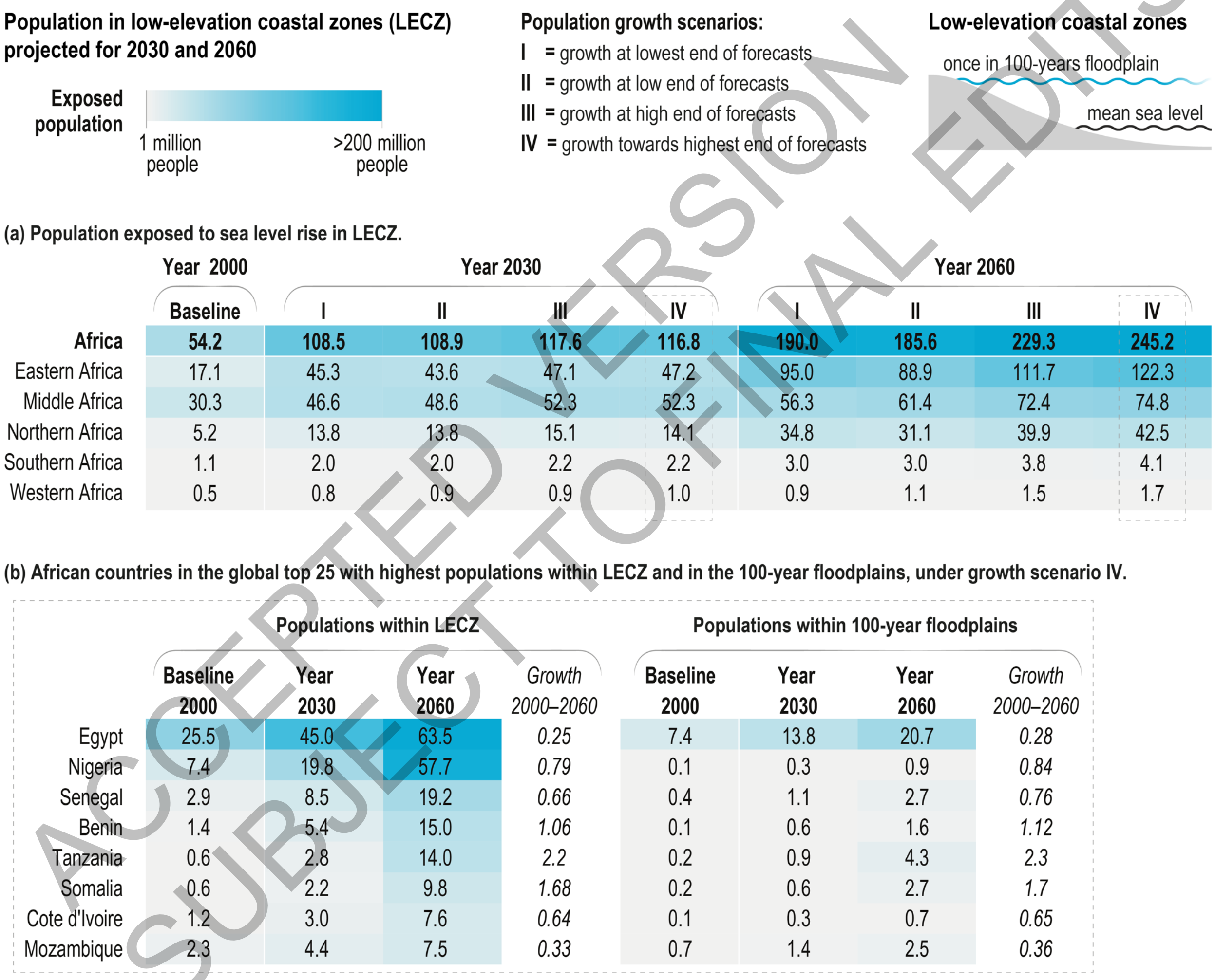
9.9.4.1 Projected Risks for Human Settlements

The extent of urban areas in Africa exposed to climate hazards will increase considerably and cities will be hotspots of climate risks, which could amplify pre-existing stresses related to poverty, exclusion and governance (*high confidence*) (IPCC, 2018b).

Flooding

Continuing current population and GDP growth trends, the extent of urban land exposed to high-frequency flooding is projected to increase around 270% in North Africa, 800% in southern Africa, and 2600% in mid-latitude Africa by 2030 when compared to 2000, without considering climate change (Güneralp et al., 2015). In addition, global warming is projected to increase frequency and magnitude of river floods in East, Central and West Africa (Alfieri et al., 2017; Gu et al., 2020; Kam et al., 2021). On average across large African river basins, the frequency of flood events with a current return period of 100 years is projected to increase to 1 in 40 years at 1.5°C and 2°C global warming, and 1 in 21 years at 4°C warming, with Egypt, Nigeria, Sudan and DRC in the top 20 countries globally for projected damages (Alfieri et al., 2017). Compared to population in 2000, human displacement due to river flooding in Sub-Saharan Africa is projected to increase 600% by 2066–2096 with moderate-to-high population growth and 2.6°C global warming, with risk reducing to a 200% increase for low population growth and 1.6°C global warming (Kam et al., 2021).

Urban population exposure to tropical cyclone hazards in southeastern Africa, in particular Mozambique, is projected to increase due to the intensification of cyclones and their extended duration associated with warmer sea surface temperatures (Fitchett, 2018; Vidya et al., 2020). Urban damage assessment based on a 10-year flood protection level for Accra shows that without flood protection, there is a 10% probability of a flood occurring annually which could cause USD 98.5 million urban damage, affect GDP by USD 50.3 million and affect 34,000 people (Asumadu-Sarkodie et al., 2015). Many urban households and Africa's growing assets could therefore be exposed to increased flooding (IPCC, 2018b).



(a) Population exposed to sea level rise in LECZ.

	Year 2000	Year 2030				Year 2060			
	Baseline	I	II	III	IV	I	II	III	IV
Africa	**54.2**	**108.5**	**108.9**	**117.6**	**116.8**	**190.0**	**185.6**	**229.3**	**245.2**
Eastern Africa	17.1	45.3	43.6	47.1	47.2	95.0	88.9	111.7	122.3
Middle Africa	30.3	46.6	48.6	52.3	52.3	56.3	61.4	72.4	74.8
Northern Africa	5.2	13.8	13.8	15.1	14.1	34.8	31.1	39.9	42.5
Southern Africa	1.1	2.0	2.0	2.2	2.2	3.0	3.0	3.8	4.1
Western Africa	0.5	0.8	0.9	0.9	1.0	0.9	1.1	1.5	1.7

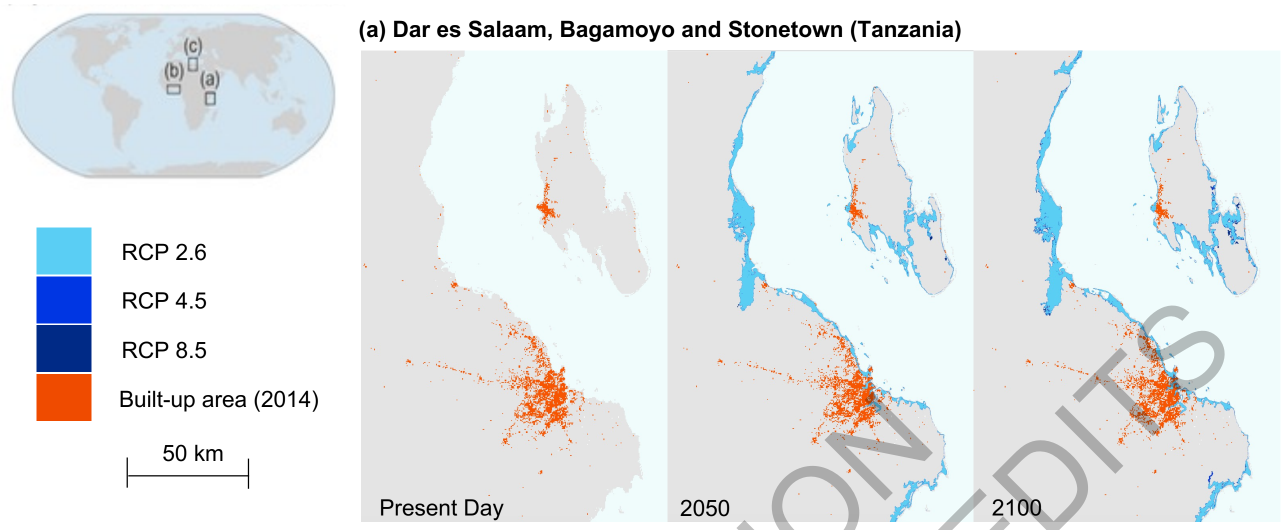
(b) African countries in the global top 25 with highest populations within LECZ and in the 100-year floodplains, under growth scenario IV.

	Populations within LECZ				Populations within 100-year floodplains			
	Baseline 2000	Year 2030	Year 2060	*Growth 2000–2060*	Baseline 2000	Year 2030	Year 2060	*Growth 2000–2060*
Egypt	25.5	45.0	63.5	*0.25*	7.4	13.8	20.7	*0.28*
Nigeria	7.4	19.8	57.7	*0.79*	0.1	0.3	0.9	*0.84*
Senegal	2.9	8.5	19.2	*0.66*	0.4	1.1	2.7	*0.76*
Benin	1.4	5.4	15.0	*1.06*	0.1	0.6	1.6	*1.12*
Tanzania	0.6	2.8	14.0	*2.2*	0.2	0.9	4.3	*2.3*
Somalia	0.6	2.2	9.8	*1.68*	0.2	0.6	2.7	*1.7*
Cote d'Ivoire	1.2	3.0	7.6	*0.64*	0.1	0.3	0.7	*0.65*
Mozambique	2.3	4.4	7.5	*0.33*	0.7	1.4	2.5	*0.36*

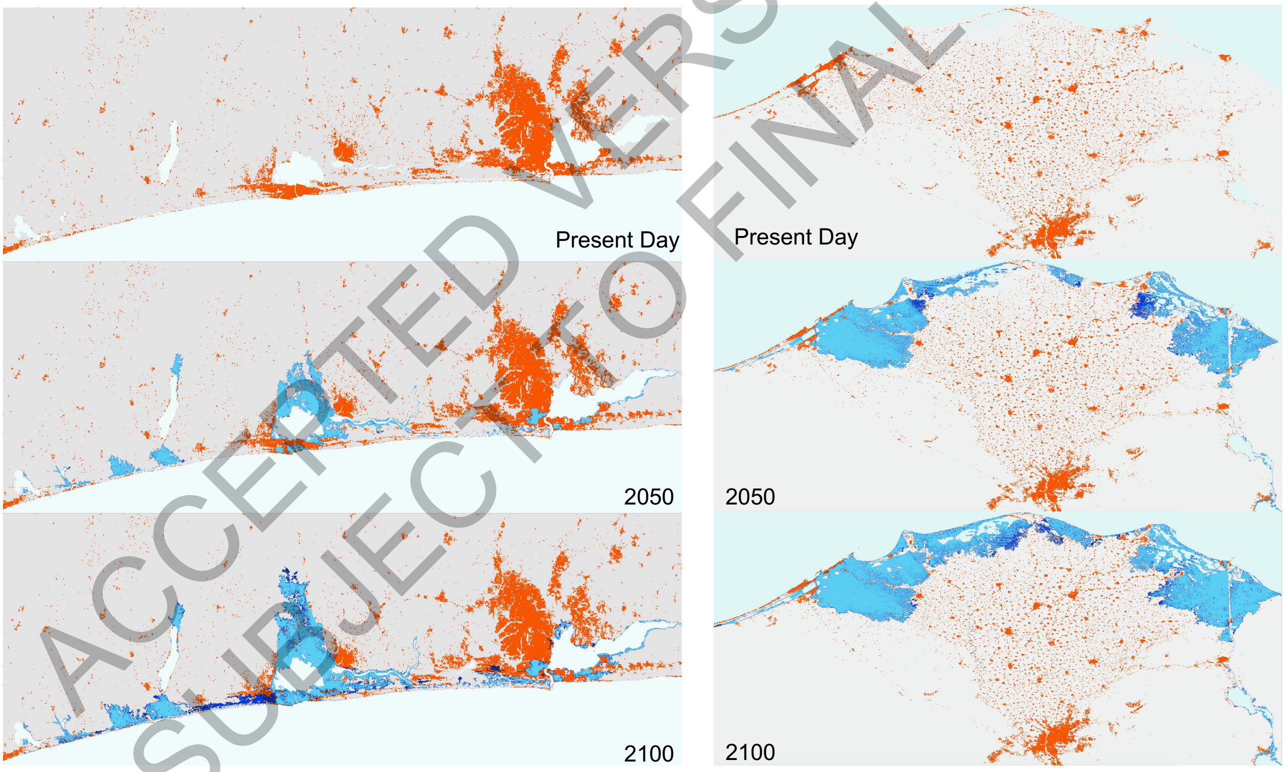
Figure 9.28: Tens to hundreds of millions of people in Africa are projected to be exposed to sea level rise, with a major risk driver being increased exposure due to population increase in low-lying areas. (a) Population in the low-elevation coastal zone (LECZ) projected for 2030 (+10cm SLR) and 2060 (+21 cm SLR). (b) African countries with highest population in LECZ, and additional population exposed in the 100-year floodplain. Data sourced from (Neumann et al., 2015).

Sea level rise and coastal flooding

Africa's low-lying coastal zone population is expected to grow more than any other region from 2000 to 2060 (see Figure 9.28) (Neumann et al., 2015). Future rapid coastal development is expected to increase existing high vulnerabilities to sea level rise (SLR) and coastal hazards, particularly in East Africa (*high confidence*) (Figure 9.29) (Hinkel et al., 2012; Kulp and Strauss, 2019). By 2100, sea levels are projected to rise at least 40 cm above those in 2000 in a below 2°C scenario, and possibly up to 1 m by the end of the century under a 4°C warming scenario (Serdeczny et al., 2017) (see also Cross-Chapter Box SLR in Chapter 3).



(a) Dar es Salaam, Bagamoyo and Stonetown (Tanzania)



(b) Lagos (Nigeria) and Cotonou and Porto-Novo (Benin)

(c) Cairo and Alexandria (Egypt)

Figure 9.29: Selected African cities exposed to sea level rise include (a) Dar es Salaam, Bagamoyo, and Stone Town in Tanzania (East Africa), (b) Lagos in Nigeria, and Cotonou and Porto-Novo in Benin (West Africa), and (c) Cairo and Alexandria in Egypt (North Africa). Orange shows built-up area in 2014. Shades of blue show permanent flooding due to sea level rise by 2050 and 2100 under low (RCP2.6), medium (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenarios. Darker colours for higher emissions scenarios show areas projected to be flooded in addition to those for lower emissions scenarios. The figure assumes failure of coastal defences in 2050 and 2100. Some areas are already below current sea level rise and coastal defences need to be upgraded as sea level rises (e.g., in Egypt), others are just above mean sea levels and they do not necessarily have high protection levels, so these defences need to be built (e.g., Dar Es Salam and Lagos). Blue shading shows permanent inundation surfaces predicted by Coastal DEM and SRTM given the 95th percentile K14/RCP2.6, RCP4.5, and RCP8.5, for present day, 2050, and 2100 sea level projection for permanent inundation (inundation without a storm surge event), and RL10 (10-year return level storm) (Kulp and Strauss, 2019). Low-lying areas isolated from the ocean are removed from the inundation surface using

connected components analysis. Current water bodies are derived from the SRTM Water Body Dataset. Orange areas represent the extent of coastal human settlements in 2014 (Corbane et al., 2018). See Figure CCP4.7 for projections including subsidence and worst-case scenario projections for 2100.

In the absence of any adaptation, Egypt, Mozambique, and Nigeria are projected to be worst affected by SLR in terms of the number of people at risk of flooding annually in a 4°C warming scenario (Hinkel et al., 2012). Recent estimates have explored the potential damages due to SLR and coastal extreme events in 12 major African cities using a stochastic approach to account for uncertainty (Abadie et al., 2020). Expected aggregate damages to these cities in 2050 are USD 65 billion for RCP4.5 and USD 86.5 billion for RCP8.5, and USD 137.5 billion under a high-end scenario that incorporates expert opinion on additional ice sheet melting (Table 9.8). When considering low-probability, high-damage events, aggregate damage risks can be more than twice as high, reaching USD 187 billion and USD 206 billion under RCP4.5 and RCP8.5 scenarios, respectively, and USD 397 billion under the high-end scenario. City characteristics and exposure play a larger role in expected damages and risk than changes in sea level. The city of Alexandria in North Africa leads the ranking, with aggregate expected damage of USD 36 billion and USD 50 billion under RCP4.5 and RCP8.5 scenarios, respectively, and USD 79.4 billion under the high-end scenario.

Table 9.8: Regional relative sea level rise and associated damage risks in 12 major African coastal cities under four SLR scenarios. Panel (a) Regional relative sea level rise by 2050 and 2100. For SLR, median and 95th percentiles are presented, in centimetres. Panel (b) Probabilistic damage estimations by 2050 include expected average damages (EAD), damages at the 95th percentile (VaR) and the Expected Shortfall (ES), which represents the average damages of the 5% worst cases. Four relative sea level projections were considered under no adaptation: the RCP2.6, 4.5 and 8.5 scenarios from the IPCC AR5, and a high-end RCP8.5 scenario that incorporates expert opinion on additional ice sheet melting. Note that figures are provided in undiscounted millions of US dollars (2005) and have been rounded off to avoid a false sense of precision (Abadie et al., 2020; Abadie et al., 2021).

a) Regional relative sea level rise (cm)

City	Year	RCP2.6		RCP4.5		RCP8.5		High end	
		Median	P95	Median	P95	Median	P95	Median	P95
Abidjan	2050	21	30	22	32	24	34	28	48
	2100	44	69	53	86	75	114	86	206
Alexandria	2050	18	26	18	28	21	30	25	43
	2100	36	58	46	73	67	102	78	186
Algiers	2050	19	27	19	29	22	31	25	45
	2100	39	62	47	76	66	98	78	192
Cape Town	2050	20	30	21	31	23	33	27	48
	2100	44	69	53	87	75	117	86	199
Casablanca	2050	19	27	20	29	22	31	26	46
	2100	39	63	47	78	65	99	77	198
Dakar	2050	21	31	21	31	23	33	27	48
	2100	43	69	53	86	73	111	85	209
Dar-es-Salam	2050	20	29	21	31	24	33	27	47
	2100	45	70	54	86	76	117	87	206
Durban	2050	20	30	22	32	25	34	28	49
	2100	46	72	55	90	78	119	89	207
Lagos	2050	21	30	22	32	24	34	28	48
	2100	44	69	54	86	75	113	86	205
Lome	2050	21	30	22	32	24	34	28	48
	2100	44	69	53	86	76	115	87	205
Luanda	2050	21	30	23	32	25	35	29	49
	2100	45	70	55	88	78	119	90	205
Maputo	2050	21	31	22	32	24	34	28	49
	2100	45	71	55	89	78	120	89	209

b) Expected damages and risk measures (USD millions)

City	RCP2.6			RCP4.5			RCP8.5			High-end scenario		
	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)	EAD	VaR(95%)	ES(95%)
Abidjan	14,290	33,910	41,690	16,730	38,230	46,390	20,910	42,140	49,550	32,670	77,750	96,570
Alexandria	32,840	74,100	92,470	36,220	83,700	104,270	49,990	99,500	117,580	79,360	180,090	221,390
Algiers	270	620	760	300	700	870	390	810	960	640	1,540	1,920
Cape Town	110	310	400	130	360	450	170	410	490	300	800	1,010
Casablanca	350	1,150	1,520	420	1,340	1,740	610	1,570	1,930	1,230	3,590	4,630
Dakar	590	1,310	1,590	620	1,390	1,690	760	1,530	1,800	1,180	2,880	3,610
Dar-es-Salam	880	2,100	2,600	1,050	2,440	2,970	1,360	2,760	3,250	2,140	5,120	6,360
Durban	110	370	470	150	420	530	210	490	590	370	970	1,230
Lagos	3,680	6,790	7,950	4,200	7,660	8,930	4,920	8,270	9,420	6,750	13,820	16,730
Lome	3,230	10,480	13,460	4,280	12,580	15,780	5,980	14,430	17,380	10,720	28,580	36,010
Luanda	160	380	470	200	440	530	260	510	600	400	910	1,130
Maputo	650	1,990	2,530	700	2,080	2,620	980	2,410	2,910	1,790	4,830	6,110
Aggregate damage and risk	57,160	133,510	165,910	65,000	151,340	186,770	86,540	174,830	206,460	137,550	320,880	396,700

Sea level rise and associated episodic flooding are identified as key drivers of projected net migration of 750,000 people out of the East African coastal zone between 2020 and 2050 (IPCC, 2019a). These trends, alongside the emergence of 'hotspots' of climate in and out-migration (Box 9.8), will have major implications for climate-sensitive sectors and the adequacy of human settlements, including urban infrastructure and social support systems. Actions which could help reduce the number of people being forced to move in distress, include adoption of inclusive and climate-resilient development policies, together with targeted investments to manage the reality of climate migration; and mainstreaming climate migration in development planning (Box 9.8).

Drought

Although an increase in drought hazard is projected for North and southwest southern Africa with increased global warming (Figure 9.15), Central African countries may have the highest drought risk because of high vulnerability and high population growth (Ahmadalipour et al., 2019). Among continents, Africa contains the second largest population of people living in drylands, which is expected to double by 2050 (IPCC, 2019a). Continuing current population and GDP growth trends, the extent of urban land in arid zones is projected to increase around 180% in Southern Africa, 300% in North Africa, and 700% in mid-latitude Africa by 2030 when compared to 2000, without considering climate change (Güneralp et al., 2015). At 1.5°C warming, urban populations exposed to severe droughts in West Africa are projected to increase (65±34 million) and increase further at 2°C (IPCC, 2018b; Liu et al., 2018b). Risks associated with increases in drought frequency and magnitudes are projected to be substantially larger at 2°C than at 1.5°C for North Africa and Southern Africa (IPCC, 2018b; Oppenheimer et al., 2019). Dryland populations exposed (vulnerable) to water stress, heat stress, and desertification are projected to reach 951 (178) million at 1.5°C, 1,152 (220) million at 2°C, and 1,285 (277) million at 3°C of global warming (IPCC, 2019a). At global warming of 2°C under a scenario of low populaton growth and sustainable development (SSP1), the exposed (vulnerable) dryland population is 974 (35) million and for higher population growth and low environmental protections (SSP3) it is 1.27 billion (522 million), a majority of which is in West Africa (IPCC, 2019a).

