



**United Nations**  
Convention to Combat  
Desertification

# The Global Threat of Drying Lands:

Regional and global  
aridity trends and future  
projections

A Report of the Science-Policy Interface



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# **The Global Threat of Drying Lands:** Regional and global aridity trends and future projections

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# Foreword

Most of the world's land—more than three-quarters—has become permanently dryer in recent decades. A combined global area equal to half the size of Australia has transformed from humid lands to drylands with less rain for crops, pastures, nature and people. These stark statistics are among the many grim revelations from new analyses revealed in this groundbreaking report. For the first time, scientists within UNCCD Science-Policy Interface have clearly documented current and future drying trends and impacts that reveal a global, existential peril previously shrouded by a fog of scientific uncertainty. Its name is aridity—the climatic and enduring condition of too little life-supporting moisture—and its effects threaten the lives and livelihoods of billions across almost every region of the globe.

Since the launch of this Convention 30 years ago, world nations have battled the growing loss of productive, fertile land by championing better, more sustainable land use and by preparing for and responding to droughts. Droughts happen when the rain doesn't fall or falls too little for extended but nevertheless limited periods. Water scarcity happens when human land and water use decisions exceed water supply. Global warming is making droughts worse and more frequent, and they can be devastating. Between 2007 and 2017, droughts affected more than 1.5 billion people globally and cost \$125 billion. Yet, droughts end, and recovery is possible.

Rising aridity is different—it is an unrelenting menace that requires lasting adaptation measures. The drier climates now affecting vast regions across the globe will not return to how they were. Today, a quarter of the global population lives in the planet's expanding drylands. Aridity projections suggest that as many as 5 billion people could inhabit drylands by the end of the century. All are, or will be, at risk of desertification—the alarming degradation of land, where water is limited, that can leave people hungry or dehydrated and ecosystems entirely transformed. Human-caused climate change is the culprit; known for making the planet warmer, it is also making more and more land drier. The result is poor soil fertility, crop losses, biodiversity declines, intense sand and dust storms frequent wildfires and, of course, greater food and water insecurity. Aridity-related water scarcity is causing illness and death and spurring large-scale forced migration around the world.

For years, rigorously documenting aridity's rise was challenging and controversial. Its long-term nature and the complexity of aridity-determining processes—rainfall, evaporation and plant transpiration, among others—led to conflicting results and an abundance of scientific caution. These concerns are addressed in this report, and the authors' clear-eyed approach finally brings aridity's inexorable rise out into the open. This clarity is critical if global nations hope to track aridity's changes and develop policies and approaches for slowing its climb, lessening its impacts and adapting to a perennially drier landscape.

The timeliness of this report—and the guidance it provides to UNCCD country Parties—can't be overstated: It reveals rising aridity as yet another great environmental challenge of our age. This publication is an important step in understanding the scale and nature of the problem, presenting ways to mitigate and adapt to the challenge.



I want to thank the UNCCD Science-Policy Interface team for their extraordinary work. Their report does more than ring an alarm that cannot be ignored—it sounds a clarion call to global action on aridity, now and in the future.

**Ibrahim Thiaw**

Executive Secretary

United Nations Convention  
to Combat Desertification



# Executive Summary

Understanding aridity and its consequences for ecosystems and societies is critical in today's changing climate. Aridity—the relative, long-term lack of available, life-sustaining moisture in terrestrial climates—significantly affects land degradation, desertification and the overall resilience of ecosystems and human communities. Aridity-related land degradation and water scarcity have been linked to food and water insecurity, poor soil fertility, losses in crop and plant productivity, biodiversity declines, ecosystem degradation, intense sand and dust storms, wildfires, poor health and large-scale human migration. Human-caused climate change, meanwhile, is a main culprit for changing aridity around the world.

Assessing aridity trends and future projections can help to develop resilient adaptation and mitigation strategies in the face of climate change. This report addresses the challenges in assessing aridity and provides a novel and thorough assessment of aridity's current and future trends—including aridity's multifaceted and often cascading impacts—using new analyses and an up-to-date literature review. The report underscores the importance of adopting a widely accepted climatic approach based on the aridity index (AI)—a measure of aridity that uses the ratio of precipitation to potential evapotranspiration over the medium to long term—and highlights the importance of distinguishing the long-term, climatic condition of aridity from the short-term, anomalous periods of water shortage known as droughts.