Extreme heat

Projections for 173 African cities show that around 25 cities will have over 150 days per year with an apparent temperature above 40.6°C for 1.7°C global warming, increasing to 35 cities for 2.1°C and 65 cities for 4.4°C warming, with West African cities most affected (Rohat et al., 2019). Across Africa, urban population exposure to extreme heat is expected to increase from 2 billion person-days per year for 1985–2005 to 45 billion person-days for 1.7°C global warming with low population growth (SSP1) and to 95 billion person-days for 2.8°C and medium-high population growth (SSP4) by the 2060s, with increases of 20–52 times 1985–2005 levels by 2080–2100, depending on the scenario (Rohat et al., 2019). West Africa (especially Nigeria) has the highest absolute exposure and Southern Africa the least. Considering the urban heat island effect, the more vulnerable populations under 5 and over 64 exposed to heat waves of >15 days over 42°C are projected to increase from 27 million in 2010 to 360 million by 2100 for 1.8°C global warming, increasing to 440 million for >4°C global warming, with West Africa most affected (Marcotullio et al., 2021). This portends increased vulnerability to risk of heat stress in big cities of Central, East and West Africa (*very high confidence*) (Gasparrini et al., 2015; Liu et al., 2017; Rohat et al., 2019). Shifting to a low urban population growth pathway is projected to achieve a greater reduction in aggregate exposure to extreme heat for most cities in West Africa whereas limiting warming through lower emissions pathways achieves greater reductions in exposure in Central and East Africa (Rohat et al., 2019).

The African population exposed to compound climate extremes, such as coincident heat waves and droughts or drought followed immediately by extreme rainfall, is projected to increase 47-fold by 2070–2099 compared to 1981–2010 for a scenario with high population growth and 4°C global warming (SSP3/RCP8.5) and only 12-fold for low population growth and 1.6°C global warming (SSP1/RCP2.6), with West, Central-East, northeastern and southeastern Africa especially exposed (Weber et al., 2020). Coincident heat waves and drought is the compound event to which the most people are projected to be exposed: ~1.9 billion person-events (a 14-fold increase) for SSP1/RCP2.6 and ~7.3 billion person-events (52-fold increase) for SSP3/RCP8.5 (Weber et al., 2020).

9.9.4.2 Projected Risks to Electricity Generation and Transmission

Climate change poses an increased risk to energy security for human settlements in Africa (*high confidence*). With burgeoning urban populations and growing economies, sub-Saharan Africa's electricity needs are growing. The IEA projects total generation capacity in Africa must grow 2.5 times from 244 GW in 2018 to 614 GW by 2040 (IEA, 2019). African nations plan to add significant generation capacity from natural gas, hydropower, wind and solar power. Each of these technologies is associated to a varying degree with climate risk.

The long lifespan of hydropower dams exposes them to decades of climatic variability. There is a wide range of uncertainty around the future climate of Africa's major river basins, but in several basins, there is the likelihood of increased rainfall variability and a drier climate (see Box 9.5). In countries that rely primarily on hydropower, climate change could have considerable impacts on electricity prices and as a result, consumers' expenditure (Sridharan et al., 2019). With increasing societal demands on limited water resources and future climate change, it is expected that there will be an intensification of water-energy-food competition and trade-offs (*high confidence*) (Section 9.7; Box 9.5).

9.9.4.3 Projected Risks to Road Infrastructure

Climate change and sea level rise will result in high economic costs for road infrastructure in sub-Saharan Africa (*medium confidence*) (Chinowsky et al., 2015). Across Africa as a whole, potential cumulative costs estimates through 2100 range from USD 183.6 billion (with adaptation) to USD 248.3 billion (no adaptation) to repair and maintain existing roads damaged by temperature and precipitation changes directly related to projected climate change (see Figure 9.30) (Chinowsky et al., 2013). Climate-related road damage and associated repairs will be a significant financial burden to countries, but to varying degrees according to flood risk, existing road asset liability, topography and rural connectivity, among other factors (Chinowsky et al., 2015; Cervigni et al., 2017; Koks et al., 2019). For example, Mozambique is projected to face estimated annual average costs of USD 123 million for maintaining and repairing roads damaged directly by precipitation and temperature changes from climate change through 2050 in a median climate change scenario for a policy that does not consider climate impacts during road design and construction (Chinowsky et al., 2015). Risk of river flooding to bridges in Mozambique under current conditions is estimated to be USD 200 million, equal to 1.5% of its GDP per year, and could rise to USD 400 million per year in the worst-case climate change scenario by 2050 (Schweikert et al., 2015).

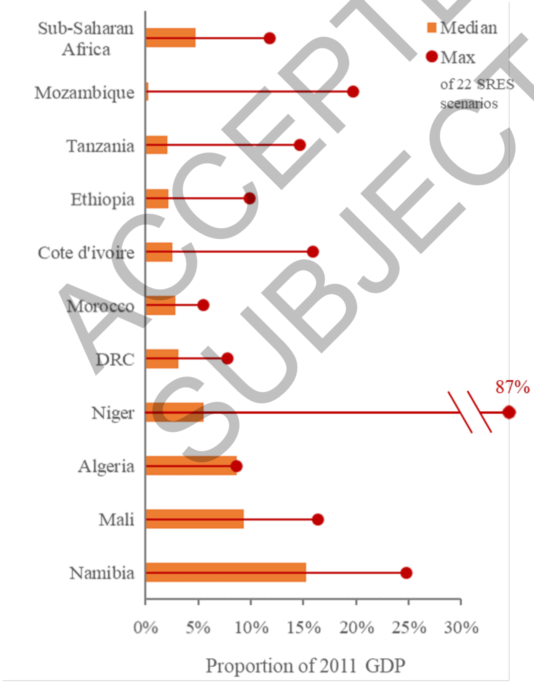


Figure 9.30: Projected costs for repair and maintenance of pre-2011 road infrastructure in selected African countries as a result of projected climate-change-related damages due directly to precipitation and temperature changes through to 2100 (Data sources: (Chinowsky et al., 2013). The analysis was run for 22 SRES climate scenarios and the median, and maximum results of the analyses are represented as proportions of the 2011 GDP of each country.

9.9.5 Adaptation in Human Settlements and for Infrastructure

9.9.5.1 Solutions and Residual Risk Observed in Human Settlements

Autonomous responses to climate impacts in 40 African cities show that excess rainfall is the primary climate driver of adaptation, followed by multi-hazard impacts, with 72% of responses focused on excess rainfall (Hunter et al., 2020). Innovation for adaptation in areas such as home design, social networks, organisations and infrastructure, is evident (Swanepoel and Sauka, 2019). Social learning platforms also increase communities' adaptive capacities and resilience to risk (Thorn et al., 2015).

There is limited evidence of successful, proactively planned climate change adaptation in African cities (Simon and Leck, 2015), particularly for those countries highly vulnerable to climate change (Ford et al., 2014). Planned adaptation initiatives in African cities since 2006 have been predominantly determined at the national level with negligible participation of lower levels of government (Ford et al., 2014). Adaptation action directed at vulnerable populations is also rare (Ford et al., 2014). There are emerging examples of cities planned climate adaptation measures, such as those advanced by Durban (Roberts, 2010), Cape Town (Taylor et al., 2016) and Lagos (Adelekan, 2016). There are also examples of community-led projects such as those in Maputo (Broto et al., 2015), which have seen meaningful help from a range of policy networks, dialogue forums and urban learning labs (Pasquini and Cowling, 2014; Shackleton et al., 2015). These researched cities can be lighthouses for wider exchange and the basis for a deeper synthesis of evidence (Lindley et al., 2019). However, planned adaptation progress is slow, especially in West and Central Africa (Tiepolo, 2014).

Nature-based solutions are also being deployed in mitigating and adapting to climate change, with demonstrated long-term health, ecological and social co-benefits (Swanepoel and Sauka, 2019) (Section 9.6.4). The cost-benefit analysis of nature-based solutions, compared to purely grey infrastructure initiatives, is discussed in Chapter 6 (Section 6.3.3). Nature-based solutions can also lengthen the life of existing built infrastructure (du Toit et al., 2018). Since 2014, an increasing number of ecosystem-based adaptation projects involving the restoration of mangrove, wetland and riparian ecosystems have been initiated across Africa, a majority of which address water-related climate risks (Table 9.9).

Table 9.9: Examples of ecosystem-based solutions to climate impacts in African cities.

Project	City	Solution	Reference
Green Urban Infrastructure (GUI)	Beira (Mozambique)	Mitigating against increased flood risks through restoration of mangrove and other natural habitats along the Chiveve river and the development of urban green spaces.	(IPCC, 2019a; CES Consulting Engineers Salzgitter GmbH and Inros Lackner SE, 2020) .
The Msimbazi Opportunity Plan (MOP) 2019-2024	Dar es Salaam, Tanzania	Enhancing urban resilience to flood risk by reducing flood hazard, and reducing people, properties and critical infrastructure exposed to flood hazard.	(Croitoru et al., 2019)
Tanzania Ecosystem Based Adaptation	Dar es Salaam and five coastal districts, Tanzania	Rehabilitation of over 3,000 hectares of climate-resilient mangrove species.	(UNEP, 2019)
Building Resilience in the Coastal Zone through Ecosystem–based approaches to adaptation	Maputo, Mozambique	Restoration of mangrove and riparian ecosystems for flood control and protection from coastal flooding enhanced water supply.	(GEF, 2019)
Addressing Urgent Coastal Adaptation Needs and Capacity Gaps in Angola	Five coastal communities in Angola	Restoration of 561 hectares of wetland, mangroves and other ecological habitats to promote flood defence and mitigate the threat of drought.	(UNEP, 2020)

Green City Kigali 2016-	Kigali (Rwanda)	600 hectares planned neighbourhood which integrates green building and design, efficient and renewable energy, recycling and inclusive living.	(SWECO, 2019)
Urban Natural Assets for Africa - Rivers for Life	Kampala (Uganda)	Preservation of natural buffers to enhance the protective functions offered by natural ecosystems that support disaster resilience benefit.	(World Bank, 2015)

For green infrastructure to be successful, however, sustainable landscapes and regions require both stewardship and management at multiple levels of governance and social scales (Brink et al., 2016).

Currently planned climate change adaptation to coastal hazards in Africa's large coastal cities has mainly been achieved through expensive coastal engineering efforts such as sea walls, revetments, breakwaters, spillways, dikes and groynes. Examples are found in West Africa (Adelekan, 2016; Alves et al., 2020). Beach nourishment efforts have also been undertaken in Egypt, Banjul and Lagos (Frihy et al., 2016; Alves et al., 2020). However, the use of vegetated coastal ecosystems presents greater opportunities for African cities because of the lower costs (Duarte et al., 2013).

Most (>80%) of Africa's large coastal cities have no adaptation policies and, where available, these are mostly, except for South Africa, dominated by national plans (Olazabal et al., 2019). Coastal adaptation actions minimally consider socioeconomic projections and are not at all aligned with future climate scenarios and risks, which is highly limiting for adaptation planning (Olazabal et al., 2019).

9.9.5.2 Anticipated Adaptation and Residual Risk for Human Settlements

Africa's smaller towns and cities have received far less scholarly and policy development attention for adaptation (Clapp and Pillay, 2017; White and Wahba, 2019). Smaller towns also have less ability to partner effectively with private entities for adaptation initiatives (Wisner et al., 2015). Political will to address climate change and information flows between key stakeholders, professional and political decision-makers may be easier to establish in smaller cities than in the megacity context (Wisner et al., 2015).

Exposure and vulnerability are particularly acute in informal areas, making coordinated adaptation challenging. Yet, there is growing recognition of the potential for bottom-up adaptation that embraces informality in order to more effectively reduce risk (Taylor et al., 2021a) (Figure 9.31). This can provide an opportunity for change towards more risk-sensitive urban development and transformative climate adaptation (Leck et al., 2018). Addressing social vulnerability is particularly important for ensuring the resilience of populations at risk. Improved monitoring, modelling and communication of climate risks is needed to reduce the impacts of climate hazards (Tramblay et al., 2020; Cole et al., 2021a).

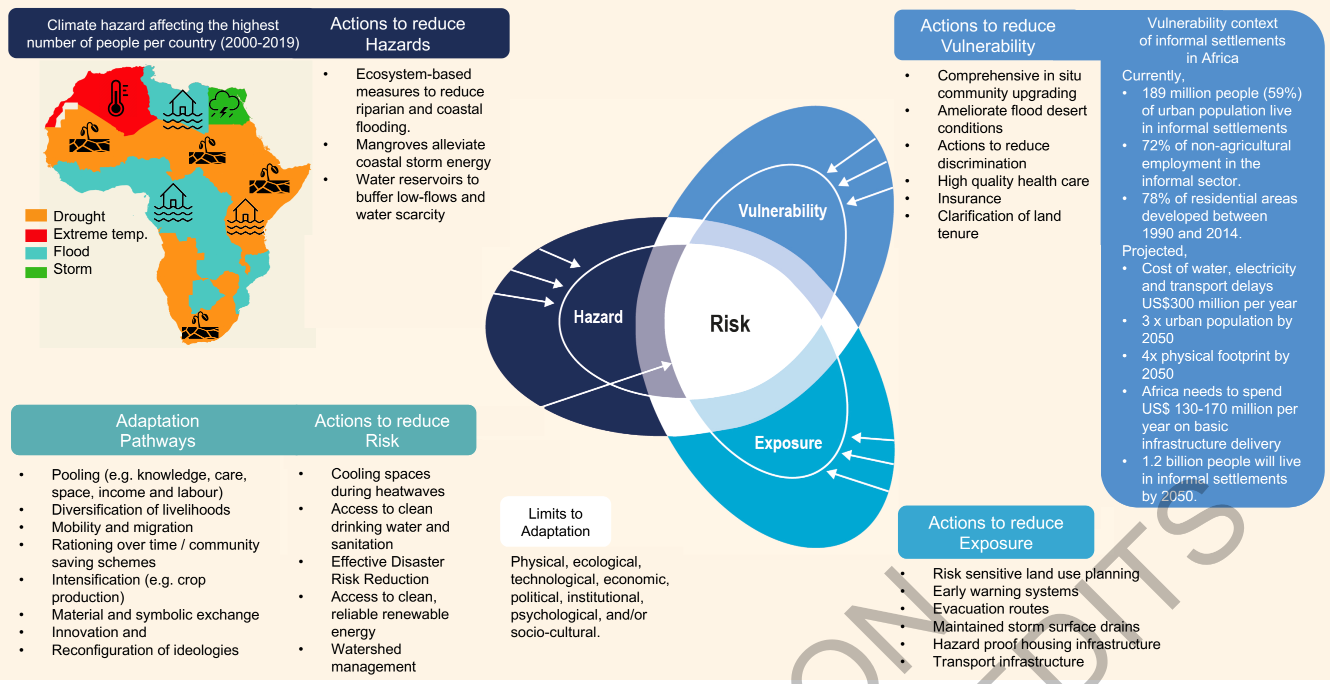


Figure 9.31: Key elements of adaptation in informal settlements in Africa. Adapted from (Thorn et al., 2015; Fedele et al., 2019; Satterthwaite et al., 2020)

9.9.5.3 *Anticipated Adaptation for Transport Systems in Africa*

Higher costs will be incurred to maintain and repair damages caused to existing roads as a result of climate change for countries with no adaptation policy for transport infrastructure (*very high confidence*) (Chinowsky et al., 2013; Cervigni et al., 2017; Koks et al., 2019). Countries with a greater percentage of unpaved roads will, however, incur higher economic costs through adaptation policy when compared to no adaptation policy (Cervigni et al., 2017).

Adaptation measures in the transport sector have focused on the climate resilience of road infrastructure. Modelling suggests that proactive adaptation of road designs to account for temperature increases is a ‘no regret’ option in all cases, but accounting for precipitation increases should be assessed on a case-by-case basis (*medium confidence*) (Cervigni et al., 2017). African governments will need climate adaptation financing options to meet the higher capital requirements of resilient road infrastructure interventions (Hearn, 2016).

Under the Nationally Appropriate Mitigation Action (NAMA) programme, investments in public transport and transit-oriented development are highlighted as desired mitigation-adaptation interventions within cities of South Africa, Ethiopia and Burkina Faso (UNFCCC, 2020). These interventions simultaneously reduce the vulnerability of low-income residents to climate shocks, prevent lock-ins into carbon-intensive development pathways and reduce poverty (*high confidence*) (Hallegatte et al., 2016; Rozenberg et al., 2019). The combined mitigation-adaptation interventions in the land use transport systems of African cities are also expected to have sufficient short-term co-benefits (reducing air pollution, congestion and traffic fatalities) to be ‘no regret’ investments (*very high confidence*) (Hallegatte et al., 2016; Rozenberg et al., 2019). Only eight African countries have transport-specific adaptation measures in their NDCs (Nwamarah, 2018). Five African countries have submitted National Adaptation Plans (NAPs) (Table 9.10).

Table 9.10: Transport sector references in the National Adaptation Plans of five African countries. Source: (Government of Burkina Faso, 2015; Government of Cameroon, 2015; Government of Togo, 2016; Government of Kenya, 2017; Government of Ethiopia, 2019).

Country	Identify climate change impacts	Promote transport as a disaster risk	Transport-specific adaptation measures			
			Climate resilient	Promote public transport	Promote non-motorized transport	Urban land use planning

		reduction measure	design standards			
Burkina Faso	X		X	X		X
Cameroon			X	X		
Ethiopia	X	X	X	X		
Kenya	X					
Togo				X	X	

9.9.5.4 Projected Adaptation for Electricity Generation and Transmission in Africa

Most electricity infrastructure in Africa has been designed to account for historical climatic patterns. Failure to take into account future climate scenarios in power system planning increases the climate risk facing infrastructure and supplies. Yet, energy demand for cooling over Africa, for example, is expected to increase, with a potential increase in heat stress, population growth and rapid urbanisation to 1.2% of total final energy demand by 2100 compared to 0.4% in 2005 (Parkes et al., 2019). Integrated energy system costs from increased demand for cooling to mitigate heat stress are projected to accumulate from 2005 to USD 51.3 billion by 2035 at 2°C and to USD 486.5 billion by 2076 at 4°C global warming (Parkes et al., 2019).

For hydropower, adaptations to different climate conditions can be made at the level of the power plant, turbine size and reservoir storage capacities, and can be adjusted to projected hydrological patterns (Lempert et al., 2015). At the river basin level, integrated water resource management practices can be implemented across sectors that compete for the same water resources (Howells et al., 2013). At the power system level, the energy mix and the protocol through which different power plants are dispatched can be adapted to different climate scenarios (Spalding-Fecher et al., 2017; Sridharan et al., 2019).

Given the uncertainty around future hydroclimate conditions, hydropower development decisions carry risk of ‘regrets’ (that is, damages or missed opportunities) when a different climate than was expected materialises. ‘Robust adaptation’ refers to an adaptation strategy that balances risks across different climate scenarios (Cervigni et al., 2015) (Cross-Chapter Box DEEP in Chapter 17). Development bank lending principles require consideration of the regional picture and interactions with other developments along a river when they determine the social and environmental impacts of the proposed hydropower project. However, these principles often do not explicitly consider climate change, so the risk of reoccurring drought-induced hydropower shortages could be missed (Box 9.5).

Lastly, given the degree to which hydropower competes with other sectors and ecosystems for the same water resources, it is critical that hydropower planning and adaptation does not occur in isolation. As discussed in Section 9.7, it must be part of an integrated water management system that balances the needs of different water-reliant sectors with other societal and ecological demands under increasingly variable climate and hydrological conditions (Section 9.7.3).

9.10 Health

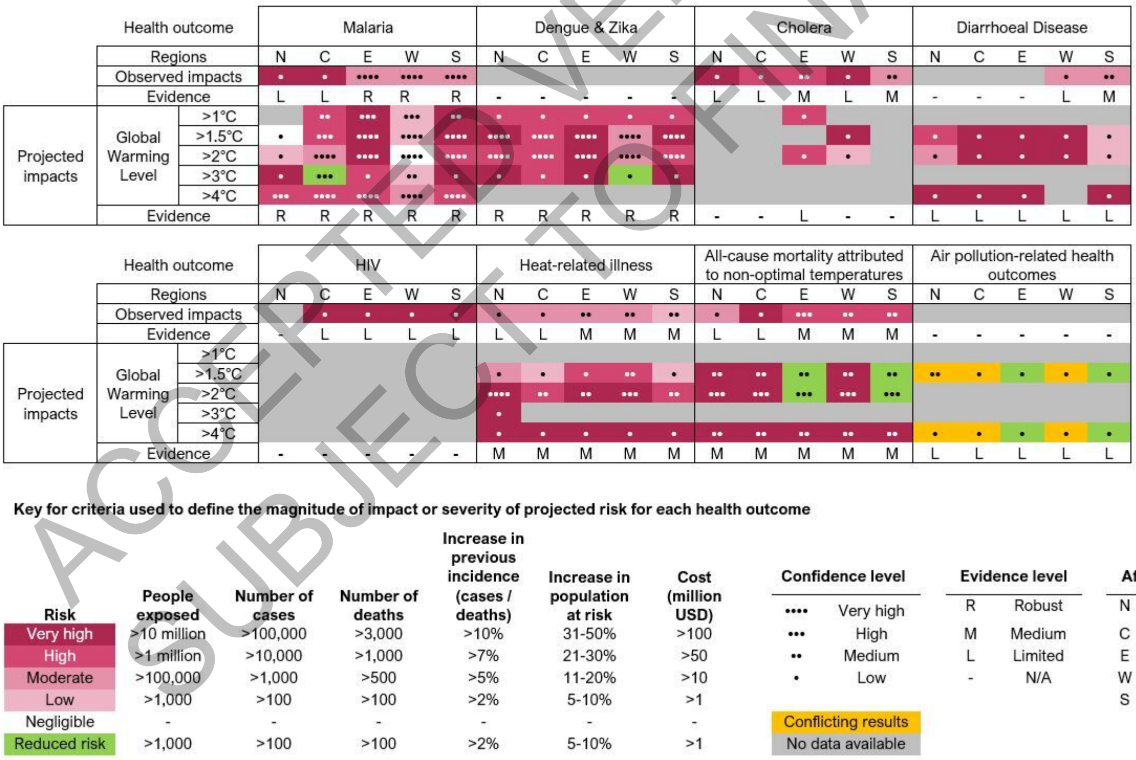
The health section is organised by disease or health outcome, with observed impacts and projected risks described for each condition. All adaptation options are presented at the end of the section, highlighting prevention and preparedness, community engagement and disease-specific adaptation options.

9.10.1 The Influence of Social Determinants of Health on the Impacts of Climate Change

The social determinants of health are ‘the conditions in which people are born, grow, live, work and age’ as well as the drivers of these, including the social circumstances which profoundly affect health and drive health disparities (Commission of Social Determinants of Health, 2008; Gurewich et al., 2020). Social features (e.g., health-related behaviours), socioeconomic factors (e.g., income, wealth and education) and environmental determinants (e.g., air or water quality) are critical for shaping health outcomes. These factors are inextricably linked (Schulz and Northridge, 2004; Moore and Diaz, 2015) and are largely outside the domain of the health sector. Climate change is already challenging the health and well-being of African communities, compounding the effects of underlying inequalities (*high confidence*). The interlinkage between climate change and social determinants of health are largely discussed at a global level (Commission of Social Determinants of Health, 2008), or for developed countries (Ahdoot et al., 2015; Levy and Patz, 2015; Department of Economic and Social Affairs, 2016), with scant evidence for Africa. Nevertheless, there is robust evidence that the health impacts of climate change disproportionately affect the poorest people and children and, in some situations, can differ by gender and age (St Louis and Hess, 2008; Nyahunda et al., 2020; Ragavan et al., 2020) (see Box 9.1). Unequal access to health care particularly affects rural communities (Falchetta et al., 2020), vulnerable women and children (Wigley et al., 2020a) and challenges the achievement of development priorities such as universal health care access (SDG 3) (Weiss et al., 2020).

9.10.2 Observed Impacts and Projected Risks

Climate change is already impacting certain health outcomes in Africa (e.g. temperature-related mortality) and risks for most (but not all) health outcomes are projected to increase with increasing global warming (Figure 9.32), with young children (<5 years old), the elderly (>65 years old), pregnant women, individuals with pre-existing morbidities, physical labourers and people living in poverty or affected by other socioeconomic determinants of health being the most vulnerable (*high confidence*). Women may be more vulnerable to climate change impacts than men (Chersich et al., 2018; Jaka and Shava, 2018; Adzawla et al., 2019a). Contextualising projected impacts of climate change on health requires an understanding of observed impacts (Figure 9.32). Without management and mitigation, current and projected morbidities and mortalities will put additional strain on health, social and economic systems (Hendrix, 2017; Alonso et al., 2019).



Health outcome		Malaria					Dengue & Zika					Cholera					Diarrhoeal Disease				
Regions		N	C	E	W	S	N	C	E	W	S	N	C	E	W	S	N	C	E	W	S
Observed impacts		•	•	••••	••••	••••						•	•	••	•	••				•	••
Evidence		L	L	R	R	R	-	-	-	-	-	L	L	M	L	M	-	-	-	L	M
Projected impacts: Global Warming Level	>1°C		••	•••	•••	••	•	•	•	•	•			•							
	>1.5°C	•	•••	••••	••••	••••	••••	••••	••••	••••	••••				•		•	•	•	•	•
	>2°C	•	••••	••••	••••	••••	••••	••••	••••	••••	••••			•	•		•	•	•	•	•
	>3°C	•	•••	•	••	•	•	•	•	•	•										
	>4°C	•••	••••	••••	••••	••••											•	•	•		•
Evidence		R	R	R	R	R	R	R	R	R	R	-	-	L	-	-	L	L	L	L	L

Health outcome		HIV					Heat-related illness					All-cause mortality attributed to non-optimal temperatures					Air pollution-related health outcomes				
Regions		N	C	E	W	S	N	C	E	W	S	N	C	E	W	S	N	C	E	W	S
Observed impacts			•	•	•	•	•	•	••	••	••	•	•	•••	••	••					
Evidence		-	L	L	L	L	L	L	M	M	M	L	L	M	M	M	-	-	-	-	-
Projected impacts: Global Warming Level	>1°C																				
	>1.5°C						•	•	•	••	•	••	••	••	••	••	••	•	•	•	•
	>2°C						••••	••	••	•••	••	•••	•••	•••	•••	•••					
	>3°C						•														
	>4°C						•	•	•	•	•	••	••	••	••	••	•	•	•	•	•
Evidence		-	-	-	-	-	M	M	M	M	M	M	M	M	M	M	L	L	L	L	L

Key for criteria used to define the magnitude of impact or severity of projected risk for each health outcome

Risk	People exposed	Number of cases	Number of deaths	Increase in previous incidence (cases / deaths)	Increase in population at risk	Cost (million USD)
Very high	>10 million	>100,000	>3,000	>10%	31-50%	>100
High	>1 million	>10,000	>1,000	>7%	21-30%	>50
Moderate	>100,000	>1,000	>500	>5%	11-20%	>10
Low	>1,000	>100	>100	>2%	5-10%	>1
Negligible	-	-	-	-	-	-
Reduced risk	>1,000	>100	>100	>2%	5-10%	>1

Confidence level	
••••	Very high
•••	High
••	Medium
•	Low
Conflicting results	
No data available	

Evidence level	
R	Robust
M	Medium
L	Limited
-	N/A

African Regions	
N	Northern
C	Central
E	Eastern
W	Western
S	Southern

Figure 9.32: Observed climate impacts and projected climate change risks across African regions for eight key health outcomes. Increased global warming levels are shown relative to pre-industrial 1850–1900. This list of health impacts and risks is not intended to be exhaustive, but instead focusses on well-documented conditions. This assessment is a synthesis across 58 studies on observed impacts and 29 studies on projected risks for health (see Supplementary Material Table SM 9.7). The category of air pollution-related health outcomes includes health impacts from changing particulate matter concentrations due to climate change.

9.10.2.1 Vector-Borne Diseases

9.10.2.1.1 Malaria

Observed impacts

Higher temperatures and shifting patterns of rainfall influence the distribution and incidence of malaria in sub-Saharan Africa (*high confidence*) (Agusto et al., 2015; Beck-Johnson et al., 2017). Up to 10.9 million km^2 of sub-Saharan Africa is optimally suitable for year-round malaria transmission (Mordecai et al., 2013; Ryan et al., 2015). Current climate suitability for endemic malaria transmission is concentrated in the central African region, some areas along the Southern coast of West Africa and the East African coast (Ryan et al., 2020).

In East Africa, there has been an expansion of the *Anopheles* vector into higher altitudes (Gone et al., 2014; Carlson et al., 2019) and increasing incidence of infection with *P. falciparum* with higher temperatures (*high confidence*) (Alemu et al., 2014; Lyon et al., 2017). Over Southern Africa, changes in temperature and rainfall are increasing malaria transmission (Abiodun et al., 2018). In West Africa, studies show both positive (Adu-Prah and Kofi Tetteh, 2015; Darkoh et al., 2017) and negative (M'Bra et al., 2018) correlations of malaria incidence with increases in mean monthly temperatures, and an abundance of *Anopheles gambiae s.s.* associated with mean diurnal temperature (Akpan et al., 2018).

Malaria incidence and outbreaks in East Africa were linked with both moderate monthly rainfall and extreme flooding (Boyce et al., 2016; Amadi et al., 2018; Simple et al., 2018), and increase one to two months after periods of rainfall in Southern and West Africa (Diouf et al., 2017; Ferrão et al., 2017; Adeola et al., 2019). The years following La Niña events (Southern Africa) (Adeola et al., 2017)) and high relative humidity (West Africa) (Adu-Prah and Kofi Tetteh, 2015; Darkoh et al., 2017) have been positively linked with malaria incidence.

Projected risks

Since AR5, significant progress has been made in understanding how changes in climate influence the seasonal and geographical range of malaria vectors, transmission intensity and burden of disease of malaria across Africa. Yet projecting changes remains challenging given the range of factors that influence transmission and disease patterns, and model outputs contain high degrees of uncertainty (Zermoglio et al., 2019; Giesen et al., 2020). Models have limited ability to account for population changes and development trends (Kibret et al., 2015; Kibret et al., 2017), investments in health sectors and interventions (McCord, 2016; Colborn et al., 2018; Caminade et al., 2019), and confounders such as age, socioeconomic status, employment and labour migration and climate variability (Bennett et al., 2016; Karuri and Snow, 2016; Byass et al., 2017; Chuang et al., 2017; Colborn et al., 2018). Nevertheless, available models do allow for projections of malaria transmission under different climate change scenarios to be made with high levels of certainty.

In East and southern Africa and the Sahel, malaria vector hotspots and prevalence are projected to increase under RCP4.5 and RCP8.5 by 2030 (1.5°C–1.7°C global warming) (*high confidence*) (Leedale et al., 2016; Semakula et al., 2017b; Zermoglio et al., 2019), becoming more pronounced later in the century (2.4°C–3.9°C global warming) (Ryan et al., 2020). Under RCP4.5, 50.6–62.1 million people in East and Southern Africa will be at risk of malaria by the 2030s (1.5°C global warming), and 196–198 million by the 2080s (2.4°C global warming) (Ryan et al., 2020). Northern Angola, Southern DRC, western Tanzania and central Uganda are predicted to be worst impacted in 2030, extending to western Angola, upper Zambezi River Basin, northeastern Zambia and the East African highlands by 2080 (Ryan et al., 2020). Under rising temperatures, by the 2050s, the greatest shifts in suitability for malaria transmission will be seen in East, Southern and Central Africa (2°C global warming) (Tonnang et al., 2014; Zermoglio et al., 2019; Ryan et al., 2020).

Conversely, in some regions, changing climatic conditions are projected to reduce malaria hotspots and prevalence. With continued greenhouse gas emissions, these include: West Africa by 2030 (1.7°C global warming) (*high confidence*) (Yamana et al., 2016; Semakula et al., 2017b; Ryan et al., 2020), parts of Southern Central Africa and dryland regions in East Africa by 2050 (2.5°C global warming) (*high confidence*) (Semakula et al., 2017b; Ryan et al., 2020), and large areas of southern Central Africa and the western Sahel by 2100 (>4°C global warming) (Yu et al., 2015; Tourre et al., 2019). These reductions in transmission correspond with decreasing environmental suitability for the malaria vector and parasite in these regions (Ryan et al., 2015; Mordecai et al., 2020). Most areas in Burkina Faso, Cameroon, Ivory Coast, Ghana, Sierra Leone, Niger, Nigeria, Zambia and Zimbabwe will have almost zero malaria transmission under RCP8.5 (Semakula et al., 2017b; Tourre et al., 2019).

The El Niño-Southern Oscillation (ENSO) cycle currently contributes to seasonal epidemic malaria in epidemic-prone areas (*high confidence*), and is projected to shift the malaria epidemic fringe southward and into higher altitudes by mid- to end-century (*high confidence*) (Bouma et al., 2016; Semakula et al., 2017b; Caminade et al., 2019). More evidence is needed, however, of climate variability impacts through ENSO cycles in future risk projections, as well as a deeper understanding of how climate change will impact the length of transmission season for mosquitoes, particularly in areas where increases in spring and autumn temperatures may increase suitability for the reproduction of malaria vectors (Ryan et al., 2020). Other gaps in knowledge include a better understanding of mosquito thermal biology and thermal limits for a variety of species, potential adaptations to extreme temperatures and how landscape changes contribute to malaria transmission (Tompkins and Caporaso, 2016).

9.10.2.1.2 Mosquito-borne viruses

Observed impacts

Climate variability has driven a global intensification of mosquito-borne viruses (e.g., dengue, Zika and Rift Valley Fever), including expansion into areas with higher altitudes (Leedale et al., 2016; Mweya et al., 2016; Messina et al., 2019). Concerns centre on diseases vectored by the yellow fever mosquito (*Aedes aegypti*), common throughout most of sub-Saharan Africa, and the tiger mosquito (*Aedes albopictus*), currently largely confined to western Central Africa (Kraemer et al., 2019; Mordecai et al., 2020).

Although warming temperatures are largely responsible for increasing environmental suitability for mosquito vectors (Mordecai et al., 2019), droughts can augment transmission when open water storage provides breeding sites near human settlements, and when flooding enables mosquitoes to proliferate and spread viruses further (Mweya et al., 2017; Bashir and Hassan, 2019). Within Africa's rapidly growing cities, diseases vectored by urban-adapted *Aedes* mosquitoes pose a major threat, especially in West Africa (Zahouli et al., 2017; Weetman et al., 2018; Messina et al., 2019). Dengue virus expansion may cause explosive outbreaks but the burden of dengue haemorrhagic fever and associated mortality is higher in areas where transmission is already endemic (Murray et al., 2013).

Projected risks

Populations of *Aedes aegypti* and *Aedes albopictus* mosquitoes and epidemics of dengue and yellow fever and other *Aedes*-borne viruses are expected to increase, including at high altitudes (Weetman et al., 2018; Messina et al., 2019; Ryan et al., 2019; Gaythorpe et al., 2020; Mordecai et al., 2020). *Aedes albopictus* may expand beyond western Central Africa into Chad, Mali and Burkina Faso by mid-century at >2°C global warming (Kraemer et al., 2019). Shifts projected in *Aedes* range due to changing environmental suitability, combined with rapid urbanisation and population growth, suggest that by 2050 populations exposed to these vectors in Africa may double, and by 2080 nearly triple at >2°C global warming (Kraemer et al., 2019). Southern limits of dengue transmission in Namibia and Botswana, and the western Sahel, may show the greatest expansions in environmental suitability under 1.8°C–2.6°C global warming (Messina et al., 2019). In the warmest scenarios (RCP8.5), however, some parts of Central Africa may become too hot for mosquitoes to transmit dengue, and thus at-risk populations may peak at intermediate warming levels (Ryan et al., 2019). Climatic conditions favourable for mosquitoes, combined with the increase of animal trade, may result in the expansion of the geographic range of zoonotic diseases like Rift Valley fever (Martin et al., 2008), a threat for human and animal health with strong socioeconomic impacts (Peyre, 2015).

9.10.2.2 Diarrhoeal Diseases, HIV and Other Infectious Diseases

9.10.2.2.1 Diarrhoeal diseases

Observed impacts

Africa has the highest rates of death due to diarrhoeal diseases in the world (Havelaar et al., 2015; Troeger et al., 2018) and many children have repeated diarrhoeal episodes with impaired growth, stunting, immune dysfunction and reduced cognitive performance (Squire and Ryan, 2017). High land and sea temperatures (Paz, 2009; Musengimana et al., 2016) and precipitation extremes increase transmission of bacterial and protozoal diarrhoeal disease agents (Boeckmann et al., 2019) through contamination of drinking water and food preparation and preservation practices (Figure 9.33) (Levy et al., 2016; Soneja et al., 2016; Walker, 2018).

Cholera incidence has been shown to increase with temperature (Trærup et al., 2011). Outbreaks, however, are most frequent in East and Southern Africa following tropical cyclones (Moore et al., 2017b; Troeger et al., 2018; Ajayi and Smith, 2019; Cambaza et al., 2019).

Africa's rapidly urbanising population increases the demand for freshwater and is occurring in places that already have stretched water and sanitation infrastructure (Howard et al., 2016). These conditions, especially during periods of water scarcity, can reduce the frequency and adequacy of hand washing and thereby increase disease transmission.

Projected risks

Disruptions in water availability, such as during droughts or infrastructure breakdown, will jeopardise access to safe water and adequate sanitation, undermine hygiene practices and increase environmental contamination with toxins (Howard et al., 2016; WWF-SA, 2016; Miller and Hutchins, 2017).

Climate change is projected to cause 20,000–30,000 additional diarrhoeal deaths in children (<15 years old) by mid-century under 1.5°C–2.1°C global warming (WHO, 2014), with West Africa most affected, followed by East, Central and southern Africa. Cholera outbreaks are anticipated to impact East Africa most severely during and particularly after ENSO events (Moore et al., 2017b).

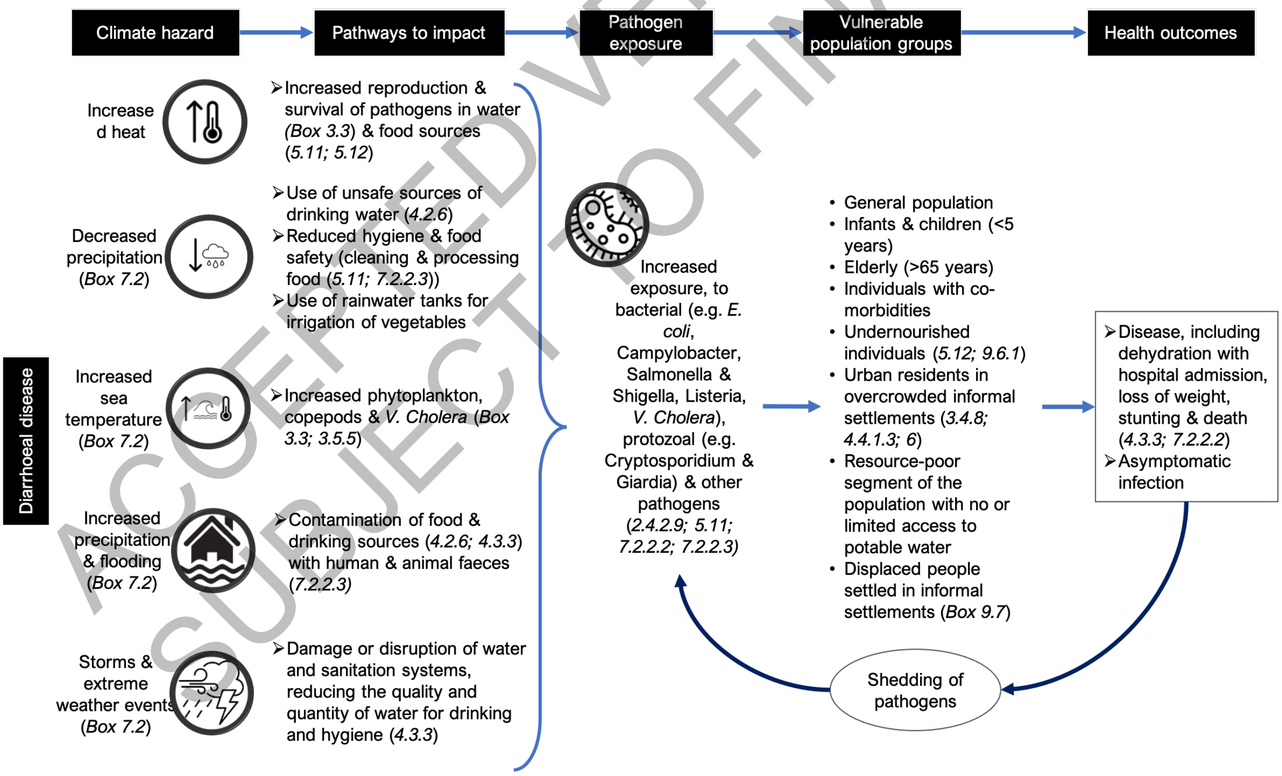


Figure 9.33: Pathways to impact: diarrhoeal disease. Schematic showing the pathways of impact diarrhoeal disease in Africa as a result of exposure to climate hazards.

[START BOX 9.6 HERE]

Box 9.6: Pandemic Risk in Africa: COVID-19 and Future Threats

Rapid advances in vaccination and other control measures in high-income countries means that the burden of COVID-19 is increasingly concentrated in low- and middle-income countries, including those in Africa. The extent to which the COVID-19 pandemic is influenced by weather or by future changes in climate remains contested (WMO, 2021). In time, COVID-19 may develop seasonal dynamics (Baker et al., 2020; Kissler et al., 2020) similar to other respiratory infections (Carlson et al., 2020b).

Early work interpreted low-reported cases of COVID-19 in Africa as suggesting evidence of a protective climatic effect, but increasing evidence indicates the role of climate is secondary to the timing of disease introduction, the pace of implementation of non-pharmaceutical interventions, and surveillance gaps (Evans et al., 2020; WMO, 2021). Going forward, testing coverage, reporting, governance, non-pharmaceutical interventions and vaccine distribution and uptake are *likely* to be far more significant for Africa's COVID-19 trajectory than climate change. Compounding risks, where climate hazards and natural disasters impair outbreak responses, may disrupt interventions or cause additional deaths (Phillips et al., 2020; Salas et al., 2020).

Emerging and future pandemic threats

Future influenza pandemics are highly *likely*, as are regional epidemics and pandemics of novel zoonotic viruses (including coronaviruses and flaviviruses) (*high confidence*). In the next decades, climate change will reshape the risk landscape for emerging zoonotic threats as wildlife-livestock-human interfaces shift, facilitating the emergence of novel zoonotic threats and spillover of known zoonoses into novel geographies (Carlson et al., 2020a; Mordecai et al., 2020). Characteristics of urban development and level of service provision, for example, crowded living spaces and transport facilities, and access to water and sanitation will influence the transmission of COVID-19 and future disease outbreaks (Wilkinson, 2020). Historically, West and Central Africa were considered especially at risk of outbreaks given their high biodiversity, high intensity of human-wildlife contact including wild meat trade, vulnerable health systems and history of Ebola virus disease outbreaks (Paige et al., 2014; Allen et al., 2017; Pigott et al., 2017). However, as the Middle East respiratory syndrome coronavirus (MERS-CoV) and COVID-19 pandemics have shown, there are multiple hotspots of viruses with pandemic potential globally, many of which are not in Africa. Thus, labelling African rainforests as unique 'hotspots' undermines global health work and pandemic preparedness.

[END BOX 9.6 HERE]

9.10.2.2.2 HIV

Observed impacts

Although levels of new HIV infections declined sharply during the last decade, still more than a million adults and children become infected each year (UNAIDS, 2020). Climate influences on HIV are predominately indirect such as through heightened migration due to climate variability, or extreme weather events leading to increased transactional sex to replace lost sources of income. Changes in climate affect each of the main drivers of HIV transmission in women, including poverty, inequity and gender-based violence (Burke et al., 2015a; Loevinsohn, 2015; Fiorella et al., 2019).

Projected risks

'Oscillating' or 'circular' migration for migrant workers in urban and mining centres drove HIV transmission in the 1990s and 2000s (Lurie, 2006), and climate-related displacement may have similar effects (see Box 9.7) (Gray and Mueller, 2012; Loevinsohn, 2015; Low et al., 2019). Food insecurity and nutritional deficiencies, projected to increase with increasingly variable climates, has been shown to increase sexual risk-taking and migration, as well as increase susceptibility to other infections (Lieber et al., 2021). Projected increases in exposure to infectious diseases pose considerable threats to HIV-infected people who may already have compromised immune function. Additionally, reduced lung function in people with HIV from previous tuberculosis infection may put them at high risk for morbidity and death during extreme heat (Abayomi and Cowan, 2014). Moreover, extreme weather events accompanied by damage to health system infrastructure could compromise the continuity of antiretroviral treatment (Weiser et al., 2010; Pozniak et al., 2020).

9.10.2.2.3 Other infectious diseases

Poor populations in the western Sahel have the highest burden of bacterial meningitis worldwide, with seasonal dynamics driven by the dry Harmattan winds that transport dust long distances across the continent (Agier et al., 2013; García-Pando et al., 2014). In Nigeria, rising temperatures are projected to increase meningitis cases by about 50% for 1.8°C global warming (RCP2.6 in 2060–2075), and by almost double for 3.4°C global warming (RCP8.5 in 2060-2075) (Abdussalam et al., 2014). Bilharzia is also highly climate-sensitive, with its distribution influenced by changes in temperature and precipitation, as well as development, such as the introduction of freshwater projects (e.g., canals, hydroelectric dams and irrigation schemes) (Adekiya et al., 2019).