The report finds that rising aridity is threatening people and environments in almost every global region. More than three-quarters of all land on Earth experienced a drier climate during the three decades leading up to 2020, compared to the previous 30-year period, and global drylands expanded by about 4.3 million km<sup>2</sup>—an area equal to half the size of the continent of Australia/Oceania—to cover more than 40 per cent of global land (excluding Antarctica). If the world fails in efforts to curb greenhouse gas emissions, another 3 per cent of the world's humid areas are projected to transform into drylands by the end of this century.

Meanwhile, people living in drylands have doubled in number—to 2.3 billion, more than a quarter of the global population—over the past three decades, and models suggest as many as 5 billion could inhabit drylands by 2100 in a worst-case climate change scenario. These billions of people face even greater threats to their lives and livelihoods from climate-related increases in aridification and desertification.

This report argues that sustainable adaptation measures are crucial to address the escalating challenges of climate change and aridity. Alongside ongoing mitigation efforts, these measures range from broad, large-scale initiatives that deliver multiple co-benefits to more localized approaches focused on marginalized, under-resourced, under-represented, vulnerable and involuntarily immobile communities. The report argues for sectoral adaptation approaches linked to sustainable agriculture and water management, as well as for education, awareness and governance of aridity and aridity responses. Proposed actions for policymakers present a multifaceted approach advocating for enhanced monitoring, sustainable adaptation practices, evidence-based planning and effective strategies for adapting to irreversible land degradation.

The report highlights effective and sustainable adaptation practices for aridity, together with recommendations for comprehensive monitoring and reporting frameworks, integrated sectoral plans, capacity-building programmes and policy incentives linked to performance

indicators. Governance frameworks for responding to aridity, based on multiscale and multisectoral partnerships, are suggested to enhance public awareness, resilience, capacity-building and technology use for risk reduction and aridity adaptation, fostering international collaboration and alignment with existing initiatives.

### The Role of UNCCD

In the face of growing challenges from rising aridity, the role of the United Nations Convention to Combat Desertification (UNCCD) in implementing measures to assess, monitor and guide aridity adaptation strategies is becoming increasingly critical. The UNCCD's expertise and global network are needed to address the intricate dynamics behind aridity and the expansion of global drylands and to foster a coordinated approach towards sustainable land management and desertification mitigation. The UNCCD advocates for the integration of traditional and local knowledge with contemporary scientific insights and private-sector knowledge to ensure that adaptation measures are grounded in local realities while benefiting from global advancements. The UNCCD emphasizes the importance of reliable data and cooperation across regions and sectors in shaping policy decisions and guiding international efforts towards climate and aridity resilience. The UNCCD's strategic guidance in implementing adaptive measures can inspire actionable solutions that address the multifaceted impacts of aridification on ecosystems and societies, paving the way for a future in which communities are better equipped to adapt to the changing landscape of our planet.

# Abbreviations

<b>AED</b>	Atmospheric Evaporative Demand
<b>AI</b>	Aridity Index
<b>CMIP</b>	Coupled Model Intercomparison Project
<b>CIS</b>	Climate Information Service
<b>CST</b>	Committee on Science and Technology
<b>ESM</b>	Earth System Model
<b>ET</b>	Evapotranspiration
<b>FAO</b>	Food and Agriculture Organization of the United Nations
<b>GWL</b>	Global Warming Level
<b>GCM</b>	General (or Global) Circulation Model
<b>GDP</b>	Gross Domestic Product
<b>IDMP</b>	Integrated Drought Management Programme
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>LAC</b>	Latin America and the Caribbean
<b>LD</b>	Land Degradation
<b>LDN</b>	Land Degradation Neutrality
<b>MAR</b>	Managed Aquifer Recharge
<b>MENA</b>	Middle East and North Africa
<b>PET</b>	Potential Evapotranspiration
<b>RCP</b>	Representative Concentration Pathways
<b>SLM</b>	Sustainable Land Management
<b>SDGs</b>	Sustainable Development Goals
<b>SDS</b>	Sand and Dust Storm
<b>SPI</b>	Science-Policy Interface
<b>SRES</b>	Special Report Emissions Scenarios
<b>SSA</b>	Sub-Saharan Africa
<b>SSP</b>	Shared Socioeconomic Pathway
<b>UNCCD</b>	United Nations Convention to Combat Desertification
<b>UNEP</b>	United Nations Environment Programme
<b>VPD</b>	Vapour Pressure Deficit
<b>WAD</b>	World Atlas of Desertification
<b>WMO</b>	World Meteorological Organization

# Glossary

**Adaptation:** The process of adjusting to current and expected climate change and associated impacts. In human systems, adaptation seeks to reduce or avoid harm as well as to exploit opportunities that may emerge. In some natural systems, human intervention may facilitate adjustment to expected climate change and its effects (UNCCD, 2024).