9.10.2.3 Temperature-Related Impacts

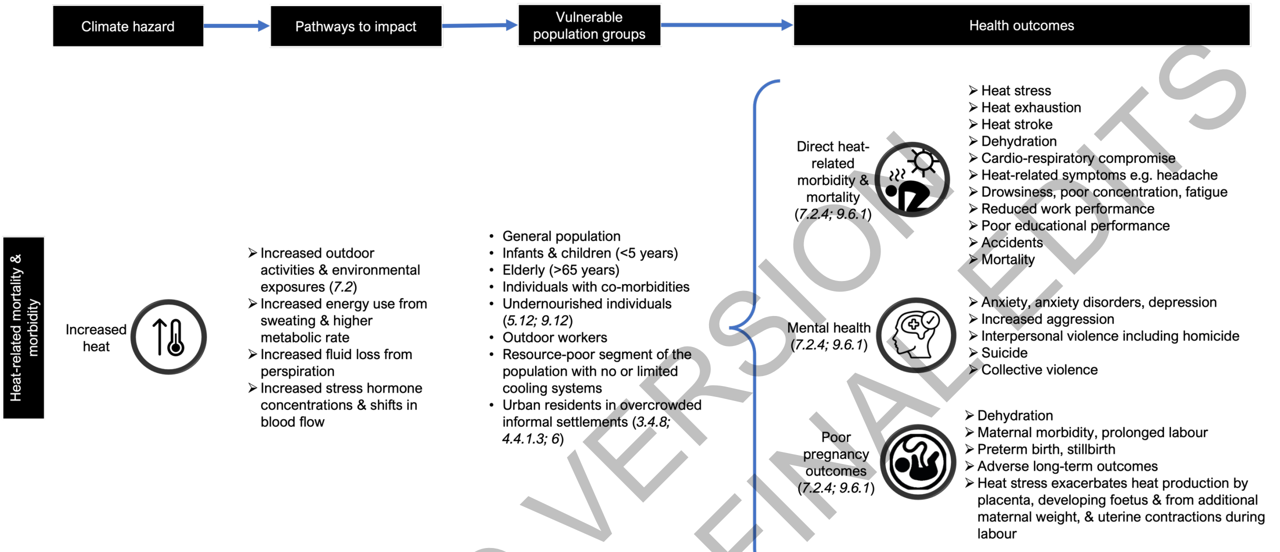


Figure 9.34: Pathways to impact: heat-related morbidities. Schematic showing the pathways of impact for heat-related morbidities in Africa as a result of exposure to climate hazards. Numbers in the figure refer to chapter sections of this report. Indirect health impacts of heat are not shown. For example, risk of malnutrition from reduced crop yields or reduced fisheries catches (see Section 9.8.5).

9.10.2.3.1 Mortality and morbidity

Observed impacts

Emergency department visits and hospital admissions have been shown to increase at moderate to high temperatures (Bishop-Williams et al., 2018; van der Linden et al., 2019), with increased levels of mortality recorded on days with raised temperatures in Burkina Faso (Kynast-Wolf et al., 2010; Diboulo et al., 2012; Bunker et al., 2017), Ghana (Azongo et al., 2012), Kenya (Egondi et al., 2012; Egondi et al., 2015), South Africa (Wichmann, 2017; Scovronick et al., 2018), Tanzania (Mrema et al., 2012) and Tunisia (Bettaieb et al., 2010; Leone et al., 2013). Cause of death most commonly involves cardiovascular diseases (Kynast-Wolf et al., 2010; Scovronick et al., 2018), but increased incidences of respiratory (Scovronick et al., 2018), stroke (Longo-Mbenza et al., 1999) and non-communicable diseases (Bunker et al., 2017) have also been linked with heat.

Excess death rates from non-optimal temperature in sub-Saharan Africa are estimated to be nearly double the global average, with 24% of the more than 5 million annual deaths associated with non-optimal temperature occurring in Africa (Zhao et al., 2021). The region had the world's highest cold-related excess death ratio and lowest heat-related excess death ratio over the period 2000–2019. However, during this time, cold-related excess deaths declined more rapidly than the increase in heat-related excess deaths, resulting in a net decrease in the excess death ratio from temperature.

Recent estimates of the burden of mortality associated with the additional heat exposure from recent human-induced warming suggest approximately 43.8% of heat-related mortality in South Africa was attributable to anthropogenic climate change from 1991–2018 (Vicedo-Cabrera et al., 2021). In many of South Africa's 52 districts, this equates to dozens of deaths per year. The elderly and children under five years are most vulnerable to heat exposure (Sewe et al., 2015; Scovronick et al., 2018).

Projected risks

Globally, Africa is predicted to suffer disproportionately higher all-cause mortality risk from higher temperature-related all-cause mortality from global warming, compared to temperate, Northern Hemisphere countries (Carleton et al., 2018). The number of days projected to exceed potentially lethal heat thresholds per year reaches 50–150 days in West Africa at 1.6°C global warming, up to 200 days in West Africa and 100–150 days in Central Africa and parts of coastal East Africa at 2.5°C, and over 200 days for parts of West, Central and East Africa for >4°C global warming (Mora et al., 2017) (see Sections 9.5.3–7; Figure 9.15). Projected rates of heat-related mortality among people in the Middle East and North Africa who are older than 65 years increase by 8–20 fold in 2070–2099, compared with 1951–2005, based on RCP4.5 and RCP8.5 (both at >2°C global warming) (Ahmadalipour and Moradkhani, 2018).

Temperature-related mortality across Africa is projected to escalate with global warming, reaching 50–180 additional deaths per 100,000 people annually in regions of North, West, and East Africa for 2.5°C global warming, and increasing to 200-600 per 100,000 people annually for 4.4°C global warming (Carleton et al., 2018) (Figure 9.35). However, some regions that currently experience cold-related mortality (e.g., Lesotho and Ethiopian highlands) are projected to have reduced temperature-related mortality risk from warming. Greenhouse gas mitigation is projected to save tens of thousands of lives: limiting warming to RCP4.5 (2.5°C) rather than RCP8.5 (4.4°C) at the end of the century is projected to avoid on average 71 deaths per 100,000 people annually across Africa with larger reductions in risk in North, West, Central and parts of East Africa (Figure 9.35). The cost of mitigating heat stress using energy-intensive cooling methods is expected to be to be unachievable for many African countries (Parkes et al., 2019) (see Section 9.9.4).

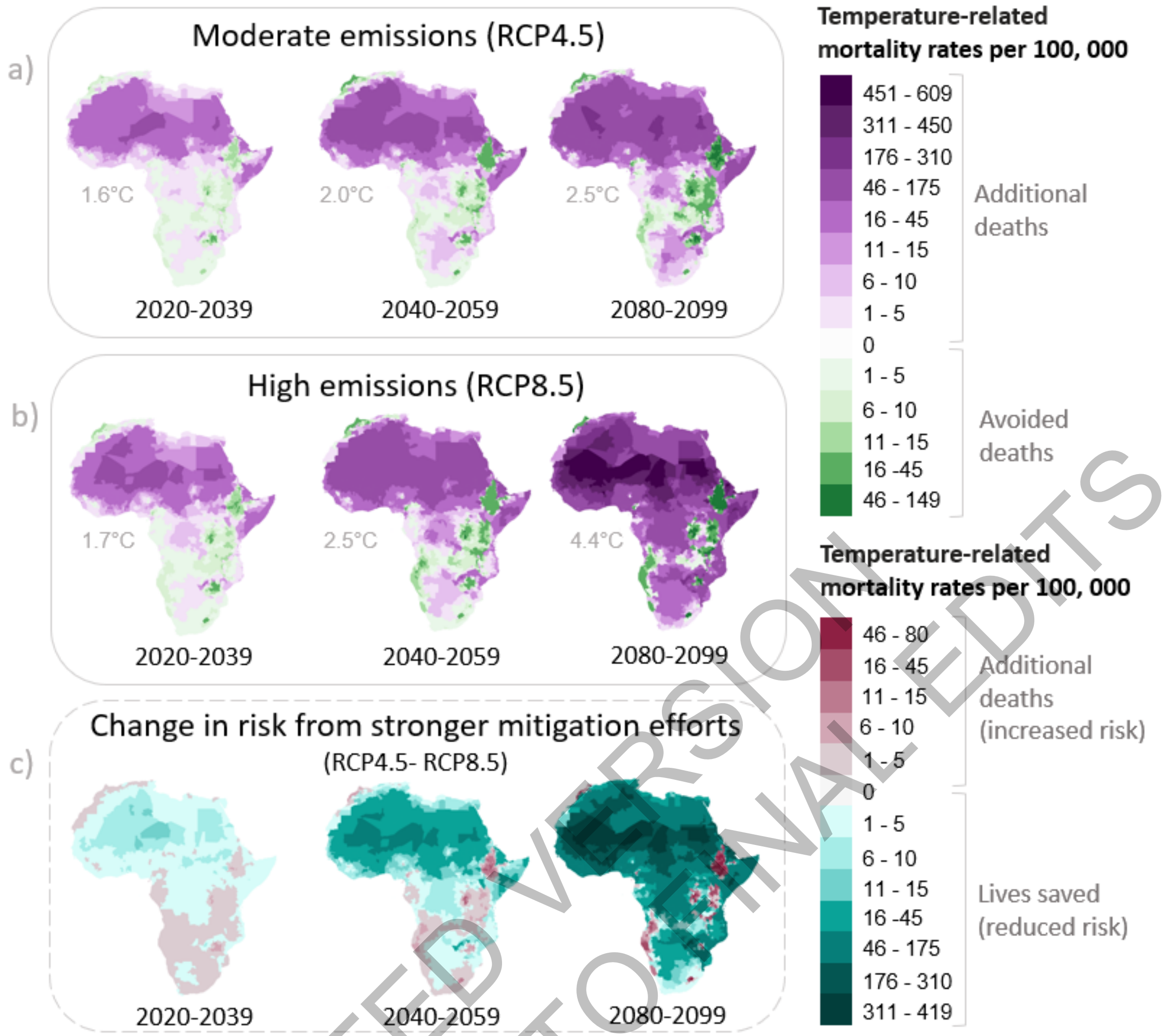


Figure 9.35: Temperature-related mortality risk in Africa with increased global warming. Maps showing changes in mortality rates in deaths per 100 000 for global warming in the years 2020–2039, 2040–2059, and 2080–2099 for (a) medium emissions scenario (RCP 4.5); (b) a high emissions scenario (RCP 8.5); and (c) showing avoidable deaths due to increased emissions mitigation to achieve reduced global warming (RCP4.5–RCP8.5). These estimates of climate change impacts on mortality rates include temperature-related impacts only. They account for the benefits of income growth and incremental adaptation to climate change, both of which reduce mortality sensitivity to extreme temperatures. Projections were based on income and demographics from Shared Socioeconomic Pathway 3 (SSP3), with future adaptation based on adaptation actions observed in the global historical record. The estimates do not include the costs of the behaviours and investments required to achieve such adaptation (Carleton et al., 2018). Areas shown in green in c) have fewer deaths due to temperature under RCP8.5 than RCP4.5. This is because cold is currently the greatest driver of temperature-related deaths in these countries, which will be alleviated with increasing levels of global warming (Zhao et al., 2021).

9.10.2.3.2 Heat stress in specific settings

Heat stress symptoms are prevalent among people in buildings that are poorly ventilated or insulated, or constructed with unsuitable materials (e.g., corrugated metal sheeting). These features are common to many structures in Africa, including in slums, informal and low-income settlements, as well as schools and healthcare facilities (Bidassey-Manilal et al., 2016; Naicker et al., 2017; Wright et al., 2019). Temperatures inside these structures can exceed outdoor temperatures by 4°C or more and have large diurnal fluctuations (Mabuya and Scholes, 2020). Daily wage labourers and residents of urban informal settlements are among the most vulnerable to heat stress because of the urban heat island effect, with congestion, little ventilation, shade, open space and vegetation (Bartlett, 2008) being associated with impacts of both hot and cold conditions on public health (Ramin, 2009), and the number of years lived depending on age, sex and comorbidities (Egondi et al., 2015). Temperature extremes are *likely* to result in relatively more deaths in informal settlements than in other settlement types (Scovronick and Armstrong, 2012).

The urban heat island effect exacerbates current and projected heat stress in Africa's rapidly growing cities (Mitchell, 2016) and is discussed in more detail in Section 9.9.3.

Escalating temperatures and longer-duration heatwaves are *likely* to heavily affect workers already exposed to extreme temperatures, e.g., outdoor workers (Kjellstrom et al., 2018) and miners (El-Shafei et al., 2018; Nunfam et al., 2019a; Nunfam et al., 2019b). Vulnerability may also be high for women who cook food for a living, and children who accompany them, due to prolonged exposure to high temperatures (Parmar et al., 2019). Prisons, commonly poorly ventilated and overcrowded, are also high-risk settings (Van Hout and Mhlanga-Gunda, 2019).

9.10.2.3.3 Maternal and child health

Exposure to high temperatures during pregnancy has been linked with adverse birth outcomes, including stillbirths or miscarriages (Asamoah et al., 2018) and long-term behavioural and developmental deficiencies (Duchoslav, 2017; MacVicar et al., 2017).

9.10.2.4 Impacts of Extreme Weather

During extreme conditions, for example, Cyclone Kenneth (Codjoe et al., 2020) and El Niño 2015-2016 (WHO, 2016; Pozniak et al., 2020), direct physical injury, loss of life, destruction of property and population displacement can occur. Flooding and landslides are common after extreme rainfall and are the most frequently described impact of climate variability in Africa's cities currently, with residents of poorly serviced or informal settlements most vulnerable (Hunter et al., 2020). Post-traumatic stress disorders in affected individuals are common, including in children (Rother, 2020). In rural areas, the resulting damage to health facilities, access routes and transport services can severely compromise health service delivery (WHO, 2016). The effects of extreme weather on urban health infrastructure depends on the characteristics, location and adaptive capacity of cities (see Section 9.9.4).

9.10.2.5 Malnutrition

Observed impacts

Africa has experienced the greatest impacts of climate change on acute food insecurity and malnutrition (FAO and ECA, 2018). Adverse climatic conditions exacerbate the impacts of an unstable global economy, conflict and pandemics on food insecurity (AfDB, 2018b; Food Security Information Network (FSIN), 2019; Fore et al., 2020) (see Chapter 5, Section 5.12.4).

More than 250 million Africans are undernourished, mostly in Central and East Africa (FAO et al., 2020), which increases childhood stunting, affects cognition and has trans-generational sequelae (IFPRI, 2016; UNICEF et al., 2019). Undernutrition is strongly linked with hot climates (Hagos et al., 2014; Tusting et al., 2020). In Burkina Faso, low crop yields resulted in around 110 deaths per 10,000 children under five, with 72% of this impact attributable to adverse climate conditions in the growing season (Belesova et al., 2019).

Increasing incidence and expanded distributions of vector-borne livestock diseases (e.g., bluetongue, trypanosomiasis and Rift Valley Fever) in response to changes in rainfall and increasing temperatures, undermine food security, especially among subsistence farmers (Samy and Peterson, 2016; Caminade et al., 2019). Locust infestations linked with changes in climate (Salih et al., 2020) are a major risk for food security in Africa.

Projected risks

Projected risks for malnutrition in Africa are high (FAO, 2016) (see Section 9.8.1): 433 million people in Africa are anticipated to be undernourished by 2030 (FAO et al., 2020) and, compared to 1961–1990, 1.4 million additional African children will suffer from severe stunting by 2050 under 2.1°C global warming (WHO, 2014). In Burkina Faso, the mortality burden due to low crop yields could double by 2100 with 1.5°C of global warming (Belesova et al., 2019). Drought risks will include crop and livestock failures

(Ahmadalipour et al., 2019). Additionally, increasing concentrations of atmospheric CO_2 will affect the nutritional quality of C_3 plant staples, lowering levels of protein and minerals like zinc and iron (Myers et al., 2014; Weyant et al., 2018). Declining fish catches due to ocean warming, illegal fishing and poor stock management are projected to increase deficiencies of zinc, iron and vitamin A for millions of people across Mozambique, Angola and multiple West African countries (Golden et al., 2016) (see Section 9.8.5).

9.10.2.6 Non-Communicable Diseases and Mental Health

Links between climate change and the environmental risk factors for non-communicable diseases (NCDs) may be direct (e.g., extreme heat exposure in people with cardiovascular disease) or indirect, such as via the global agriculture and food industry (Landrigan et al., 2018). These effects are largely unreported for Africa (Amegah et al., 2016), where the burden of many NCDs is growing rapidly with increasing urbanisation and pollution (Rother, 2020).

Many urban poor populations have unhealthy dietary practices, which present major risks for obesity, type II diabetes and hypertension. Paradoxically, despite growing levels of undernutrition, the incidence of overweight and obesity continues to rise in Africa, particularly in children under five from the northern and southern parts of the continent (FAO and ECA, 2018). Diabetes is increasingly prevalent and outcomes may worsen if climate change undermines health infrastructure and the range of available foods (Keeling et al., 2012; Kula et al., 2013; Chersich and Wright, 2019).

The relationship between cancer and climate change is complex and indirect. Changing temperature and humidity may alter the distribution of Aflatoxin-producing fungi, contaminating food (grains, maize) and causing cancer (see Box 5.9 in Chapter 5) (Sserumaga et al., 2020; Valencia-Quintana et al., 2020). Severe storms and flooding may disrupt wastewater treatment or disposal, potentially contaminating drinking water with carcinogenic substances.

Areas with low service provision (e.g., informal settlements in Africa) suffer from increased infestations of pests such as flies, cockroaches, rats, bedbugs and lice, which may be controlled by chemical pesticides (Rother et al., 2020) and may become more prevalent with a changing climate (Mafongoya et al., 2019). Inappropriate pesticide use and disposal cause endocrine disruption and increased incidences of some cancers (Rother et al., 2020).

9.10.2.6.1 Mental health and well-being

Mental health and well-being are affected by local climate conditions and are therefore sensitive to climate change (Burke et al., 2018b; Obradovich et al., 2018). High temperatures are strongly associated with poor mental health and suicide in South Africa (Kim et al., 2019). Exposure to extreme heat directly influences emotional control, aggression and violent behaviour, escalating rates of interpersonal violence, with homicides rising by as much as 18% in South Africa when temperatures are above 30°C compared with temperatures below 20°C (Burke et al., 2015a; Chersich et al., 2019b; Gates et al., 2019).

Extreme weather events are often severely detrimental to mental health (Scheerens et al., 2020), with elevated rates of anxiety, post-traumatic stress disorder and depression in impacted individuals (Schlenker and Lobell, 2010; Nuvey et al., 2020). Youth may be at especially high risk (Barkin et al., 2021).

Loss of livestock from disease or lack of pastures is strongly linked with poor mental health among farmers (Nuvey et al., 2020). Climate change impacts on mental health among refugees is concerning but remains under-researched (Matlin et al., 2018).

9.10.2.7 Air Quality-Related Health Impacts

Links between air quality and climate change are complex (Smith et al., 2014; Szopa et al., 2021). Increases in particulate matter concentrations are driven more by vehicle emissions, solid waste, biomass burning and development (Abera et al., 2021) than by climate change, and these factors vary widely across regions of the continent (West et al., 2013). Women and children who are exposed to high particulate matter concentrations when cooking indoors and HIV-infected people are more vulnerable to the health impacts of air pollution (Abera et al., 2021). Information on the direction of change of air quality in different African regions attributable to climate change are contradictory (Westervelt et al., 2016; Silva et al., 2017). Additionally, much uncertainty remains about interactions between air quality and climate change and relative impacts of different modes of development and climate change on pollutants. However, increasing temperatures combined with a reduction in rainfall are *likely* to increase particulate matter concentrations (Abera et al., 2021), particularly in North Africa (Westervelt et al., 2016; Silva et al., 2017).

Nevertheless, continued dependence on fossil-fuelled power plants will result in tens of thousands of avoidable deaths due to air pollution by 2030 (Marais and Wiedinmyer, 2016), and accelerate climate change. Actions to reduce air pollution can both mitigate climate change and have major co-benefits for health (West et al., 2013; Rao et al., 2016; Markandya et al., 2018; Rauner et al., 2020a; Rauner et al., 2020b) (see also AR6 WGIII, Chapters 3, 4, 8 and 10). Investing in renewable energy resources rather than reliance on the combustion of fossil fuels would mark an important step forward for African population health (Marais et al., 2019). This is especially important in South Africa which emits approximately half the total carbon emissions for Africa, ranking 12th in the world for carbon emissions (Mohsin et al., 2019).

Dust events in West Africa have severe health impacts (cardiorespiratory and infectious diseases, including meningitis) (Ayanlade et al., 2020) given the proximity of the Sahara, which produces about half of the yearly global mineral dust (de Longueville et al., 2013). Wildfires are projected to become the main source of particulate matter in West, Central and southern Africa under both the lowest and highest future emissions scenarios, whereas, under intermediate scenarios (i.e., SSP3/RCP4.5), anthropogenic sources of particulate matter are projected to exceed that produced by wildfires (Knorr et al., 2017).

[START BOX 9.7 HERE]

Box 9.7: The Health-Climate Change Nexus in Africa

The intersections between climate change and human health are involve interactions of numerous systems and sectors (Lindley et al., 2019; Yokohata et al., 2019). This complexity means that holistic, transdisciplinary and cross-sectoral (systems) approaches like One Health, EcoHealth and Planetary Health can improve the long-term effectiveness of responses to health risks (Zinsstag, 2012; Whitmee et al., 2015; Nantima et al., 2019). More research is needed to identify sustainable solutions (Rother et al., 2020), as recently re-emphasised by the Intergovernmental Panel on Biodiversity in its report on the COVID-19 pandemic (IPBES, 2020). The close dependency of many Africans on their livestock and surrounding ecosystems forms a context where integrated health approaches are especially critical for addressing climate change risks to health (Figure Box 9.7.1) (Watts et al., 2015; Cissé, 2019).