**Aridity:** A climatic condition characterized by a significant deficiency of moisture, typically measured by a low ratio of long-term average precipitation to atmospheric evaporative demand. This results in drylands with limited water availability.

**Aridification:** The long-term process that can lead to shifts from non-drylands to drylands or from one aridity class to a drier aridity class and can cause systemic and abrupt changes in multiple ecosystem attributes.

**Desertification:** Land degradation in non-desert drylands (i.e., arid, semi-arid and dry subhumid areas) resulting from many factors, including climatic variation and human activities (UNCCD, 1994).

**Drylands:** Drylands are defined using the aridity index (AI) and include areas classed as hyperarid, arid, semi-arid, and dry subhumid. The AI is calculated by dividing mean precipitation by potential evapotranspiration. Drylands have an AI of 0.65 or lower, meaning that potential evapotranspiration is at least 45 per cent greater than actual mean precipitation (UNCCD, 1994).

**Enabling conditions:** Conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strong policy instruments, institutional capacity, multilevel governance and changes in human behaviour and lifestyles (IPCC, 2022).

**Land degradation:** The reduction or loss of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland or range, pasture, forest and woodlands, resulting from a combination of pressures, including land-use, land-cover and management practices (UNCCD, 2024).

**Impacts:** The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services) and infrastructure. Impacts may be referred to as consequences or outcomes and can be adverse or beneficial (IPCC, 2022).

**Resilience:** The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning. It includes the capacity for self-organization and the capacity to adapt to stress and change (UNCCD, 2024).

**Risk:** The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems (IPCC, 2022).



**Vulnerability:** Conditions determined by physical, social, economic and environmental factors or processes that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards, such as drought. Hence, vulnerability is an inherent property of a system that exists independently of the external hazard (i.e., the same level of hazard may impose different consequences for different individuals, communities, countries, regions and other systems due to the distinct underlying vulnerabilities of these systems). In turn, vulnerability to a hazard and its impacts can be altered by the actions of society, such as land and water management practices, among others (UNCCD, 2024).

# Key Messages

More than three-quarters of all land on Earth experienced a drier climate during the three decades leading up to 2020, compared to the previous 30-year period.

Global drylands—areas in which precipitation is less than 65 per cent of atmospheric evaporative demand—expanded by about 4.3 million km<sup>2</sup>, an area equal to about half the size of the continent of Australia/Oceania. Drylands now cover almost 41 per cent of global lands (excluding Antarctica).

Much of aridity's recent rise can be attributed to human-caused climate change. If the world fails in efforts to curb greenhouse gas emissions into the future, another 3 per cent of the world's humid areas are projected to transform into drylands by the end of this century.

People living in drylands have doubled in number in recent decades to 2.3 billion in 2020, up from 1.2 billion 30 years earlier. That is, those living in drylands comprised almost a third of all people on Earth (30.9 per cent) in 2020, compared to just over a fifth (22.5 per cent) in 1990.

About half of the world's dryland inhabitants are found in Asia and Africa. The most densely populated drylands are in California, Egypt, eastern and northern Pakistan, large parts of India and north-eastern China.

Climate models suggest as many as 5 billion people could inhabit drylands by 2100 in a worst-case climate change scenario characterized by regional rivalries. Dryland inhabitants in this scenario would more than double the current number and would mean two in every five people on the planet live in drylands.

Hotspots showing significant dryland expansion include the western United States, the Yucatan Peninsula, north-eastern Brazil, north-western Argentina, the entire Mediterranean region, the northern side of the Black Sea, the Sahel, the Rift Valley, north-eastern South Africa, the bordering area between Russia and Kazakhstan, large parts of Mongolia and north-eastern China and south-eastern Australia.

Human-made greenhouse gas emissions have played a key role in the expansion of drylands, especially over the past three decades, according to climate simulations that show a pronounced global drying trend beginning in the 1950s and accelerating from the 1990s.

Impacts from increasing aridification coupled with anthropogenic processes, lead to land degradation (and desertification) and water scarcity. These, in turn, can trigger cascading effects among many associated negative environmental and socioeconomic consequences, including food and water insecurity, poor soil fertility, losses in crop and plant productivity, biodiversity declines, ecosystem degradation, intense sand and dust storms, wildfires, poor health and large-scale human migration.

More than a fifth of all land could experience abrupt ecosystem transformations in response to rising aridity by the end of the century, according to recent projections.

Increasing aridity is expected to play a role in larger and more intense wildfires in the climate-altered future—not least because of its impacts on tree deaths in semi-arid forests and the consequent growing availability of dry biomass for burning. Europe is likely to be especially affected.