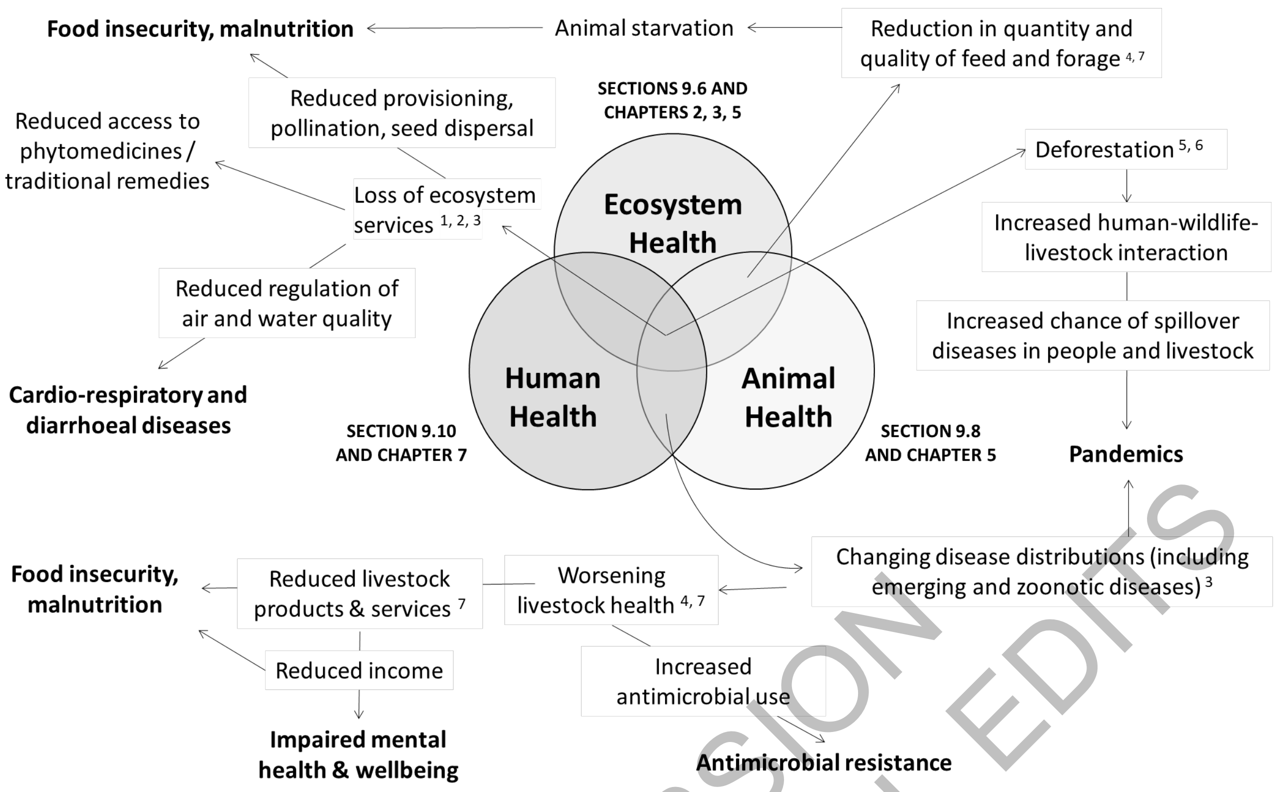


Figure Box 9.7.1: Human, ecosystem and animal health are intimately interlinked, and require transdisciplinary approaches such as One Health, EcoHealth and Planetary Health for effective, sustainable, long-term management. This schematic shows some examples of these interlinkages, and how they impact human health, highlighting the complex interactions and the importance of holistic, systems approaches to health interventions, including for climate change adaptation. Supporting literature: 1 (Egoh et al., 2012); 2 (Wangai et al., 2016); 3 (Failler et al., 2018); 4 (Ifejika Speranza, 2010); 5 (Brancalion et al., 2020); 6 (Bloomfield et al., 2020); 7 (Rojas-Downing et al., 2017).

Integrated approaches to health in Africa can deliver multiple benefits for humans and ecosystems For example, rather than addressing micronutrient deficiencies with supplements, which may not be accepted culturally and can be disrupted by stockouts or similar, addressing nutrient deficiencies in staple crops by selecting or breeding more nutritious varieties (e.g., orange-fleshed sweet potatoes or 'golden rice' for vitamin A deficiency) may prove to be more sustainable options (Datta et al., 2003; Nair et al., 2016; Laurie et al., 2018; Oduor et al., 2019; Stokstad, 2019). Additionally, some micro- or macronutrient deficiencies and food insecurities may be improved by addressing the depletion of soils through better management, including the incorporation of holistic, sustainable principles, such as those promoted by agroforestry or regenerative agriculture (Rhodes, 2017; Elevitch et al., 2018; LaCanne and Lundgren, 2018) (5.12.4).

[END BOX 9.7 HERE]

9.10.3 Adaptation for Health and Well-Being in Africa

In this section, we focus on adaptation actions that are well-documented or shown to have the potential for substantially improving health or well-being. These adaptation options are assessed in Figure 9.36 and Table 9.11.

In Africa, adaptive responses have begun to be implemented by local, national and international entities (Ebi and Otmani Del Barrio, 2017). With strong leadership, these initiatives can be used as an opportunity for comprehensive, transformative change rather than incremental improvements to existing systems. Adaptation responses are necessarily context-specific and can focus on providing services for vulnerable and high-risk populations (Dumenu and Obeng, 2016; Herslund et al., 2016).

Adaptation actions in the health sector range from building resilient health systems to preparing responses to health impacts of extreme weather events to reducing effects of increasing temperatures in residential and occupational settings (Kjellstrom et al., 2016; Chersich and Wright, 2019). A climate-resilient health system involves functional and effective health systems (WHO, 2015), national and local policy plans with resources for implementation, and long- and short-term communication strategies to raise awareness around climate change (Nhamo and Muchuru, 2019).

Many health conditions associated with climate change are not new, and existing evidence-based interventions can be modified to address shifting disease patterns (Ebi and Otmani Del Barrio, 2017). Adaptation options can build on a long tradition of community-based services in Africa (Ebi and Otmani Del Barrio, 2017). Indeed, strengthening many of the services already provided (e.g., childhood vaccinations and vector control) will help curtail emerging burdens of climate-sensitive conditions. However, a disproportionate focus on emerging zoonotic and vector-borne viruses could undermine climate change adaptation efforts in Africa if it shifts the focus away from health system strengthening and leaves few resources for addressing other health impacts of climate change.

Core components of an adaptation response include rapid impact packages (e.g., mass drug administration for schistosomiasis), education of women and direct poverty alleviation (Bailey et al., 2019). Where droughts are more frequent and rainfall patterns have shifted, adaptation support can be provided for strategies developed by communities, including the adaptation of livelihoods and diversification of crops and livestock (Mbereko et al., 2018; Bailey et al., 2019). Continued efforts through partnerships, blending adaptation and disaster risk reduction, and long-term international financing are needed to bridge humanitarian and sustainable development priorities (Lindley et al., 2019) (Cross-Chapter Box HEALTH in Chapter 7).

9.10.3.1 Risk Assessment and Warning Systems

Improved institutional capacity for risk monitoring and early warning systems is key to support emergency preparedness and responsiveness in Africa, as well as shock-responsive and long-term social protection (FAO and ECA, 2018). Climate risk assessments grounded in evidence and locally appropriate technologies are important for identifying priority actions, the scale of intervention needed and high-risk geographical areas and populations. Potential tools include those developed by WHO (Ceccato et al., 2018) and the Strategic Tool for Analysis of Risk (Ario et al., 2019).

Warning systems that predict seasonal to intra-seasonal climate risks could assist in improving response times to extreme weather events (such as droughts, flooding or heat waves) and shifts in infectious diseases. Weather and other types of forecasting provide an advanced warning – a central tenet of disaster risk reduction (Funk et al., 2017; Okpara et al., 2017a; Lumbroso, 2018). Models encompassing each component of the human-animal-environmental interface, including disease surveillance in humans and animals and remote sensing of vegetation indexes, water and soil can be used to project patterns of zoonose outbreaks (UNDP, 2016; Bashir and Hassan, 2019; Durand et al., 2019). Early warning systems may help better prepare for these and other forms of infectious disease outbreaks (Thomson et al., 2006) but adaptation is possible in the absence of statistical tools through vaccination and surveillance, for example.

Surveillance systems for diseases and vectors are well-established in many parts of Africa (Ogden, 2017). However, many data gaps remain, especially in monitoring climate-sensitive conditions such as diarrheal- and arbovirus-related diseases, and morbidity and mortality stemming from heat exposure (Ogden, 2017; Buchwald et al., 2020).

Climate and health adaptation indicators are required for Africa to strengthen institutional capacity for risk monitoring and early warning systems, emergency preparedness and response, vulnerability reduction measures, shock-responsive and long-term social protection and planning and implementing resilience building measures (FAO and ECA, 2018). National-level progress is assessed through the Lancet Countdown indicators (Watts et al., 2018), however, district- and local-level indicators are needed to measure levels of vulnerability and response effectiveness at a local level, and for informing planning local service delivery. Potential indicators include monitoring the number of excess health conditions during extreme heat events. Indoor temperature monitoring in sentinel houses and health facilities is a related indicator (Ebi and Otmani Del Barrio, 2017), linked with threshold temperature levels at which health impacts occur, and the ability of the built environment to protect against these impacts (e.g., for heatwaves).

Measuring climate-health linkages is challenging due to the considerable diversity of the exposures, impacts and outcomes, as well as constraints in key technical areas. Increasing our understanding of this diversity and how this is influenced by adaptative changes is a major knowledge gap. This could be facilitated through a pan-African database of climate and other environmental exposures, together with real-time statistical support for analyses of climate and health associations.

9.10.3.2 Community Engagement

Increased awareness can facilitate community engagement and action (see Section 9.4.3). In Ghana, for example, local communities understand the climate hazards that drive outbreaks of meningitis and adapt accordingly by improving housing to limit heat and exposure, changing funeral practices during outbreaks, increased vaccination uptake and afforestation (Codjoe and Nabie, 2014). Similarly, participation in community organisations improved child nutrition in vulnerable rural households in Eswatini (Anchang et al., 2019). Interventions specifically targeting women are beneficial for food security, although they may be undermined by harmful gender norms in communities that are patriarchal, led by chiefs or have high rates of gender-based violence (Jaka and Shava, 2018; Kita, 2019; Masson et al., 2019). The BRACED project in Burkina Faso and Ethiopia specifically adopted a gender-transformative approach as an integral part of resilience-building (McOmber et al., 2019). Improving 'climate literacy' could empower youth, women and men to be active citizens in promoting adherence of governments to international agreements in climate change (Mudombi et al., 2017; Chersich et al., 2019a).

9.10.3.3 9.10.3.1Health Financing

Poor and low-income households often are not able to afford high out-of-pocket costs for medical care, or it consumes a large portion of their income. As a result, without financial aid, peoples' health needs may not be met after a climate shock (Hallegatte and Rozenberg, 2017). Microfinance (the provision of small-scale financial products to low income and otherwise disadvantaged groups by financial institutions) and disaster contingency funds can serve to reduce health risks of climate change for low-income communities (Agrawala and Carraro, 2010; Ozaki, 2016), as can different forms of insurance and disaster relief (Fenton et al., 2015; Dowla, 2018). Unconditional cash transfers in Kenya, Uganda and Zambia assisted vulnerable groups to absorb the negative impacts of climate-related shocks or stress and to prepare for these (Lawlor et al., 2019; Ulrichs et al., 2019). Based on several case studies in Africa, the Food and Agriculture Organization recommends a 'Cash+' approach which combines cash transfers with productive assets, inputs or technical training to address the needs of vulnerable households in emergency situations, and enhance livelihoods potential, income generation and food security (FAO, 2017). New economic models have been implemented in North Africa, focused on poor households, youth and women that enable access to credit and support the implementation of policies that balance cash and food crops, social safety nets and social protection (Mumtaz and Whiteford, 2017; Narayanan and Gerber, 2017) (see also Sections 9.4, 9.8 and 9.11).

9.10.3.4 Disease-Specific Adaptations

Adaptation to prevent malaria

Increasing distribution and coverage of long-lasting insecticide-treated bed nets, improved diagnostic tests and increasing health service access could mitigate the impacts of climate change on malaria if aligned with the predicted or actual burden of malaria (*medium confidence*) (Kienberger and Hagenlocher, 2014; Thwing et al., 2017). Understanding seasonal shifts in malaria transmission suitability as a result of climate change can guide more targeted seasonal public health responses and better planning for different types of management and control interventions based on the impact. For example, an increase in the number of months where climate conditions are suitable for mosquito survival will require public health responses for an extended period of time (Ryan et al., 2020).

In malaria-endemic areas, repeated malaria infections can provide temporary immunity, which reduces new clinical cases (Laneri et al., 2015; Yamana et al., 2016). Conversely, where people have little or no immunity, exposure to malaria can lead to epidemics (Semakula et al., 2017a; Ryan et al., 2020). Pregnant women and infants remain at risk for severe malaria, regardless of immunity status. Vector control and case management capacity should be rapidly scaled up in newly affected areas where risks for epidemics are high and populations are especially vulnerable. Poverty-alleviation initiatives underpin malaria control as the malaria burden is strongly tied to socioeconomic status (Huldén et al., 2014; Degarege et al., 2019).

Contextualised risk studies on local drivers of transmission are still lacking and present a major gap in developing appropriate adaptation strategies (*high confidence*). Progress has been made identifying and ranking vulnerability and exposure indicators (Protopopoff et al., 2009; Onyango et al., 2016a), however, better linking of biophysical and socioeconomic determinants of risk in integrated assessment models are needed (Caminade et al., 2019; Zermoglio et al., 2019), as are applied approaches to develop adaptation strategies for risk management (Leedale et al., 2016; Onyango et al., 2016b; Sadoine et al., 2018).

Adaptation to reduce diarrhoeal disease

Reducing pathogen concentrations in water and across food chains is fundamental for controlling diarrhoeal diseases (van den Berg et al., 2019). Diarrhoea prevention and treatment post-disaster, encompass social mobilisation campaigns, water treatment, enhanced surveillance and vaccination and treatment centres for cholera (Cambaza et al., 2019) and typhoid (Neuzil et al., 2019).

Improved water, sanitation and hygiene (WASH) requires robust water and sanitation infrastructure (Duncker, 2017; Kohlitz et al., 2017; Venema and Temmer, 2017) and technological adaptations (Gabert, 2016; van Wyk et al., 2017), such as waterless on-site sanitation (Sutherland et al., 2021), diversification of water sources (e.g., rainwater harvesting (Lasage and Verburg, 2015) and groundwater abstraction (MacDonald et al., 2012)), and sharing of best practices across the continent (WASH Alliance International, 2015; Jack et al., 2016) (see also Section 9.7.3; Chapter 4, Section 4.6.4). Hand hygiene can be improved through the creation of handwashing stations, increased access to soap and simple technologies such as the foot-operated Tippy taps (Coultas and Iyer, 2020; Mbakaya et al., 2020).

Adaptation to reduce conditions related to heat exposure

Reducing morbidity and mortality during extreme heat events requires changes in behaviour and health promotion initiatives, health system interventions and modifications to the built and natural environment. Health promotion initiatives include promoting adequate hydration and simple cooling measures such as drinking cold liquids, water sprays and raising awareness of the symptoms and importance of heat stress, including heatstroke (Aljawabra and Nikolopoulou, 2018). Adaptive measures are especially important for high-risk groups such as outdoor workers, the elderly, pregnant women and infants. Health systems interventions may include early warning systems, heat health regulation, and health workers providing cooling interventions, such as supplying cool water or fans, during heat waves. Changes to the built environment include painting the roofs of houses white and improving ventilation during extreme heat (Codjoe et al., 2020), the use of insulation materials or altering the building materials used for the construction of housing to improve their ability to moderate indoor temperatures (Mathews et al., 1995; Makaka and Meyer, 2006).

Adaptation to prevent malnutrition

Transformative adaptation requires integration of resilience and mitigation across all parts of the food system including production, supply chains, social aspects and dietary choices (IPCC, 2019a). Adaptation to prevent malnutrition goes hand-in-hand with adaptation to prevent food insecurity, as is discussed in Section 9.8.3 and Chapter 5, Section 5.12.5.

Urban agriculture and forestry can improve nutrition and food security, household income and mental health of urban farmers while mitigating against some of the impacts of climate change like flooding and landslides (by stabilising the soil and reducing runoff, for example), heat (by providing shade and through evapotranspiration) and diversifying food sources in case of drought (Zezza and Tasciotti, 2010; Lwasa et al., 2014; Battersby and Hunter-Adams, 2020).

The health sector needs to collaborate and coordinate adaptation activities with other sectors, as well as civil society and international agencies, to engage communities in health promotion (Irwin et al., 2006; Commission of Social Determinants of Health, 2008; Braveman and Gottlieb, 2014). The importance of social determinants of health, such as socioeconomic status, education and the physical environment in which people live and work and their consideration during development are highlighted in Chapter 7 (see Sections 7.1.6 and 7.4.2)

		Health outcome/benefit								
Response category	Adaptation options	NCDs	Heat-related illnesses	Infectious diseases	Vector-borne diseases	Food- & water-borne diseases	Nutrition	Potential for risk reduction	Positive outcomes (vulnerable populations)	Requires sensitivity & consideration of cultural & traditional practices
Policy development ▲▲	Mainstreaming climate change into all health policies	x	x		x	x	x	█	█	░
	Occupational setting interventions (labour laws; avoiding heat during the day; education re adaptations)	x	x					█	█	░
Education & awareness ▲▲	Local knowledge strengthening and education	x	x	x		x		▓	▓	█
	Community, community health workers, and leadership resilience	x	x					▓	▓	█
	Teaching of climate change risks and behavioural changes in schools and universities	x	x					▓	▓	▓
Health systems & primary healthcare services ▲	Access to healthcare	x	x	x	x	x	x	█	█	░
	Universal Health Coverage, including of services for climate-related diseases	x	x	x	x	x	x	▓	█	░
	Infectious disease surveillance, early warning, outbreak response and control			x	x			█	█	░
Surveillance, risk assessments, monitoring, & research ▲▲▲	Heat health plans	x	x					▓	▓	░
	Vulnerability assessments	x	x	x	x		x	▓	▓	░
	Intervention studies	x	x				x	▓	▓	▓
	Risk assessments	x	x	x	x	x	x	▓	▓	░
	Early warning systems forecasting/disaster management for smallholder farmers	x	x			x	x	█	█	░
	Disaster Preparedness	x	x	x	x	x	x	█	█	░
	Health information systems for climate-related diseases	x	x	x	x	x	x	▓	▓	░
	Surveillance of health and environmental factors	x	x	x	x	x	x	█	▓	░
Resource management ▲▲▲▲▲▲▲	Improved management of environmental determinants of health (water quality; waste and sanitation; air quality)	x		x	x	x	x	█	█	░
	Strengthening of health systems and infrastructure against threat of extreme weather events, and for post-disaster recovery	x	x	x	x	x	x	▓	█	░
	Transport (sustainable; public) (infrastructure)	x	x					▓	█	░
	Sustainable land use, forestry, water management	x	x		x	x	x	█	█	░
	Sustainable farming	x	x		x	x	x	█	█	░
	Solar power / biogas for electricity	x						█	█	░
	Tree and seed planting	x	x		x		x	█	█	░
Vector control & disease prevention ▲▲▲	Improved housing, including painting roofs white	x	x		x	x		█	█	▓
	Insecticide-treated bed nets				x			█	█	▓
	Indoor residual spraying				x			█	█	▓
	Genetic modification				x			█	█	░

Key for sectors involved in each response category, and level of confidence (based on the literature)

Sectors involved
▲ Policy, governments, environmental health practitioners, community
▲ Forestry
▲ Agriculture, terrestrial
▲ Indigenous & local knowledge
▲ Water & sanitation
▲ Weather & climate services
▲ Research, innovation, & development

Confidence
█ High
▓ Medium
░ Low

Figure 9.36: Adaptation options across multiple sectors have potential for reducing risk across multiple health outcomes, considering their potential to reduce vulnerability, and potential barriers to implementation (e.g., lack of social acceptance). Reduced risk for health may result from targeted actions or as a result of co-benefits (see Supplementary Material Table SM9.8 for a full list of references).

Table 9.11: Co-benefits, barriers and enablers of adaptation responses to climate change impacts on human health in Africa (see Supplementary Material Table SM 9.9 for a full list of references).

Response category	**Co-benefits**	**Inter-sectoral trade-offs and/or drawbacks**	**Enablers**	**Barriers**
Policy development	Policies and plans that facilitate service delivery and guide national and international funding; decreased number of work hours lost; improved work performance, increased productivity		Willingness of policymakers; political support; politically willing environment; inter-sectoral collaboration	Lack of implementation; poor governance
Education & awareness	Promotion of sustainable living and circular economy		Guarantee to sustained funding; political support; politically willing environment; increased accessibility of learning institutions	Lack of implementation; historical and colonisation-related insensitivities
Health systems & primary healthcare services	Capacity building in communities; buffered economic impact of outbreaks/ disasters; job creation	Increased GHG from building; increased energy demand; decreased productivity and increased work hours lost due to waiting times	Guarantee to sustained funding; political support; politically willing environment	Corruption and fraudulent activities around resource allocation
Surveillance, risk assessments, monitoring, & research	Evidence to improve adaptation response; fast post-disaster recovery; increased awareness and disease prevention; improved health system functioning post-disasters		Requires effective institutional arrangements and inter-sectoral collaboration; guarantee to sustained funding; requires skills development	May be limited by uncertainty in modelled predictions and thresholds
Resource management	Improved health system functioning post-disasters; capacity building in communities; promotes economic growth/stability; increases the tourism potential of the area; increased accessibility/ mobility of the community; reduced land degradation, desertification, and bush encroachment; food security; decreased emissions	Increased GHG from building; increased energy demand; increased crowding/ population density; land use; microclimate and ecosystem disruption	Guarantee to sustained funding; political support; politically willing environment; requires effective institutional arrangements and inter-sectoral collaboration; requires skills development	Corruption and fraudulent activities around resource allocation
Vector control & disease prevention	Decreased mortality; improved work performance; increased productivity; improved mental health	Increased GHG; decreased biodiversity; environmental impacts of production, packaging, and delivery; potentially detrimental to health	Guarantee to sustained funding; funding and resources; future planning or retrofit required	Last-mile access; cost per capita and capacity for service delivery

9.11 Economy, Poverty and Livelihoods

9.11.1 Observed Impacts of Climate Change on African Economies and Livelihoods

9.11.1.1 Economic Output and Growth

Increased average temperatures and lower rainfall have reduced economic output and growth in Africa, with larger negative impacts than other regions of the world (Abidoye and Odusola, 2015; Burke et al., 2015a; Acevedo et al., 2017; Kalkuhl and Wenz, 2020). In one estimate, GDP per capita is on average 13.6% lower for African countries than it would be if anthropogenic warming since 1991 had not occurred (Diffenbaugh and Burke, 2019), although impacts vary substantially across countries (see Figure 9.37). As such, global warming has increased economic inequality between temperate, Northern Hemisphere countries and those in Africa (Diffenbaugh and Burke, 2019). Warming also leads to differential economic damages within Africa (Baarsch et al., 2020). One estimate found a 1°C increase in 20-year average temperature reduced GDP growth by 0.67 percentage points, with the greatest impacts in Central African Republic, Democratic Republic of Congo and Zimbabwe (Abidoye and Odusola, 2015). Changes in rainfall patterns also influence individual and national incomes. Had total rainfall not declined between 1960 and 2000, the gap between African GDP and that of the rest of the developing world would be 15–40% smaller than today, with the largest impacts in countries heavily dependent on agriculture and hydropower (Barrios et al., 2010).

Aggregate macroeconomic impacts manifest through many channels (Carleton et al., 2016). Macroeconomic evidence suggests aggregate impacts occurred largely through losses in agriculture with a smaller role for manufacturing (Barrios et al., 2010; Burke et al., 2015b; Acevedo et al., 2017). Sector-specific analyses confirm that declines in productivity of food crops, commodity crops and overall land productivity contribute to lower macroeconomic performance under rising temperatures (Schlenker and Lobell, 2010; Bezabih et al., 2011; Jaramillo et al., 2011; Lobell et al., 2011; Adhikari et al., 2015). Labour supply and productivity declines in manufacturing, industry, services and daily wage labour have been observed in other regions (Graff Zivin and Neidell, 2014; Somanathan et al., 2015; Day et al., 2019; Nath, 2020) and contribute to aggregate economic declines, countering aggregate poverty reduction strategies and other sustainable development goals (Satterthwaite and Bartlett, 2017; Day et al., 2019). In a case study of a rural town in South Africa, over 80% of businesses (both formal and informal) lost over 50% of employees and revenue due to agricultural drought (Hlalele et al., 2016). Drought and extreme heat events have also reduced tourism revenues in Africa (Section 9.6.3). Infrastructure damage and transport disruptions from adverse climate events reduce access to services and growth opportunities (Chinowsky et al., 2014). In global datasets including Africa, tropical cyclones have been shown to have large and long-lasting negative impacts on GDP growth (Hsiang and Jina, 2014).