More than two thirds of all land on the planet (excluding Greenland and Antarctica) is projected to store less water by the end of the century, if greenhouse gas emissions continue to rise even modestly.

Aridity is considered the world's largest single driver behind the degradation of agricultural systems, affecting 40 per cent of Earth's arable lands.

Rising aridity has been blamed for a 12 per cent decline in gross domestic product (GDP) recorded for African countries between 1990–2015.

Rising aridity's impacts on poverty, water scarcity, land degradation and insufficient food production have been linked to increasing rates of sickness and death—especially among children and women around the world.

Rising aridity and drought play a key role in increasing human migration around the world—particularly in the hyperarid and arid areas of southern Europe, the Middle East and North Africa and southern Asia.

Quantifying future socioeconomic impacts can enhance equitable societal resilience. While some successful local and regional adaptation measures exist, transformational approaches are needed that blend traditional and local knowledge with evolving, up-to-date scientific understanding.

Stakeholder engagement is crucial to enhance resilience to aridity, requiring sufficient financial resources, governance structures, partnerships, capacity-building initiatives, evaluation and learning, along with robust monitoring mechanisms.

Aridity-driven desertification—the degradation of land and terrestrial ecosystems in non-desert drylands—can result in a cascade of potentially devastating environmental and socioeconomic consequences.

While many aridification impacts in the world's drylands are expected to intensify and expand to new areas in the climate-altered future, a better quantification of future socioeconomic impacts is needed to plan and implement adaptation measures that increase the resilience of vulnerable people.

Many poor, rural dryland populations have historically implemented sustainable practices to adapt their agriculture and pastoral activities to aridity, but intensifying aridification and the expansion of global drylands in the future will require transformational approaches that combine traditional knowledge with evolving scientific understanding and technical solutions.

Stakeholder engagement—supported by sufficient financial resources, governance structures and partnerships, capacity-building initiatives and robust monitoring and reporting mechanisms—is needed to promote an enabling environment to significantly enhance the resilience of societies to climate aridification.

## Key Messages

Access to aridity information is essential for governments and institutions to address aridity's impacts and to develop better adaptation tools.

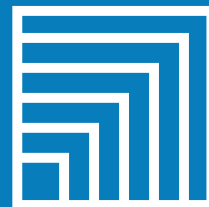
Information generated for this report has been included in an Aridity Visual Information Tool, available at <https://global-aridity-monitoring-system.csic.es>. The tool features the global spatial distribution of the average aridity index (AI)—the aridity indicator used in this report based on the ratio of precipitation to potential evapotranspiration over the medium to long term—and various aridity classes across two time periods (1961–1990 and 1991–2020).

The tool also includes aridity projections for 2100 based on two different emissions scenarios (SSP1-2.6 and SSP5-8.5) and highlights the uncertainties in these projections. It provides a monitoring feature that updates the AI annually, using data from the past five years.

The tool helps assess long-term changes in aridity by filtering out high-frequency climate variability, which is more closely related to drought events. All data within the system can be downloaded in various gridded formats or as time series.

The Aridity Visual Information Tool is also linked to the UNCCD Knowledge-Sharing Systems search tool (<https://www.unccd.int/resources/knowledge-sharing-systems>), which provides highly relevant information for assessing aridity at local to global scales and for developing socioeconomic and environmental aridity mitigation and adaptation efforts.





# Chapter 1.

# INTRODUCTION

## 1.1. JUSTIFICATION, OBJECTIVES AND STRUCTURE OF THE REPORT

The primary objective of this technical report is to better understand the current and future changes in aridity around the world, including their impacts for affected populations, and to identify the best adaptation approaches to mitigate consequent risks to global environmental, social and economic processes and systems. The report is intended to contribute to the realization of Objective 2 outlined in the UNCCD Science-Policy Interface (SPI) Work Programme for 2022–2024. This objective aims to advance understanding by the “Provision of science-based evidence on the historical regional and global aridity trends and projections” (UNCCD Decision 18/COP.15).

This report marks a pioneering effort, serving as the first review, analysis and assessment of aridity trends undertaken for the UNCCD and its country Parties. The overarching purpose is to provide valuable insights into the socioeconomic and environmental implications of aridity for national and international governments and organizations. The report provides projected impact scenarios and explores potential mitigation, prevention and adaptation practices. Its target audience includes policymakers, managers and specialists for land- and water-use planning, as well as a broader community of stakeholders concerned with aridity within the context of climate change.