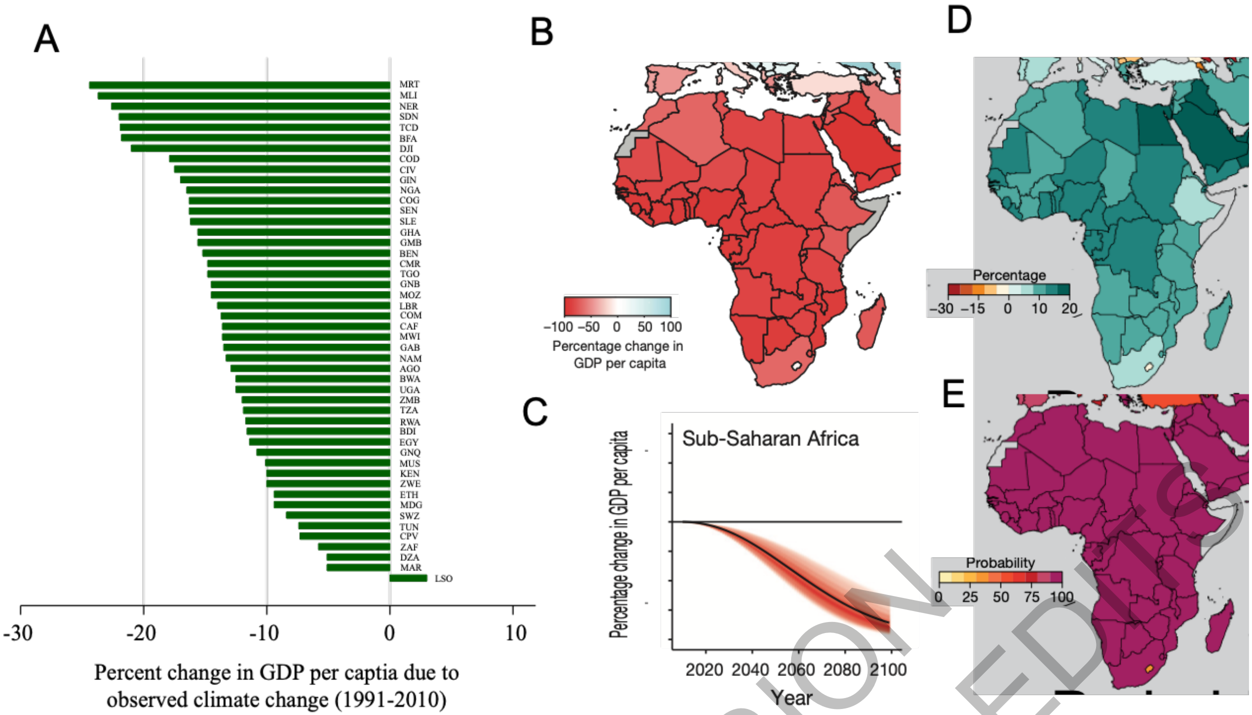


Figure 9.37: Observed aggregate economic impacts and projected risks from climate change in Africa. (A) Estimated effect of anthropogenic climate change on GDP per capita for 48 African countries between 1991 and 2010. (B, C) Projected effect on GDP per capita of global warming of ~4°C by 2100 compared to no global warming after 2010 at country level (B) and averaged across sub-Saharan Africa (C). (D) Benefits to GDP per capita of holding warming to 1.5°C versus 2°C above pre-industrial. (E) Probability of realising any economic benefits by holding warming to 1.5°C versus 2°C. Data sources: (Burke et al., 2015b; Burke et al., 2018a; Diffenbaugh and Burke, 2019).

9.11.1.2 Human Capital Development and Education

Investments in human capital, particularly education, are critical for socioeconomic development and poverty reduction by providing valuable skills and expanding labour market opportunities. Much progress has been made in improving education access, however, in sub-Saharan Africa, 32% of children, adolescents and youth (~97 million people) remain out of school (UNESCO Institute of Statistics, 2018). Climate variability and change can undermine educational attainment with negative impacts on later life earning potential and adaptive capacity to future climate change (Lutz et al., 2014) (Figure 9.11).

Several studies indicate experiencing low rainfall, warming temperatures or extreme events reduce education attainment and that future climate change may reduce children's school participation, particularly for agriculturally-dependent and poor urban households. In West and Central Africa, experiencing lower-than-average rainfall during early life is associated with up to 1.8 fewer years of completed schooling in adolescence while more rainfall and milder temperatures during the main agricultural season were positively associated with educational attainment for boys and girls in rural Ethiopia (Randell and Gray, 2016; Randell and Gray, 2019). In Uganda, low rainfall reduced primary school enrolment by 5% for girls (Björkman-Nyqvist, 2013), and in Malawi, in utero drought exposure was associated with delayed school entry among boys (Abiona, 2017). In rural Zimbabwe, experiencing drought conditions during the first few years of life was associated with fewer grades of completed schooling in adolescence, which translates into a 14% reduction in lifetime earnings (Alderman et al., 2006). In Cameroon, warming temperatures have negatively affected plantain yields, which in turn is linked to lower educational attainment (Fuller et al., 2018). One suggested mechanism underlying the relationship between climate and schooling is that adverse climatic conditions can reduce income among farming households, leading them to pull children out of school (Randell and Gray, 2016; Marchetta et al., 2019). Other potential mechanisms are poor harvests from droughts or supply interruptions from extreme weather events leading to undernutrition among young children, negatively affecting cognitive development and schooling potential (Alderman et al., 2006; Bartlett, 2008).

More research is needed on climate change impacts on education in Africa. This information can help ensure families keep children in school amidst climate-related income shocks. For example, in Mexico, a conditional cash transfer program mitigated the negative effect of natural disasters on school attendance (de Janvry et al., 2006).

9.11.2 Projected Risks of Climate Change for African economies and livelihoods

Future warming will have negative consequences for economic growth in Africa, relative to a future without additional climate change and assuming current levels of adaptation (*high confidence*) (Dell et al., 2012; Burke et al., 2015a; Burke et al., 2015b; Acevedo et al., 2017; Baarsch et al., 2020). Statistically-based empirical analyses project that global warming of 2.3°C by 2050 could lower GDP per capita across sub-Saharan Africa by 12% (SSP2) (Baarsch et al., 2020) and 80% for warming >4°C by 2100 (SSP5, 75% for MENA) (Burke et al., 2015b). Depending on the future socioeconomic scenario, this could increase global inequality and leave some African countries poorer than at present (Burke et al., 2015b). Inequalities between African countries are projected to widen under climate change, with negative impacts estimated to be largest in West and East Africa (Baarsch et al., 2020). While negative impacts across African economies are highly *likely* under climate change, precise magnitudes are debated in the literature. Alternative statistical analyses suggest a 12% reduction of GDP per capita by 2100 under RCP8.5 across African countries relative to a future without climate change (Kahn et al., 2019), while computable general equilibrium models generate smaller damages as well, ranging from 3.8% reduction across sub-Saharan Africa in 2060 under warming of 2.5°C (Dellink et al., 2019) to 12% across all of Africa in 2100 under warming of 5°C (SSP4) (Takakura et al., 2019).

Substantial avoided economic damages to African countries are projected from ambitious, near-term global mitigation limiting global warming well below 2°C above pre-industrial levels (*high confidence*). Increased economic damage forecasts for Africa under high emissions scenarios start diverging rapidly from low emissions scenarios by the 2030s (Baarsch et al., 2020). Across nearly all African countries, GDP per capita is projected to be at least 5% higher by 2050 and 10–20% higher by 2100 if global warming is held to 1.5°C versus 2°C (Burke et al., 2018a; Baarsch et al., 2020) (Figure 9.37). The probability of this positive gain to GDP per capita from achieving 1.5°C versus 2°C is reported as close to 100% (Burke et al., 2018a). While these estimates rely on temperature and rainfall-driven damages, sea level rise also poses a risk for Africa. By 2050, damages from sea level rise across sub-Saharan Africa could reach 2–4% of GDP, depending on the socioeconomic, adaptation and emissions scenario (Parrado et al., 2020).

Heat stress is projected to reduce working hours and work capacity under climate change, with among the largest declines in sub-Saharan Africa and for workers in vulnerable occupation groups, such as those working outdoors (Kjellstrom et al., 2014; Kjellstrom et al., 2016; de Lima et al., 2021) (AR6 WGII, Chapter 5). Global warming of 3°C is projected to reduce labour capacity in agriculture by 30–50% in sub-Saharan Africa (relative to the baseline in 1986–2005) (de Lima et al., 2021). These effects lead to substantial aggregate losses, for example, in West Africa, labour productivity impacts under a 3°C temperature increase are estimated to cost up to 8% of GDP (Roson and Sartori, 2016). Manufacturing productivity across Africa is projected to decline under RCP8.5 by 0–15% by 2080–2099, with the largest effects in the Democratic Republic of Congo, Ethiopia, Somalia, Mozambique and Malawi (Nath, 2020).

Large risks to road, rail and water infrastructure are projected from climate change with substantial economic cost implications (see Section 9.9.3; Box 9.5).

9.11.3 Informality

Aggregate GDP data capture formal economic activity but informal employment is the main source of employment in Africa, accounting for 85.8% of all employment (71.9%, excluding agriculture), which is 21.4% higher than the global average (ILO, 2018b). Estimates of national levels of informal employment range from 30% in South Africa, to 94.6% in Burkina Faso (ILO, 2018b), with high variability within countries such as South Africa and Nigeria (Etim and Daramola, 2020). Informal employment is a greater source of employment for women than for men in sub-Saharan Africa and young and old have especially high rates of informal employment: 94.9% of persons between ages 15 and 24 in employment and 96% of persons aged 65 and older (ILO, 2018b).

Informal sector impacts are omitted from GDP-based impacts projections. Yet informal sector activity and small to medium-sized enterprises can be highly exposed to climate extremes, as they are often located in low-lying areas, coastal areas, sloped or other hazardous zones (Thorn et al., 2015; Satterthwaite et al., 2020). Businesses and individuals in the informal sector, including construction workers, domestic workers, street vendors and transport workers, often cannot operate during climate shocks due to interruptions in transportation and commodity flows and, without the ability to insure against risk, struggle to recover assets from extreme events such as flooding, landslides and waterlogging (Chen, 2014; Thorn et al., 2015; Roy et al., 2018a). Women are overrepresented in the more poorly remunerated sections of the informal economy (Satterthwaite et al., 2020).

There is scope for governments to better harness the role of the informal sector in mitigation and adaptation (Douxchamps et al., 2015; Satterthwaite et al., 2020). Multi-level governance that includes informal service providers, such as informal water and sanitation networks, into planned adaptation programmes can increase climate resilience, in part because these networks can respond with more flexibility than hard infrastructure projects (Satterthwaite et al., 2020; Peirson and Ziervogel, 2021). Climate risk is often concentrated in urban informal settlements (Section 9.9.4). Here, informal land markets influence development patterns and can help ensure adherence to building codes to ensure safety of informally built structures at high risks of landslides and floods and enforce compliance with regulations relating to planning and land use (Thorn et al., 2015; Satterthwaite et al., 2020). Improving land management practices of charcoal producers and artisanal gold miners, combined with appropriate alternative livelihood and energy sources, can reduce emissions and increase resilience (e.g., reduce erosion and sedimentation, increase water infiltration) and benefit health (Atteridge, 2013; Paz et al., 2015; Macháček, 2019; Barenblitt et al., 2021; Eniola, 2021). Providing concessional loans, commercial financing or equity investment to informal brick makers can boost delivery of low emission social housing while the use of crop residues or renewable energy for brick making can replace wood biomass and reduce pressure on forests (Alam, 2006; Paz et al., 2015).

9.11.4 Climate Change Adaptation to Reduce Vulnerability, Poverty and Inequality

High temperature-related income losses have been observed in low- and high-income countries, suggesting optimistic economic development trajectories may not substantially reduce climate change impacts on aggregate economic performance in Africa (*low confidence*) (Burke et al., 2015b; Deryugina and Hsiang, 2017; Henseler and Schumacher, 2019). Nevertheless, climate change impacts on poverty in Africa will depend on how socioeconomic development unfolds over the coming decades (*medium confidence*) (Rozenberg and Hallegatte, 2015; Hallegatte and Rozenberg, 2017; Henseler and Schumacher, 2019). Climate change by 2030 is projected to push 39.7 million Africans into extreme poverty[3] under a baseline scenario of delayed and non-inclusive growth, with food prices acting as the dominant channel of impact, but this number is cut roughly in half under an inclusive economic growth scenario (Rozenberg and Hallegatte, 2015; Hallegatte and Rozenberg, 2017; Jafino et al., 2020).

People in Africa are disproportionately employed in highly climate-sensitive sectors: 55–62% of the sub-Saharan African workforce is employed in agriculture and while between 90–95% of cropland is rainfed (Woodhouse et al., 2017; ILO, 2018a; International Institute of Water Management, 2019; World Bank, 2020c), there has been an expansion of small-scale ‘farmer-led irrigation’ (Woodhouse et al., 2017). Agricultural GDP also appears more strongly affected by increasing temperatures than non-agricultural GDP, implying livelihood diversification out of agriculture may help minimise future economic damage (Bezabih et al., 2011; Burke et al., 2015b; Acevedo et al., 2017; Deryugina and Hsiang, 2017), although such workforce reallocation requires careful management and planning depending on the overall livelihood portfolios, type of farmer and profitability (Stringer et al., 2020). De-agrarianisation can feed urbanisation, which may exacerbate inequality within and between countries (Stringer et al., 2020).

Changes in trade patterns may help mitigate projected aggregate economic losses by reallocating agricultural production abroad and encouraging economic diversification toward less affected sectors. Temperature increases have been shown to lower agriculture and manufacturing exports with especially large declines in

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[3] Extreme poverty is defined using a consumption poverty line at US$1.25 per day, using 2005 purchasing power parity exchange rates.

poor countries (Jones and Olken, 2010; Roberts and Schlenker, 2013). Further, imports of agricultural products are projected to rise across most of Africa by 2080-2099 under a high emissions scenario (RCP8.5), with increases ranging from ~30% of GDP in the Central African Republic to ~5% of GDP in South Africa and Nigeria, although some countries will experience increases in net agricultural exports (Nath, 2020). While these reallocation effects may be large, current evidence is mixed regarding whether such adjustment of production will dampen or amplify overall social costs of climate change in Africa (Costinot et al., 2012; Bren d'Amour et al., 2016; Wenz and Levermann, 2016; Nath, 2020), as food prices are projected to rise by 2080-2099 across all African countries under a scenario with high challenges to mitigation and adaptation (SSP3 and RCP8.5), with the largest price effects (up to 120%) experienced in Niger, Chad and Sudan (Nath, 2020). Moreover, reallocating production of agriculture abroad could be maladaptive if it leads to decline or replacement of traditional sectors by industrial and service sectors which could lead to land abandonment, food insecurity and loss of traditional practices and cultural heritage (Thorn et al., 2020; Gebre and Rahut, 2021; Nyiwul, 2021).

African countries have high inequality: the average within-country share of income accruing to the top 10% of households was estimated at 50% for 2019 (Robilliard, 2020). However, analysis of INDCs across 54 African countries suggests current climate policies do not, on average, target social inequality in energy, water and food security; proposed mitigation and adaptation actions fell about 23% for every 1% rise in social inequality across these sectors (Nyiwul, 2021). In contrast, adaptation actions can be designed in ways that actively work towards reducing inequality, whether gender, income, employment, education or otherwise (Andrijevic et al., 2020).

In rural Africa, poor and female-headed households face greater livelihood risks from climate hazards (*high confidence*). Women often constitute a high proportion of the informal workforce and are also more *likely* to be unemployed than men (ILO, 2018a). These factors leave women, and particularly female-headed households, at greater risk of poverty and food insecurity from climate hazards. Controlling for multiple factors, income of female-headed households in agricultural districts in South Africa is more vulnerable to precipitation variability than those headed by men (Davidson, 2016; Flatø et al., 2017). Across nine countries in East and West Africa women tend to control smaller plots of land that is often of poorer quality, have less access to inputs such as fertilizer, tools and improved seeds, have lower educational attainment and benefit less from extension services, government agencies and non-governmental organisations (Perez et al., 2015). Gender assessments prior to adaptation programmes can identify disparities in division of labour and income and socio-cultural norms, hindering women from holding leadership positions or determining livelihood and resource-use activities, thereby helping ensure equitable benefits from livelihood diversification and improving women's working conditions (ILO, 2018a). Gender-responsive policy instruments can measure success using sex-disaggregated data to monitor impact and meaningful participation in decision-making (GCF, 2018b).

Exposure to climate hazards can trap poorer households in a cycle of poverty (Dercon and Christiaensen, 2011; Sesmero et al., 2018) and poor people in Africa are often more exposed to climate hazards than non-poor people. For example, poor people live in hotter areas in Nigeria and in multiple African countries, poor households are more exposed to flooding (Hallegatte et al., 2016) (Section 9.9.2). Daily wage labourers and residents of urban informal settlements are vulnerable to heat stress because of the urban heat-island effect combined with congestion, little shade and ventilation (Bartlett, 2008). Climate change can negatively affect household poverty through price spikes, destroying assets or ability to invest in new assets and reducing productivity (Hallegatte et al., 2016) with important impact pathways operating through agriculture, ecosystem functioning and health (Sections 9.6, 9.8, 9.10; Chapters 5, 7, 8). Non-poor people can lose more in absolute terms from climate shocks because of having more assets and higher incomes, but in relative terms, poor people often lose more than the non-poor. These relative losses matter most for livelihoods and welfare (Hallegatte et al., 2016).

In Malawi, wealthier households were able to maintain more diversified livelihoods, buffering them from extreme weather-related income losses (Sesmero et al., 2018). Poorer households have limited access to resources such as savings, credit, irrigation technologies and insurance, which can lead to larger crop and other income losses from climate hazards, preventing investments to improve resilience to future climate shocks (Castells-Quintana et al., 2018). Poor households may reduce risk or aid recovery by cooperating with other households in their community to adapt collectively to climate change, for example, through informal insurance networks (Paul et al., 2016; Wuepper et al., 2018). Prioritising poor households for interventions including social protection, ecosystem-based adaptation, universal healthcare, climate-smart buildings and agriculture, flexible work hours under extreme heat and early warning systems will increase adaptation to climate shocks (Angula and Menjono, 2014; Moosa and Tuana, 2014; Hallegatte et al., 2016; Day et al., 2019) (Section 9.6.4; Chapter 6). Pro-poor policies that link mitigation and adaptation, such as using renewable energy to increase rural electrification or using revenues from a carbon tax, combined with international financial support to increase social assistance, could support sustainable eradication of poverty under near-term climate change (Hallegatte et al., 2016; Aklin et al., 2018; Simpson et al., 2021c). Integrating urban green infrastructure into adaptation planning in informal settlements can simultaneously unlock pathways for inclusivity and social justice (Tozer et al., 2020; Wijesinghe and Thorn, 2021) (Section 9.9.5).

Social protection has been used for decades, particularly in eastern and southern Africa, to safeguard poor and vulnerable populations from poverty and food insecurity (Niño-Zarazúa et al., 2012). Instruments of social protection include public works programs, cash transfers, in-kind transfers, social insurance and microinsurance schemes that assist individuals and households to cope during times of crisis and minimise social inequality. Evidence from Kenya, Ethiopia and Uganda indicates national social protection programmes are effective in improving individual and household resilience to climate-related shocks, regardless of whether they aim specifically to address climate risks (Ulrichs et al., 2019). Strengthening social protection and better integrating climate risk management into design of social protection programs can help build long-term resilience to climate change (Hallegatte et al., 2016; Agrawal et al., 2019). For example, Public Works programs can build climate resilience by targeting soil, water and ecosystem conservation and carbon sequestration, such as South Africa's Working for Water Programme that restores river catchments to reduce fire risk and increase water supplies (Turpie et al., 2008; Norton et al., 2020).

9.11.4.1 Climate Insurance

African countries and communities are inadequately insured against climate risk. Insurance penetration is less than 2% of GDP (Swis Re, 2019) and 90% of natural catastrophe losses were uninsured in Africa in 2018 (Swis Re, 2019) leaving a large risk protection gap. The cost of reinsurance in Africa's most mature insurance market – South Africa – has increased since 2017 due to climate-related payouts (SAIA, 2018; Simpson, 2020), *likely* to further reduce the extent of insurance coverage. Emerging trends that seek to address this gap include innovative weather and drought index-based insurance schemes to transfer risk, forward-looking climate data and models to manage risk and insurers transitioning from risk transfer providers to proactive risk managers.

The most significant area of climate risk insurance innovation has occurred in weather and drought index-based insurance schemes that pay out fixed amounts based on the occurrence of an event instead of full indemnification against assessed losses (Table 9.12). However, despite the relatively low cost, uptake remains low due to affordability constraints, lack of awareness, access to and trust in products, distribution challenges, basis risk, poor transparency, challenges regarding the integration of complementary interventions (e.g., access to improved inputs or informal savings/credit) and poor perceptions/norms of insurance and risk transfer. Lack of data and models further hinders insurers' ability to price risk correctly, which reduces value to clients (Greatrex et al., 2015; Di Marcantonio and Kayitakire, 2017; WEF, 2021). Impact assessments point to potential but remain context-specific (Awondo, 2019; Hansen et al., 2019b; Noritomo and Takahashi, 2020). In addition, there is no comprehensive overview of the number of people covered by such schemes, nor of the value they provide in terms of actual claims payouts. Lastly, donor and/or public funds still play an outsized role in launching and/or sustaining these schemes and schemes beyond weather and drought remain limited (Table 9.12).

Insurers and their clients are often unaware of their risk exposure, partly due to data and modelling gaps. Climate information services and related collaborations are increasingly helping to address this problem (see Section 9.4.5). Climate change attribution methods to estimate the contribution of anthropogenic climate change to the cost of parametric insurance offers possibilities for a sharing of the premium between the impacted African country and a global climate fund, such as the Green Climate Fund (New et al., 2020). Technology companies and start-ups (including fintechs) are also emerging as solutions to fill risk gaps, leveraging new approaches to data and technology through the use of sensors, drones and satellite imaging to speak to mainly agricultural risks, but also urban risks such as informal settlement fires, exacerbated by heat and drought (Table 9.12).

Ten African insurers formally committed to help manage climate risk on the continent through the Nairobi declaration of the UNEP Principles for Sustainable Insurance (PSI) in 2021 (UNEP PSI, 2021). Some early examples of public-private partnerships with municipalities and governments to better manage climate risk are also emerging (Table 9.12).

Table 9.12: Insurance opportunities to mitigate climate risk.