Motivating this initiative is the absence of prior assessments grounded in robust

scientific evidence on current aridity trends and future projections. The report addresses this gap by establishing a connection between aridity trends and prevailing societal and ecological vulnerabilities and by laying a foundation for understanding and implementing adaptation practices to effectively mitigate aridification processes in a changing world.

The report is organized into five comprehensive chapters, each one addressing distinct facets of aridity. In Chapter 1, the foundational concepts used in the report are laid out, along with the overarching justification, objectives and structure. This chapter explains existing concepts and definitions related to aridity, clarifying the distinction between aridity and other critical concepts, such as water scarcity and drought. Importantly, the general methodology applied in the study is also described within this chapter, with a clear explanation of the use of the aridity index (AI) as the most parsimonious, useful and readily comparable metric for assessing current and future aridity trends in this report. Chapter 2 describes the results of an assessment of current and future regional and global changes in aridity. The chapter details recent trends and an evaluation of the attribution of aridity changes to climate shifts. The chapter then provides aridity projections for the climate-altered future. Chapter 3 includes an examination of the current and future impacts of climate-

related aridity changes on socioeconomic and environmental processes, offering a forward-looking perspective on potential challenges and vulnerabilities. Chapter 4 describes current aridity adaptation practices and future approaches. It outlines factors contributing to the increased vulnerability of societies and environments to aridity, evaluates the merits of transformational adaptation versus incremental adaptation, explores existing regional-scale sectoral adaptation approaches and identifies the

enabling conditions necessary for successful adaptation strategies. The concluding Chapter 5 synthesizes the findings from the preceding chapters, offering insightful recommendations and highlighting necessary actions. It serves as a crucial guide, distilling the wealth of information presented in the report into practical steps and measures that can inform decision makers and stakeholders in navigating the complex processes of aridity and climate change adaptation.

## 1.2. CONCEPTS AND DEFINITIONS

### Aridity versus drought and water scarcity

Aridity refers to a climatic condition that can be characterized by the amount of available moisture to support life. Drought, by contrast, is defined as an exceptional period of water shortage for existing ecosystems and human populations, often attributed to low rainfall, high temperatures and/or wind (IPCC, 2021). Drought is temporary, in contrast to the permanent climate features associated with aridity. Drought is often considered as abnormally dry weather with a sufficiently prolonged lack of precipitation causing a serious hydrological imbalance. Drought is recognized as part of natural climate variability, although human factors can act as amplifiers, and is capable of occurring in virtually any climatic regime, including both high and low rainfall areas.

Water scarcity is an additional concept different from drought and aridity. Water scarcity is predominantly centred on the availability and use of water resources and is characterized as “a gap between available supply of and expressed demand for freshwater in a specified domain, under prevailing institutional arrangements (including both resource pricing and retail charging arrangements) and infrastructural

conditions, always involving a human dimension to the reduction in the natural water supply” (IDMP, 2022, p. 4). The primary driver of water scarcity is typically a human-induced increase in water demand in relation to available water. The severity of water scarcity is influenced by water resource management strategies and practices, often exacerbated by the long-term overuse and misuse of water resources.

In contrast to these two concepts, aridity refers to an average long-term condition that is not a departure from the norm, as in the case of drought. Aridity is primarily related to natural factors, reflecting the baseline climatic characteristics of a region, while water scarcity reflects the significant consequences of human actions driven by increased demand and often influenced by water mismanagement.

### Aridity and “drylands”

The concept of aridity has changed with advances in scientific comprehension and shifts in societal perspectives, but its key elements remain the same. These elements tie aridity predominantly to a climatic condition characterized by low precipitation and high atmospheric evaporative demand

(AED). AED is the drying power of the atmosphere, which is typically linked to warmer temperatures, as well as to available radiation, air humidity and wind speed. AED is typically measured using potential evapotranspiration (PET), which is the amount of water that would be evaporated and transpired (by plants) in an area given enough available water. The term “drylands” refers to areas where the amount of rain is less than 65 per cent of what could be potentially evaporated. Drylands include four classes of aridity situated along an aridity continuum, including hyperarid, arid, semi-arid and dry subhumid areas.

In past scientific assessments, regions of the world were often evaluated as either arid or non-arid based on the climatic parameters of precipitation and temperature. A prime example of this approach is the Köppen-Geiger climate classification developed at the end of the 19th century and updated at the onset of the 21<sup>st</sup> century (Beck and others, 2018). Today, this climate perspective continues to inform the most widely understood scientific concept of aridity. For instance, the glossary of the most recent report of the Intergovernmental Panel on Climate Change (IPCC) defines aridity as “the state of a long-term climatic feature characterized by low average precipitation or available water in a region. Aridity generally arises from widespread persistent atmospheric subsidence or anticyclonic conditions and from more localised subsidence in the lee side of mountains” (IPCC, 2021). Similarly, the American Meteorological Society emphasizes the climatic aspects of aridity by describing it as “the degree to which a climate lacks effective, life-promoting moisture” (<https://glossary.ametsoc.org/>). Soil conditions are also considered important as high soil permeability may modulate aridity by favouring rainfall infiltration and soil drying.