Initiatives	Drought/ heatwave	Flood	Cyclone	Fire	Example	Policyholders/ beneficiaries	Reference
Index and parametric schemes – smallholder farmer	x	x			ACRE Africa, Pula, R4 Rural Resilience Initiative, KLIP, FISP, Ghana Agricultural Insurance Pool, Oko Crop Assurance	Smallholder farmers	(Greatrex et al., 2015; CTA, 2019; Global Index Insurance Facility, 2019; WFP, 2020; Fava et al., 2021; OKO Finance, 2021; Pula, 2021; Tsan et al., 2021)
Index and parametric schemes – sovereign and sub-sovereign	x	x	x		African Risk Capacity	Governments	(ARC, 2019)
Index and parametric schemes – global	x	x			African and Asian Resilience in Disaster Insurance Scheme (ARDIS)	Individuals and smallholder farmers	(Global Parametrics, 2018)
Risk management and data collaboration	x	x	x	x	UNEP PSI Santam Tripartite Agreement	Insurers and reinsurers, local municipalities, governments	(Santam, 2018; Forsyth et al., 2019; UNEP-FI, 2019a; InsurResilience, 2020; Simpson, 2020)
FinTech	x	x		x	Lumkani, WorldCover, Econet, PlaNet Guarantee	Individuals, smallholder farmers	(Greatrex et al., 2015; Hunter et al., 2018; CTA, 2019; UK Space Agency, 2020; Tsan et al., 2021)

[START BOX 9.8 HERE]

Box 9.8: Climate Change, Migration and Displacement in Africa

Climatic conditions are important drivers of migration and displacement with migration responses to climate hazards strongly influenced by economic, social, political and demographic processes (Cross-Chapter Box MIGRATE in Chapter 7).

Most climate-related migration and displacement observed currently is within countries or between neighbouring countries, rather than to more geographically distant high-income countries (Hoffmann et al., 2020; Kaczan and Orgill-Meyer, 2020). Natural-related disaster displacements in sub-Saharan Africa were over 2.6 million in 2018 and 3.4 million in 2019 (13.9% of the global total and one of the highest historical figures for the region), with East (1,437,7000) and West Africa (798,000) being hotspots in 2018 (Mastrorillo et al., 2016; IDMC, 2019; IDMC, 2020) (Table Box 9.8.1). Estimates indicate future climate change effects on internal migration in Africa will be considerable (Rigaud et al., 2018) (Table Box 9.8.2).

Internal migration, displacement and urbanisation

Climate change can have opposing influences on migration flows. Deteriorating economic conditions caused by climate hazards can encourage out-migration (Wiederkehr et al., 2018). However, these same economic losses undermine household resources needed to migrate (Cattaneo and Peri, 2016). The net effect of these two forces leads to mixed results across study methodologies and contexts (Carleton and Hsiang, 2016; Borderon et al., 2019; Cattaneo et al., 2019; Hoffmann et al., 2020).

Urbanisation in Africa is affected by climate conditions in rural agricultural areas (*high confidence*). Urbanisation can increase when reduced moisture availability depresses farm incomes or pastoral livelihoods become unviable (Marchiori et al., 2012; Henderson et al., 2014; Mastrorillo et al., 2016). The influence of rainfall on rural-urban migration increased since decolonisation, possibly due to more lenient legislation on internal mobility, with each 1% reduction in precipitation below a long-term average associated with a 0.45% increase in urbanisation (Barrios et al., 2006). Rate of rural-urban migration is anticipated to increase (Neumann et al., 2015) as a result of increasing vulnerability of agricultural livelihoods to climate change (Serdeczny et al., 2017). Nevertheless, rural-urban migration is not a simple one-way process. Peri-urban and rural areas provide developmental feedback loops, helping create a ‘regional agglomeration’ effect, for instance, through growing food demand, family and social connections, and flows back to rural areas of goods and services and financial investments (UN-Habitat, 2016; Dodman et al., 2017).

Migration is an important and potentially effective climate change adaptation strategy in Africa and must be considered in adaptation planning (*high confidence)* (Williams et al., 2021). The more agency migrants have (that is, degree of voluntarity and freedom of movement), the greater the potential benefits for sending and receiving areas (*high agreement, medium evidence*) (Cross-Chapter Box MIGRATE in Chapter 7). In a synthesis of 63 studies covering over 9,700 rural households in dryland sub-Saharan Africa, 23% of households employed migration (primarily temporary economic) to adapt to changes in rainfed agriculture (Wiederkehr et al., 2018). Migration responses to climate change tend to be stronger among wealthier households, as poorer households often lack financial resources necessary to migrate (Kaczan and Orgill-Meyer, 2020).

International migration

Studies on propensity to emigrate have uncovered conflicting results. Some findings suggest in low-income countries high temperatures ‘trap’ people at home and lower migration rates abroad, but in middle-income countries, these same high temperatures encourage emigration (Cattaneo and Peri, 2016). However, other research finds in poor and agriculturally-dependent countries, high temperatures encourage international out-migration, particularly to the OECD (Cai et al., 2016). Some evidence indicates people who leave tend to be more educated, possibly leading to ‘brain drain’ (Mbaye, 2017). Recent evidence suggests hotter-than-normal temperatures across 103 countries, including many in Africa, increased asylum applications to the European Union (Missirian and Schlenker, 2017). Assuming no change in present-day vulnerability, asylum applications are projected to increase 34% across Africa (relative to 2000–2014) at 2.2°C global warming (Missirian and Schlenker, 2017), although this finding has been challenged in the literature (Abel et al., 2019; Boas et al., 2019).

International remittances are a vital resource for developing countries that can help aid recovery from climate shocks (Hallegatte et al. 2016). Estimated at USD 48 billion in 2019 their importance is expected to grow further due to foreign direct investment declines during the COVID-19 pandemic (World Bank, 2020a). Furthermore, domestic remittances from rural-urban migration can help rural households respond to climate risks (KNOMAD, 2016). However, adequate finance and banking infrastructure are essential for remittances and, on average, cash transfer costs for sub-Saharan African countries remain the highest globally (World Bank, 2020a). Mobile money technologies and regulation that promotes competition in the remittances market can reduce transaction costs (World Bank, 2020a). Governments can further address challenges facing internal and international migrants by including them in health services and other social programmes and protecting them from discrimination (World Bank, 2020a).

Table Box 9.8.1: Reported impacts of climate on migration in Africa (Findings on the linkages between climatic conditions and migration vary greatly across countries in Africa)

Climate driver	Country	Climate - Migration linkages	Reference
Temperature	Kenya	Cool temperatures linked to internal labour migration among males	(Gray and Wise, 2016)
	Uganda	High temperatures linked to increased non-labour migration among females. Short hot spells linked to increased temporary migration. Long-term heat stress linked to permanent migration through an agricultural livelihoods pathway.	(Gray and Wise, 2016; Call and Gray, 2020)
	Tanzania	Temperature-induced income shocks linked to decreased long-term rural-urban migration among men.	(Hirvonen, 2016)
Precipitation	Kenya	Increased precipitation linked to decreased rural-urban migration.	(Mueller et al., 2020)
	Zambia	Increased precipitation linked to increased internal migration.	(Mueller et al., 2020)
	Burkina Faso	Drier regions linked to increased temporary and permanent migrations to other rural areas. Short-term precipitation deficits linked to increased long-term migration to rural areas and decreased risk of short-term migration to distant destinations.	(Henry et al., 2004)
	Ethiopia	Drought linked to men's labour migration from rural to urban areas, especially in land-poor households. Drought linked to decreased marriage-related migration by women. Precipitation variability and drought linked to labour migration from rural to urban areas. Precipitation variability and drought linked to out-migration to communities where precipitation variability and drought probability are lower. High precipitation variability linked to increased migration, either through increased non-farm activities, which enable migration through economic resources or through insufficient agricultural production, which increase migration needs.	(Gray and Mueller, 2012; Morrissey, 2013; Hermans-Neumann et al., 2017; Groth et al., 2021)
	Ghana	Increased severity of drought and household insecurity linked to reduced future migration intentions of households.	(Adger et al., 2021)
	Malawi	Precipitation shocks linked to rural out-migration to communities where precipitation variability and drought probability are lower. Precipitation shocks (flood and droughts) linked to longer-term urban migration and/or reverse (i.e., urban-rural) migration.	(Lewin et al., 2012; Suckall et al., 2015)
	Mali	Decreased precipitation linked to overall increase in out-migration – where farming families or individuals from farming communities will leave their origin community – and some changes in duration and destination of trips. These moves can be either permanent or short-term, domestic or international.	(Grace et al., 2018)

	Niger	Drought linked to economically-induced migration of households from rural areas to cities. Drought also linked to temporary international migration.	(Afifi, 2011)
Temperature and precipitation	Burkina Faso	High temperatures linked to negative effects on all migration streams including international migration, much of which is to neighbouring countries. International migration also declines with precipitation.	(Gray and Wise, 2016)
	Senegal	No detected linkages between climate and migration.	(Gray and Wise, 2016)
	Nigeria	No detected linkages between climate and migration.	(Gray and Wise, 2016)
	Botswana	Increased temperatures and precipitation linked to decreased internal migration.	(Mueller et al., 2020)
	South Africa	Higher temperatures and precipitation extremes linked to increased rural out-migration, especially among black and low-income South Africans.	(Mastrorillo et al., 2016)
	Senegal	Precipitation variability, drought and increased temperatures linked to seasonal migration from rural to urban areas.	(Hummel, 2016)
	Zambia	Hotter and drier climate linked to inter-district migration of wealthy districts. Poor districts characterised by climate-related immobility.	(Nawrotzki and DeWaard, 2018)

Table Box 9.8.2: Projected numbers and shares of internal climate migrants in 2050 by sub-regions of sub-Saharan Africa. Projections are for internal migration driven by three slow-onset climate hazards (water stress, crop failure, and sea level rise), and excluding rapid-onset hazards such as floods and tropical cyclones. As such, they present a lower-bound estimate of potential climate change impacts on internal migration. Projections are for two warming scenarios: low emissions (RCP2.6) and high emissions (RCP8.5), both coupled with a socioeconomic pathway (SSP4) in which low-income countries have high population growth, high rates of urbanisation, and increasing inequality within and among countries. By 2050, between 17.4 million (RCP2.6) and 85 million (RCP8.5) people (up to 4% of the region's total population) could be moving as a consequence of climate impacts on water stress, crop productivity and sea level rise. More inclusive socioeconomic pathways with lower population growth are projected to reduce these risks. West Africa has the highest levels of climate migrants, potentially reaching more than 50 million, suggesting that climate impacts will have a particularly pronounced impact on future migration in the region. In East Africa, out-migration hotspots include coastal regions of Kenya and Tanzania, western Uganda and parts of the northern highlands of Ethiopia. Kampala, Nairobi and Lilongwe may become hotspots of climate in-migration, coupled with existing rural to urban migration trends, and a high likelihood of movement toward non-climate-related sources of income in cities. Source: (Rigaud et al., 2018).

Region		Global warming around 2.5°C above pre-industrial by 2050 (RCP8.5)	Global warming around 1.7°C above pre-industrial by 2050 (RCP2.6)
East Africa	Average number of internal migrants by 2050 (million)	10.1	6.9
	Internal climate migrants as percent of population	1.28%	0.87%
West Africa	Average number of internal migrants by 2050 (million)	54.4	17.9
	Internal climate migrants as percent of population	6.87%	2.27%

Central Africa	Average number of internal migrants by 2050 (million)	5.1			2.6		
	Internal climate migrants as percent of population	1.31%			0.66%		
Southern Africa	Average number of internal migrants by 2050 (million)	1.5			0.9		
	Internal climate migrants as percent of population	2.31%			1.40%		
Sub-Saharan Africa	Average number of internal migrants by 2050 (million)	71.1			28.3		
	Minimum (left) and maximum (right) million	56.6	85.7		17.4	39.9	
	Internal climate migrants as percent of population	3.49%			1.39%		
	Minimum (left) and maximum (right) percent	2.71%		4.03%	0.91%		2.04%

[END BOX 9.8 HERE]

9.11.5 COVID-19 Recovery Stimulus Packages for Climate Action

The COVID-19 pandemic recovery effort includes significant opportunities for African countries to reduce future vulnerability to compound climate, economic and health risks. Fiscal recovery packages could set economies on a pathway towards net-zero emissions, reducing future climate risk or entrench fossil-fuel intensive systems, exacerbating risk (Hepburn et al., 2020; Dibley et al., 2021; IEA, 2021). Investments in renewable energy, building efficiency retrofits, education and training, natural capital (that is, ecosystem restoration and ecosystem-based adaptation), R&D, connectivity infrastructure and sustainable agriculture can help meet both economic recovery and climate goals (Hepburn et al., 2020; Dibley et al., 2021).

The impacts of the COVID-19 pandemic have been substantially worsened by climate hazards in many places. In others, outbreak response has been disrupted (Phillips et al., 2020; Kruczkiewicz et al., 2021). These vulnerabilities are rooted in insufficient disaster preparedness infrastructure but are almost always worsened by social and economic inequality. Ensuring the most vulnerable populations are properly protected from climate change has co-benefits for recovery from the COVID-19 pandemic (Manzanedo and Manning, 2020). In particular, efforts to reduce syndemic vulnerabilities across key sectors (especially health, livelihoods and food security) will lessen climate change impacts and will also reduce the risk and impacts of future epidemics and pandemics, for example, during the pandemic, water scarcity has been a barrier to a key risk mitigation behaviour (handwashing). In the long-term, development efforts focused on water, sanitation and hygiene (WASH) will reduce this vulnerability and also reduce the health toll of diarrheal disease linked to climate change (Anim and Ofori-Asenso, 2020; Zvobgo and Do, 2020). Spending recovery funds on social safety nets will reduce inequality and protect the most vulnerable communities (especially women and low-income and marginalised communities) from the social and economic impacts of disasters. Key among these safety nets is universal health coverage, including low- or no-cost access to essential medicine, high-quality preventative care, financial protections against medical debt and increased geographic and population coverage for all services (Hallegatte et al., 2016). All of these are key components of climate change adaptation for health and will reduce both the rate at which future outbreaks start and their total scope and impact (Carlson et al., 2021). The co-benefits of multilateral cooperation on the attainment of universal health coverage will be a key determinant of success or failure in both climate change adaptation and pandemic preparedness.

[START BOX 9.9 HERE]

Box 9.9: Climate Change and Security: Interpersonal Violence and Large-scale Civil Conflict

There is substantial evidence that climate variability influences human security across Africa (see Chapter 7 WGII Section 7.2.7 and 7.3.3 7). However, the strength and nature of this link depend on socioeconomic and institutional conditions, and climate is just one of many factors influencing violence and civil conflict (Schleussner et al., 2016a; von Uexkull et al., 2016; Linke et al., 2018; Mach et al., 2019; van Weezel, 2019; Ide et al., 2020).

Projections of security implications of long-run climate change in Africa are uncertain, as they rely on extrapolating observed effects of short-run climate variability (Burke et al., 2014). Lack of detection and attribution studies limit assessment of the impacts of observed anthropogenic climate change on security.

Interpersonal violent crime

Evidence from across the globe finds that interpersonal violence, ranging from use of profanity to violent crime, increases with temperature and sometimes low rainfall (Hsiang et al., 2013a; Burke et al., 2014; Gates et al., 2019). The effect of temperature may be driven by a physiological mechanism (Morrison et al., 2008; Seo et al., 2008; Ray et al., 2011), while effects of rainfall may operate through an agricultural yield impacts channel (Burke et al., 2014). While few studies link interpersonal violence to climate in Africa, Gates et al. (2019) documents homicide risks increasing under high temperatures in South Africa, and similarity across diverse study settings suggests temperature-induced violent crime *likely* generalizes to Africa (Burke et al., 2014).

Large-scale intergroup conflict

Climatic conditions also change the risk of large-scale conflicts such as riots, ethnic conflicts and civil war (Burke et al., 2014; Koubi, 2019). The effects of temperature are particularly well-studied in Africa. Risk of violent conflict rises with temperature in Sudan and South Sudan (Maystadt and Ecker, 2014; Maystadt et al., 2014; Scheffran et al., 2014), Kenya (Hsiang et al., 2013b; Scheffran et al., 2014), the East African region (O'Loughlin et al., 2012) and across sub-Saharan Africa (Burke et al., 2009; O'Loughlin et al., 2014; Witmer et al., 2017). Estimates indicate that warming trends since 1980 have elevated conflict risk across sub-Saharan Africa by 11% (Burke et al., 2009; Carleton et al., 2016).

Periods of low rainfall or flooding also contribute to social instability and upheaval across Africa (Miguel et al., 2004; Ralston, 2015; von Uexkull et al., 2016; Harari and Ferrara, 2018; van Weezel, 2019; Ide et al., 2020). The link between rainfall and conflict appears *likely* due to crop losses and declines in economic opportunity. One study finds that dry growing seasons increase conflict incidence across 36 African nations, with spillover effects from the location of climate shock to neighbouring communities (Harari and Ferrara, 2018). Conflict-inducing impacts of drought have also been uncovered in Somalia (Maystadt and Ecker, 2014), Uganda, Sudan, Ethiopia and Kenya (Fjelde and von Uexkull, 2012; Hendrix and Salehyan, 2012; Couttenier and Soubeyran, 2014; Ralston, 2015; Linke et al., 2018; van Weezel, 2019), the Democratic Republic of Congo (von Uexkull et al., 2020) and in a pooled sample of African and Asian countries (von Uexkull et al., 2016). Extremely high rainfall may also incite conflict risk, although results are mixed (Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012). This uncertainty, combined with large uncertainties in rainfall projections under climate change, render future impacts of anthropogenic emissions on rainfall-induced conflict in Africa highly uncertain.

While conflict-climate links have been repeatedly identified in Africa, climate is one of many interacting conflict risk factors and appears to explain only a small share of total variation in conflict incidence (von Uexkull et al., 2016; Mach et al., 2019; van Weezel, 2019).

Opportunities for adaptation

Adaptive capacity with respect to climate and conflict remains low in Africa (Sitati et al., 2021). For example, one study finds that relative to each country's optimal annual temperature, realized temperatures across sub-Saharan Africa increase the annual incidence of war by 29.3% on average (Carleton et al., 2016). Another finds that rising temperatures due to climate change may lead to higher levels of violence in sub-Saharan Africa if political rights do not improve from current conditions (Witmer et al., 2017). Available studies on adaptation in conflict-affected areas tend to have a narrow focus, particularly on agriculture-related adaptation in rural contexts and adaptation by low-income actors, with little known beyond these contexts (Sitati et al., 2021). Literature on the gender dimension of climate adaptation in conflict-affected countries is also limited (Sitati et al., 2021).

Migration is a common response (Sitati et al., 2021) and may be an effective adaptive response to climate-induced conflict. Bosetti et al. (2018) find that countries with high emigration propensity display lower sensitivity of conflict to temperature, with no evidence of detrimental impacts on the destination countries. Indigenous knowledge has also been applied to enable adaptation amidst conflict, for example, in Libya, to deal with erratic rainfall (Biagetti, 2017).

Other socioeconomic factors have been identified as adaptive opportunities. Rising incomes may mitigate conflict-climate relationships (Carleton et al., 2016), while weak institutions, lack of political freedom, agricultural dependence and exclusion of ethnic groups increase their strength (Schleussner et al., 2016a; von Uexkull et al., 2016; Witmer et al., 2017; Ide et al., 2020). In particular, agriculturally dependent and politically excluded groups in Africa are especially vulnerable to the impact of drought on conflict (von Uexkull et al., 2016; Koubi, 2019). Household-level resilience to economic shocks has been shown to lower support for violence after drought (von Uexkull et al., 2020). Local-level institutions have also been shown to support non-violence under adverse climate conditions (Bogale and Korf, 2007).

These findings suggest that ameliorating ethnic tensions, improving political institutions, and investing in economic diversification and household resilience could mitigate future impacts of climate change on conflict.

[END BOX 9.9 HERE]

9.12 Heritage

Africa is a rich reservoir of heritage resources and indigenous knowledge, showcased by about 96 sites inscribed by UNESCO as World Heritage Sites (UNESCO, 2018b). These include 53 sites specifically denoted as having great cultural importance and 5 sites with mixed heritage values. Unfortunately, valuable cultural heritage in forms of tangible evidence of past human endeavour, and the intangible heritage encapsulated by diverse cultural practices of many communities (Feary et al., 2016), is under great threat from climate change.

9.12.1 Observed Impacts on Cultural Heritage.

For more than 10,000 years, Africans recorded over 8,000 painted and engraved images on rock shelters and rock outcroppings across 800 exceptional rock art sites of incalculable value (Hall et al., 2007; di Lernia and Gallinaro, 2011; di Lernia, 2017; Clarke and Brooks, 2018; Barnett, 2019), but which are exceptionally fragile to the elements. Unfortunately, there has been a poor study of direct climate change impacts on rock art across Africa.

Underwater heritage includes shipwrecks and artefacts lost at sea and extends to prehistoric sites, sunken towns and ancient ports that are now submerged due to climatic or geological changes (Spalding, 2011). Off the shores of Africa, about 111 shipwrecks have been documented, with South Africa having a major share of about 41 sites. The sunken Egyptian city of Thonis-Heracleion and its associated 60+ shipwrecks reflect the richness of Africa's waters. Unfortunately, increased storm surges and violent weather currently threaten the integrity of shipwrecks by accelerating the destruction of wooden parts and other features (Harkin et al., 2020). However, climate change impacts on underwater cultural heritage sites are poorly studied, as it requires specialist assessment techniques (Feary et al., 2016), and marine archaeology studies are not well-established in Africa.

Intangible heritage includes instruments, objects, artefacts and cultural spaces associated with communities, and are almost always held orally (UNESCO, 2003). Loss of heritage assets may be a direct consequence of climate change/variability (Markham et al., 2016), or a consequence of indirect factors resulting from climate change, for example, economic instability and poor decision-making in areas of governance. In northern Nigeria, climate change exacerbates the impact of poor land use decisions, reducing the flow of the Yobe River and negatively impacting the Bade fishing festival because the available fish species continue to decline (Oruonye, 2010). Similarly, Lake Sanké in Mali has been degraded by a combination of urban development and poor rainfall, threatening the Sanké mon collective fishing rite (UNESCO, 2018b).

Migration related to climate change and climatic events could offer openings to women and young people to become de facto family heads (Kaag et al., 2019). However, such societal changes also increase community vulnerability to the loss of cultural knowledge held by village elders. For example, in Mauritius, the Sega tambour Chagos music is at risk, as elders familiar with the landscape pass on (Boswell, 2008).

Case study: Traditional earthen 'green energy' buildings

Historically, Africa has had a unique and sustainable architecture (Diop, 2018) characterised by area-specific, traditional earthen materials and associated indigenous technology. Key examples include Tiébélé in Burkina Faso, Walata in Mauritania, Akan in Ghana, Ghadames in Libya, Old Towns of Djenné in Mali (World Heritage Site) and other diverse earthen architecture across sub-Saharan Africa. Adegun and Adedeji (2017) indicate that earthen materials provide advantages in thermal conductivity, resistivity and diffusivity, indoor and outdoor temperature, as well as cooling and heating capacities. Moreover, earthen materials are recyclable and environmentally 'cleaner' (Sanya, 2012) because of the absence or small quantity of cement in production, thus reducing carbon emissions. Despite these advantages, the expertise and socio-cultural ceremonies that accompany building and renewal of earthen architecture are disappearing fast (Adegun and Adedeji, 2017). Further, earthen construction is being threatened by extreme climatic variability and changing climate that exacerbates decay (Brimblecombe et al., 2011; Bosman and Van der Westhuizen, 2014; Brooks et al., 2020).

9.12.2 Projected Risks

Sea level rise and its associated hazards will present increasing climate risk to African heritage in the coming decades (Marzeion and Levermann, 2014; Reimann et al., 2018; Brito and Naia, 2020) (Figure 9.38). Although no continental assessment has quantified climate risk to African heritage and little is known of near term exposure to hazards such as sea level rise and erosion, for a handful of coastal heritage sites included in global or Mediterranean studies, 10 cultural sites are identified to be physically exposed to sea level rise by 2100 at high emissions scenarios (RCP8.5) (Marzeion and Levermann, 2014; Reimann et al., 2018), of which, 7 World Heritage Sites in the Mediterranean are also projected to face medium or high risk of erosion (Reimann et al., 2018) (Figure 9.38). Further, Brito and Naia (2020) identify natural heritage sites across 27 African countries that will be affected by sea level rise by 2100 (RCP8.5), of which 15 sites covering eight countries demonstrated a high need for proactive management actions because of high levels of biodiversity, international conservation relevance and exposure to sea level rise (Figure 9.38). These nascent studies highlight the potential severity of risk and loss and damage from climate change to African heritage, as well as gaps in knowledge of climate risk to African cultural and natural, particularly concerning bio-cultural heritage.

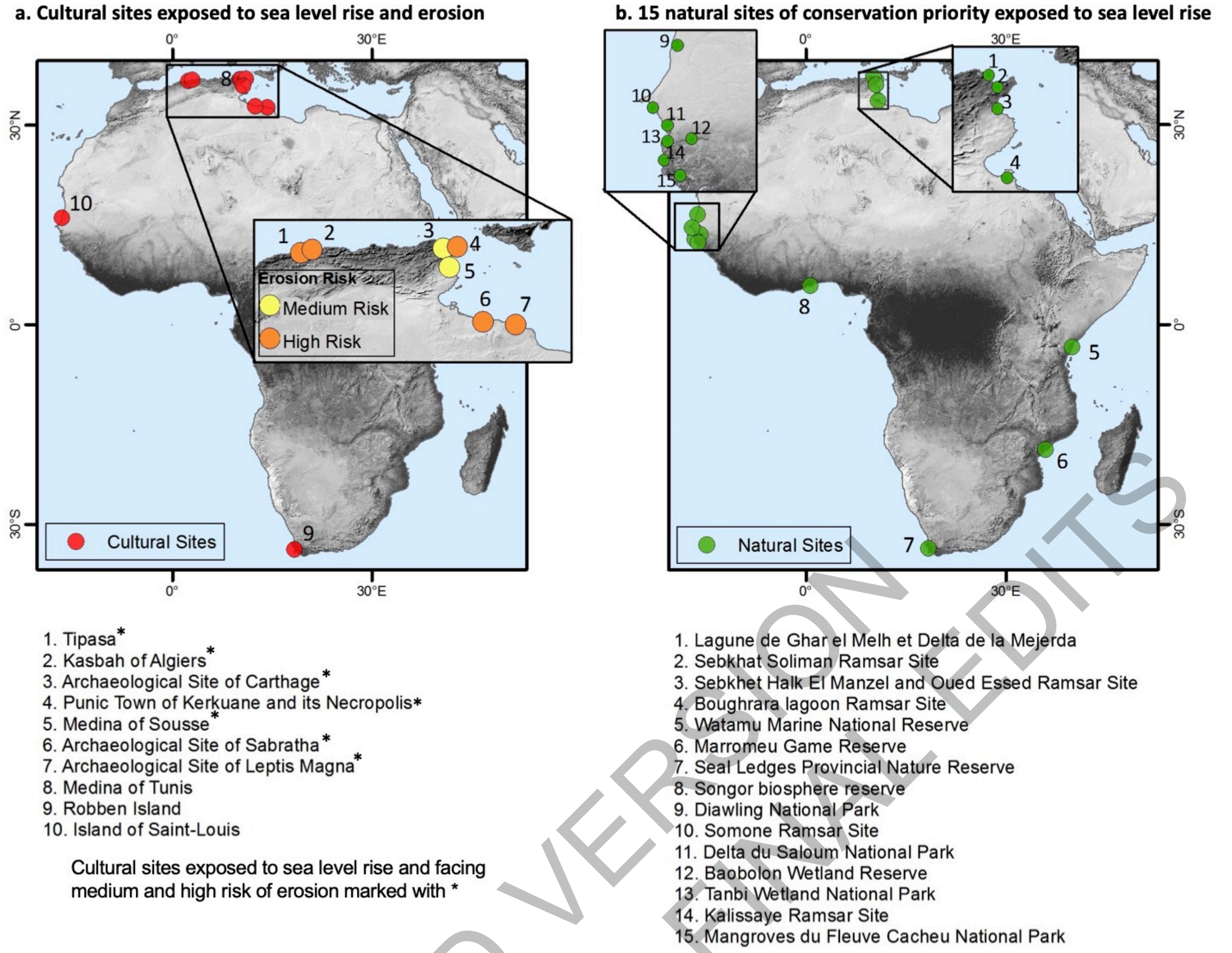

Figure 9.38: Risk to Africa's cultural and natural coastal heritage sites from sea level rise and erosion by 2100 (RCP8.5). Panel (a) Exposed World Heritage sites projected to be affected by sea level rise under a high-end sea level rise scenario (RCP8.5, 2100) (Marzeion and Levermann, 2014; Reimann et al., 2018). Panel a call out) Sites identified to be also exposed to medium and high erosion risk under current and future conditions (2000 and 2100) under a high-end sea level rise scenario (Reimann et al., 2018). Panel (b) The 15 topmost African natural sites (coastal protected areas) identified to be exposed to negative impacts from sea level rise and as priority for conservation (Brito and Naia, 2020).

Although climate change is a significant risk to heritage sites (Brito and Naia, 2020), there is little research on how heritage management is adapting to climate change, and particularly, whether the capacity of current heritage management systems can prepare for and deal with consequences of climate change (Phillips, 2015) (see also Cross-Chapter Box SLR in Chapter 3).

Worsening climate impacts are cumulative and often exacerbate the vulnerability of cultural heritage sites to other existing risks, including conflict, terrorism, poverty, invasive species, competition for natural resources and pollution (Markham et al., 2016). These issues may affect a broad range of tourism segments, including beach vacation sites, safari tourism, cultural tourism and visits to historic cities (UNWTO, 2008). Climate change impacts have the potential to increase tourist safety concerns, especially at sites where increased intensity of extreme weather events or vulnerability to floods and landslides are projected (Markham et al., 2016) (see also Cross-Chapter Box EXTREMES in Chapter 2). There may also be circumstances where interventions required to preserve and protect the resource alter its cultural significance (van Wyk, 2017).

9.12.3 Adaptation

Research highlights potential in integrating indigenous knowledge, land use practices, scientific knowledge and heritage values to co-produce tools that refine our understanding of climate change and variability and develop comprehensive heritage adaptation policy (Ekblom et al., 2019) (Table 9.13).

Table 9.13: Examples of responses to climate change impacts to heritage sites.

Heritage	Type	Example		Type of Climate Impact	Intervention Focus or Activity	Main Intervention Activity	State of Materials	Final State of Heritage	Literature
Tangible	Ancient	Historic buildings	Ounga Byzantine Fort and associated archaeological remains, Tunisia	Coastal erosion	Archaeological conservation of fort	Building repairs to outer walls of fort but other archaeological areas no intervention	Mixed. Fort is in good condition, but other parts of the site are under threat of coastal erosion, particularly lesser archaeological remains of other periods	Some aspects of site well preserved, other parts damaged	(Slim et al., 2004)
		Archaeological sites	Sabratha, Roman City, Libyan coast	Sea level rise, local flooding and coastal erosion	Monitoring of condition	None	Loss of archaeological remains into the sea	Some aspects of site well preserved, other parts damaged	(Abdalahh, 2011)
	Living	Cities / towns	Lamu Old Town and archipelago, Kenya	Sea Level Rise impacting low lying areas and climate variability impacting protective mangroves	Lamu Old Town managed by National Museums of Kenya the mangrove forests by Community Forest Associations and Forest Conservation and Management Act of 2016. Changes in biodiversity and cultural resilience to climate shocks.	Draft for National Policy for Disaster Management in Kenya	Mangrove forests provide protection from storm surges and coastal erosion. Changing biodiversity of mangroves is threatening mangroves which threaten Lamu Old Town	Continuing deterioration	(Wanderi, 2019)
		Mud buildings	Tiébélé, Burkina Faso	Climate variability causing flooding, erosion.	Local community conservation	Improvements to drainage and land security, development of conservation and management plans.	Current and ongoing conservation	Stable	(Birabi and Nawangwe, 2011)
Bio-cultural		Rock art	Golden Gate Highlands, South Africa	Precipitation and atmospheric changes	Monitoring of condition	No known intervention	Biodeterioration of condition of rock surface	Increasing loss of rock surfaces	(Viles and Cutler, 2012)

			causing luxuriant lichen growth				and images on the rock surfaces	
Intangible (indigenous)	Language	!Xun and Khwe Indigenous Youth of South Africa	Climate variability causing drought and loss of plants	Groups (youth)	Documentation	Non-formal, local	Enhancement, promotion	(Bodunrin, 2019)
		Indigenous Language Use in Agricultural Radio Programming in Nigeria	Climate variability increasing frequency of drought	Farmer groups, communities	Research, documentation	Formal, local	Promotion, transmission	(Adeyeye et al., 2020)
	Rituals	Enkipaata, Eunoto and Olng'esherr Maasai male rites of passage	Climate variability causing drought	Maasai community groups	Identification, documentation, research	Formal, non-formal, local, foreign	promotion	(UNESCO, 2018a)
	Customs & beliefs	Sanké mon fishing festival in Mali	Climate variability reducing rainfall	Malinkés, Bambara and Buwa communities	Identification, documentation, preservation	Formal, non-formal, local	promotion	(UNESCO, 2009)
	Indigenous engineering systems	Water measurers of the Foggara irrigation system in Algeria	Increased siltation and sandstorms Climate variability causing flooding	Touat and Tidikelt communities	Research, identification, documentation	Formal, local	transmission	(Mokadem et al., 2018)
	Arts and crafts	Traditional crafts made from various parts of the Date Palm in Egypt, Mauritania, Morocco, Sudan, Tunisia and other countries outside Africa	Climate variability causing shift in plant habitats	Residents of oases, groups, communities, agricultural cooperative societies	Research, identification, documentation, preservation, protection	Formal, non-formal, local, foreign	Transmission, promotion, enhancement, revitalization	(UNESCO, 2003) (Shabani et al., 2012)

Conservation of heritage may require offsetting the impact of loss through partial or total excavation under certain circumstances, like environment instability, or where *in situ* heritage preservation is exorbitant in cost (Maarleveld and Guérin, 2013).

Although many underwater shipwrecks and ruins of cities are currently preserved better *in situ* than similar sites on land (Feary et al., 2016), preserving such heritage is often financially prohibitive with many physical and technical challenges. Further, skill capacities of heritage agencies are limited to a few qualified archaeologists in Africa (Maarleveld and Guérin, 2013).

For centuries, Africans have drawn on intangible heritage to enhance their resilience to climatic variability and support adaptation practices. For example, pastoralist communities have historically translated their experiences into memories that can be 'translated' into diverse adaptive practices (Oba, 2014). In coastal Kenya, Mijikenda communities rely on indigenous knowledge and practices used in the management of the sacred Kaya Forests to adapt their farming to a changing climate (Wekesa et al., 2015).

Hence, preservation measures for transforming oral information into written records should ensure viability of intangible cultural heritage by giving due consideration to the confidentiality of culturally sensitive information and intellectual property rights (Feary et al., 2016).

Inclusion of cultural landscapes and intangible heritage in the landscape approach at the regional scale development planning processes may have significant impacts on protected area management (Feary et al., 2016). For example, at the Domboshava rock art site in Zimbabwe, all management decisions are taken in direct consultation with traditional leaders and other stakeholders from surrounding communities (Chirikure et al., 2010). Such adaptation strategies promote a more open-minded approach to heritage by leveraging local development (UNESCO, 2018b).

Lack of expertise and resources, together with legislation that privileges certain typologies of heritage, seem to limit implementation of approved policies (Ndoro, 2015). Additionally, cultural heritage has least priority in terms of budgetary allocation, capacity building and inclusion into school curricula. Failure to consider the views of people who attach spiritual significance to places is detrimental to the conservation of heritage places (Bwasiri, 2011). In particular, documented cases of local people having to pay an entrance fee, like tourists, to access burial grounds and places of pilgrimage negate local participation in cultural site management (Ndoro, 2015).

In the long term, heritage managers and local authorities could shift from planning primarily for disaster response and recovery to strategies that focus on disaster preparedness, reducing the vulnerability of sites and strengthening resilience of local communities (UNFCCC, 2007; Domke and Pretzsch, 2016). This could evolve into innovative approaches that integrate community, government and the research sector in productive cultural heritage management partnerships.

There is a need for institutions to establish, maintain and update a comprehensive inventory of underwater cultural heritage. This can be done using non-intrusive, detailed mapping of the wreck site and a 3D model from which scientists can reconstruct the site in detail (Maarleveld and Guérin, 2013).

[START FAQ9.1 HERE]

FAQ 9.1: Which climate hazards impact African livelihoods, economies, health and well-being the most?

Climate extremes, particularly extreme heat, drought, and heavy rainfall events, impact the livelihoods, health, and well-being of millions of Africans. They will also continue to impact African economies, limiting adaptation capacity. Interventions based on resilient infrastructure and technologies can achieve numerous developmental and adaptation co-benefits.

Rainfall impacts African livelihoods and well-being primarily through drought and heavy rainfall events. Drought frequency, duration and intensity is projected to increase in most parts of Africa, but particularly in

West Africa and the Sahel. By 2030, about 250 million people may experience high water stress in Africa, with up to 700 million people displaced as a result. In sub-Saharan Africa, floods are expected to displace an average of 2.7 million people in any given year in the future. Changing rainfall distributions together with warming temperatures will alter the distributions of disease vectors like mosquitoes and midges. Malaria vector hotspots and prevalence are projected to increase in East and southern Africa and the Sahel under RCP4.5 by the 2030s, exposing an additional 50.6–62.1 million people to malaria risk.

Increases in the number of hot days and nights, as well as in heatwave intensity and duration, have had negative impacts on agriculture, human health, water availability, energy demand and livelihoods. By some estimates, African countries' GDP per capita is on average 13.6% lower since 1991 than if anthropogenic warming had not occurred. In the future, high temperatures combined with high humidity exceed the threshold for human and livestock tolerance over larger parts of Africa and with greater frequency. Increased average temperatures and lower rainfall will further reduce economic output and growth in Africa, with larger negative impacts than on other regions of the world.

Resilient infrastructure and technologies are required to cope with the increasing climate variability and change (Figure FAQ 9.1). These include improving housing to limit heat and exposure, along with improving water and sanitation infrastructure. Such interventions to ensure that the most vulnerable are properly protected from climate change have many co-benefits, including for pandemic recovery and prevention.

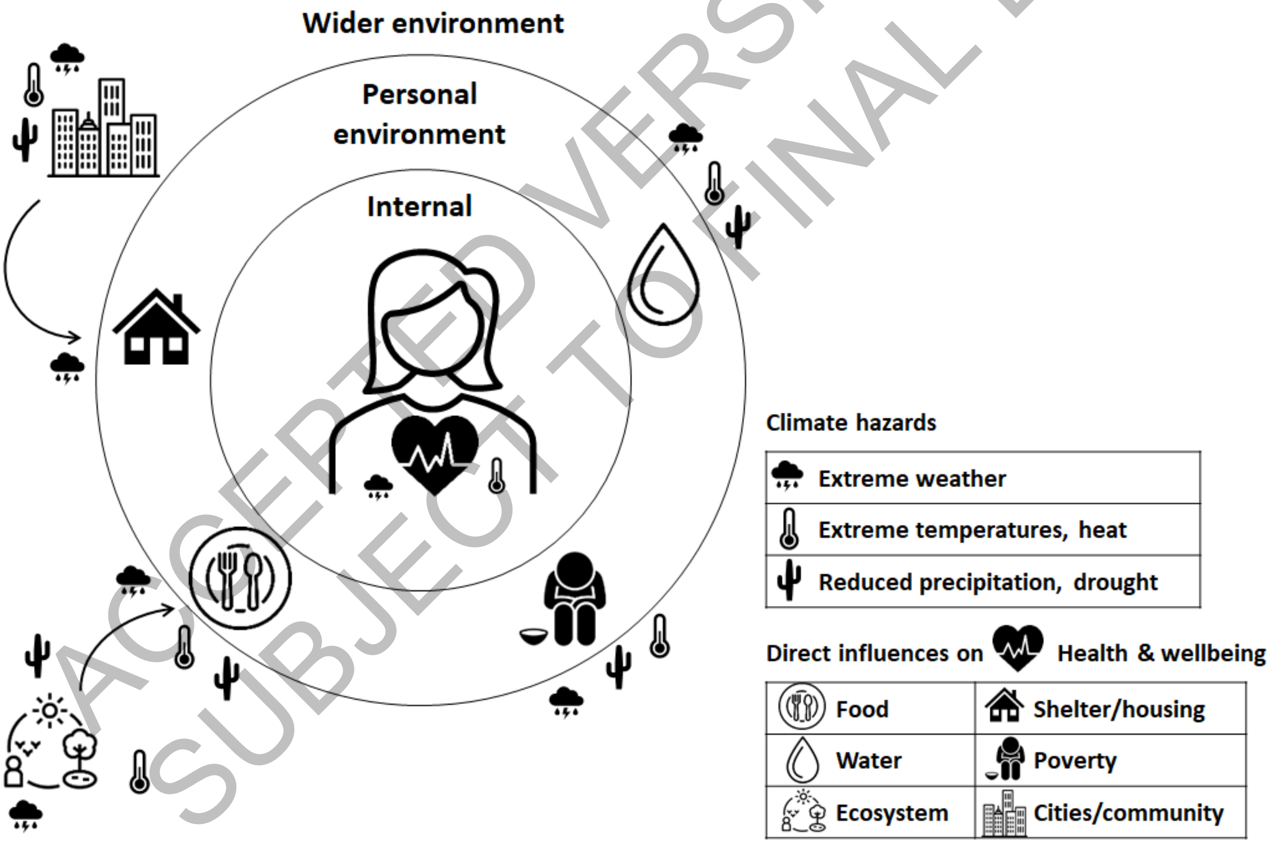

Figure FAQ9.1.1: A schematic illustration of the interconnectedness of different sectors and impacts that spillover to affect the health and well-being of African people.

[END FAQ9.1 HERE]

[START FAQ9.2 HERE]

FAQ9.2: What are the limits and benefits of climate change adaptation in Africa?

The capacity for African ecosystems to adapt to changing environmental conditions is limited by a range of factors, from heat tolerance to land availability. Adaptation across human settlements and food systems are further constrained by insufficient planning and affordability. Integrated development planning and increasing finance flows can improve African climate change adaptation.

Many species will lose all suitable habitats due to increases in temperature by 2100. Coupled with projected losses of Africa's protected areas, higher temperatures will also reduce carbon sinks and other ecosystem services. Many nature-based adaptation measures (e.g., for coral reefs, mangroves, marshes) are no longer effective at 1.5ºC of global warming. Human-based adaptation strategies for ecosystems reach their limits as availability and affordability of land decreases, resulting in migration, displacement and relocation.

The limits to adaptation for human settlements arise largely from developmental challenges associated with Africa's rapid urbanisation, poor development planning, and increasing numbers of urban poor residing in informal settlements. Further limits arise from insufficient consideration of climate change in adaptation planning and infrastructure investment and insufficient financial resources. There are also limits to adaptation for food production strategies. Increasing climate events – droughts and floods – impose specific adaptation responses which poorer households cannot afford. For instance, the use of early-maturing or drought-tolerant crop varieties may increase resilience, but adoption by smallholder farmers is hindered by the unavailability or unaffordability of seed.

Adaptation in Africa can reduce risks at current levels of global warming. However, there is very limited evidence for the effectiveness of current adaptation at increased global warming levels. Ambitious, near-term mitigation would yield the largest single contribution to successful adaptation in Africa.

Current adaptation finance flows are billions of USD less than the needs of African countries and around half of finance commitments to Africa reported by developed countries remain undisbursed. Increasing adaptation finance flows by billions of dollars (including public and private sources), removing barriers to accessing finance and providing targeted country support can improve climate change adaptation across Africa.

[END FAQ9.2 HERE]

[START FAQ9.3 HERE]

FAQ 9.3: How can African countries secure enough food in changing climate conditions for their growing populations?

Climate change is already impacting African food systems and will worsen food insecurity in sub-Saharan Africa in the future. An integrated approach to adaptation planning can serve as a flexible and cost-effective solution for addressing African food security challenges.

Maize and wheat yields have decreased on average 5.8% and 2.3%, respectively, in Sub-Saharan Africa due to climate change. Among the 135 million acutely food-insecure people in crisis globally, more than half (73 million) are in Africa. This is partly due to the growing severity of drought. Adding to these challenges, Africa has the fastest-growing population in the world. Its population is expected to increase by roughly 50% over the next fifteen years, growing from 1.2 billion people to over 1.8 billion by 2035.

Sustainable agricultural development combined with enabling institutional conditions, such as supportive governance systems and policy, can provide farmers with greater yield stability in uncertain climate conditions. It is also widely acknowledged that an integrated approach for adaptation planning that combines (i) emerging Climate Information Services, (ii) capacity building, (iii) local and indigenous knowledge systems and (iv) strategic financial investment can serve as a flexible and cost-effective solution for addressing African food security challenges (Section 9.4.1.2; Box 9.2).

[END FAQ9.3 HERE]

[START FAQ9.4 HERE]

FAQ9.4: How can African local knowledge serve climate adaptation planning more effectively?

A strong relationship between scientific knowledge and local knowledge is desirable, especially in developing contexts where technology for prediction and modelling is least accessible.

In many African settings, farmers use the local knowledge gained over time – through experience and passed on orally from generation to generation – to cope with climate challenges. Indigenous knowledge systems of weather and climate patterns include early warning systems, agroecological farming systems and observation of natural or non-natural climate indicators. For instance, biodiversity and crop diversification are used as a buffer against environmental challenges: if one crop fails, another will survive. Local knowledge of seasons, storms, and wind patterns is used to guide and plan farming and other activities.

Collaborative partnerships between research, agricultural extension services and local communities would create new avenues for the co-production of knowledge in climate change adaptation to better inform adaptation policies and practices across Africa (Section 9.4.3; Box 9.2).

[END FAQ9.4 HERE]

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