Regions of high aridity exhibit pronounced and persistent negative values in the difference between precipitation and AED

(i.e., AED quantities surpass precipitation amounts), with the degree of arid conditions intensifying as this deficit increases. In global drylands, the annual average AED surpasses the annual average precipitation by several hundred millimetres. This excess AED does not equate to the evaporation of all demanded water. Instead, it primarily reflects the limited availability of accessible water in soil and water reservoirs. Therefore, the apparent demand for water by the atmosphere in these arid areas exceeds the actual amount that can be evaporated based on the available water resources.

While precipitation stands as the foremost driver of aridity on a global scale, elevated AED plays a pivotal role in intensifying aridity conditions through two primary mechanisms:

- i) **Increased water evaporation and transpiration:** High AED amplifies water evaporation and sublimation from the soil and transpiration from plants. The impact of evaporation is significant, with an estimated 90 per cent of rainfall in world drylands evaporating back into the atmosphere, leaving a mere 10 per cent available for productive transpiration (Koohafkan and Stewart, 2008).
- ii) **Plant water stress:** Independent of the amount of water evaporated, heightened AED exacerbates plant water stress by enlarging the disparity between water available for evaporation and atmospheric water demand. This phenomenon influences plant hydraulics and may lead to plant mortality (Anderegg and others, 2018). Notably, in regions with low precipitation worldwide, variations in AED are decisive factors influencing differences in aridity conditions (Vicente-Serrano and others, 2020). These factors are crucial for comprehending aridity trends within projected climate change scenarios.

In regions characterized by low precipitation, the interplay between low

evaporation and alterations in the partition between sensible and latent heat fluxes (Berg and others, 2016) is responsible for the connection between low precipitation and high AED. This connection explains why world drylands experience more

pronounced warming in response to enhanced anthropogenic forcing (Huang and others, 2017a). The complex relationship between precipitation and AED shapes aridity patterns, especially in the context of ongoing climate change.

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### Box 1. Rising CO<sub>2</sub> and its impacts on aridity

Rising atmospheric CO<sub>2</sub> caused by emissions from human fossil fuel use is recognized as a key driver of climate change. Climbing CO<sub>2</sub> concentrations, however, have a complicated relationship with aridity.

While more CO<sub>2</sub> increases temperatures and influences the global climate system (IPCC, 2021) to affect aridity, it also exerts biophysiological effects (Toreti and others, 2020), such as changing leaf stomatal conductance and plant water-use efficiency (Brodrribb and McAdam, 2017), to alter photosynthetic activity (Ainsworth and Rogers, 2007; Dubey and Ghosh, 2023) and affect overall plant growth (Keenan and others, 2023). The interplay of these hydroclimatic and physiological mechanisms underscores the complexity of the influence of greenhouse gas emissions on aridity.

While Earth System Model (ESM) simulations—used to simulate climatic, ecological and hydrological variables for future scenarios—project significant future climate-affected reductions in precipitation over large regions and increased AED (due to higher temperatures and decreased relative humidity), most do not suggest projected changes in aridity. Instead, these models project a widespread increase in net primary production and leaf area as a result of i) enhanced photosynthesis from higher CO<sub>2</sub> concentrations (Zhao and others, 2020) and ii) no substantial change in surface water availability (i.e., soil moisture and run-off; Yang and others, 2019) attributed, in general, to lower water demand by plants (Lemordant and others, 2018; Swann and others, 2016). These two biophysical responses help explain why certain studies (relying on the outputs of ESMs) do not support an increase in aridity in future projections (Greve and others, 2017; Roderick and others, 2015).

However, incomplete knowledge of the biophysiological impacts of atmospheric CO<sub>2</sub>—including uncertainties affecting these processes (e.g., those linked to the interplay of climate extremes), their nonlinear responses to varying CO<sub>2</sub> concentrations and the potential for acclimation (Toreti and others, 2020)—make the effects of CO<sub>2</sub> in future scenarios difficult to project.

Three factors, in particular, are important. First, models have trouble accurately representing the diversity of leaf stomatal conductance and its CO<sub>2</sub> response among different species and forest ages (Körner and others, 2005). Considering the entire plant hydraulic system, not just leaf stomatal conductance, is widely considered essential for determining vegetation responses to aridity under conditions of elevated atmospheric CO<sub>2</sub> (Liu and others, 2020a). Second, atmospheric CO<sub>2</sub> also influences plant morphology, phenology and biomass allocation (as well as stomatal conductance), enhancing leaf area (Mankin and others, 2019) and extending periods during which plants can transpire and consume water. Third, the reduction in leaf stomatal conductance from increased CO<sub>2</sub> is expected to coincide with CO<sub>2</sub>-related warming, ensuring the water-saving effects of the physiological response may not compensate for enhanced water losses caused by increased atmospheric demand. Thus, both factors cannot be easily separated when determining future water evaporation (Vicente-Serrano and others, 2022).



Projected increases in plant mortality from heat and drought (McDowell and others, 2016; Williams and others, 2013) and uncertainties in land management by people introduce additional complexities and uncertainties to the role of CO<sub>2</sub> in future aridity. These uncertainties are exacerbated by the significant limitations of the ESM carbon modules (Gentine and others, 2019; Zhou and others, 2022) and their profound implications for simulations of evapotranspiration (ET) and, consequently, the future aridity from a hydrological perspective. Addressing these uncertainties is crucial for improving the accuracy and reliability of future projections related to the complex interactions between elevated CO<sub>2</sub> and hydroclimatic variables.

While existing research supports the idea that elevated CO<sub>2</sub> concentrations have contributed to a global increase in photosynthesis (Keenan and others, 2023), particularly in dryland ecosystems (Donohue and others, 2013), doubts persist about whether these effects will continue into the future. Some researchers suggest, for example, that the fertilizing capacity of CO<sub>2</sub> may reach saturation and acclimation (Toreti and others, 2020) so that further increases in concentration do not contribute to additional photosynthesis and plant growth fails to offset increased aridity.

Observations already suggest that the biophysiological effects of increasing atmospheric CO<sub>2</sub> may not be sufficient to offset the challenges posed by a drier and hotter world, particularly in drylands (Allen and others, 2015; Lobell and others, 2011). Similarly, scenarios of future rising aridity are also unlikely to be adequately mitigated solely by biophysiological responses to rising CO<sub>2</sub>.

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### Why measure aridity?

Arid conditions impose limitations on ecosystems and profoundly impact human ways of life. Generally, drylands exhibit sparse vegetation cover, and water scarcity poses substantial challenges to both natural ecosystems and human activities. In drylands, water availability emerges as a decisive factor shaping the distribution of microbiota, flora and fauna. The combination of low precipitation and higher AED creates an inhospitable environment for many life forms, ultimately contributing to the formation of hyperarid or desert landscapes. Arid lands are usually fragile and vulnerable to climate change impacts on socioeconomic and environmental conditions, including biodiversity, food security, gender, loss of traditional lifestyles, migration, etc. These impacts from climatic conditions within drylands underscore the necessity for adaptive strategies in both natural and human systems to meet the challenges posed by limited water resources and harsh environmental conditions.

Climatic classes of drylands span a spatial gradient of aridity levels ranging from hyperarid deserts, characterized by extremely low precipitation, to dry sub-humid areas, where water scarcity—while less severe—remains a significant limiting factor. The ecological potential across this spectrum is strongly contingent on the aridity gradient, both for current conditions and for potential future scenarios. The physiological mechanisms affected by aridity are complex (e.g., Lian and others, 2021). The consequence of these impacts from changes in aridity, therefore, can lead to profound changes in the structure and function of many ecosystems around the world.

In drylands, for example, the scarcity of water results in sparse vegetation cover, and the existing flora and fauna have evolved to adapt to the challenging conditions. Biodiversity in drylands tends to be lower compared to that of more temperate climates, as only the most resilient species can thrive in such inhospitable environments. An increase in climate aridity can produce a three-phase

cascading effect on the ecological balance, influencing soil nutrients and the soil carbon cycle (Figure 1): first, the vegetation declines; second, soil disruption starts; and third, a breakdown of the ecological system occurs. These phases disrupt the intricate relationships within ecosystems and potentially result in species loss (Berdugo and others, 2020; Delgado-Baquerizo and others, 2017).

In extreme cases—if specific aridity thresholds are reached—a shift in an ecosystem’s structure and function may follow (Hirota and Olivera, 2020). For example, arid areas may experience replacement of grass and forest by shrubs (Reynolds and others, 2007), and a total loss of soil fertility can result in degradation (Kéfi and others, 2007). Land degradation is defined by the UNCCD (<https://www.unccd.int/data-knowledge/unccd-terminology>) as the “reduction or loss of the biological or economic productivity and complexity of lands in arid, semi-arid and dry subhumid areas” and more recently by the IPCC as the “trend in land condition [...] expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans” (Olsson and others, 2019). Land degradation

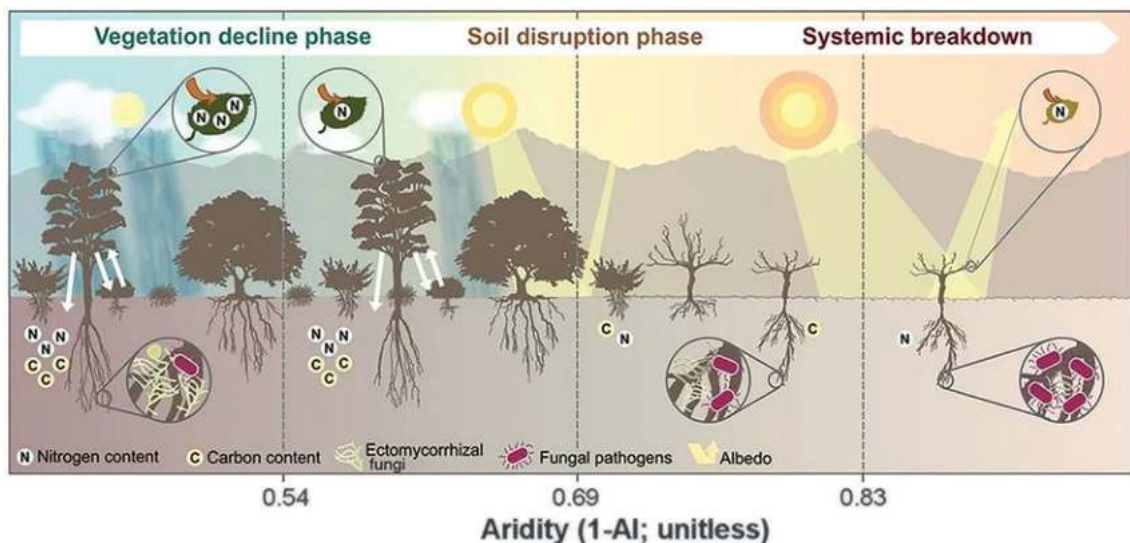
is the result of complex interactions between human activities, physical, chemical and biological processes (Olsson and others, 2019) and occurs in all latitudes and climates where humans use land as a resource.

Ecosystem shifts precipitated by rising aridity may be irreversible, but in some circumstances, they can be reversed. One example is the controversial “greening” of the Sahel (Brandt and others, 2015), a massive reforestation of degraded lands driven by both natural causes (Hickler and others, 2015) and human interventions (Goffner and others, 2019).

Thus, sustaining arid ecosystems is a delicate balance that makes them vulnerable to climate impacts. Understanding and addressing these impacts is critical for the conservation and sustainable management of drylands.

The impacts of high aridity extend beyond ecological considerations and exert profound effects on human societies, as well. For example, the constrained availability of water in drylands directly influences agriculture and pastures, posing challenges for farmers by reducing agricultural productivity and diminishing natural vegetation for livestock.

**FIGURE 1** Consequences of increased aridity on ecosystems and land degradation processes (Berdugo and others, 2020).



This contributes to food shortages and jeopardizes the livelihoods and food security of communities in arid areas.

Human settlements in drylands confront unique challenges related to water supply and infrastructure and are required to adopt efficient and sustainable water management practices. Drylands are often susceptible to desertification, a process wherein fertile land is degraded due to various factors, including prolonged droughts and inadequate

land management. Desertification poses a direct threat to human survival, compelling communities to adapt and implement measures to combat soil degradation and sustain their livelihoods in the face of aridity.

The multifaceted impacts of rising aridity underscore the importance of integrated approaches that address both ecological and societal dimensions in mitigating the challenges posed by arid conditions.

### 1.3. METHODOLOGY: WHY USE THE ARIDITY INDEX (AI)?

#### The difficulty with aridity assessments

This report uses the climate-based metric known as the aridity index (AI; UNEP, 1992) to assess current and future trends in aridity around the world and throughout its many regions and macroregions. AI is defined by the ratio of precipitation (P) to potential evapotranspiration (PET) aggregated over medium to long time periods (i.e., 30-year periods in this study). PET is used as a measure of AED and is the conventional metric for calculating AI values. The choice of AI is motivated by its widespread use in climate-related studies, including the Intergovernmental Panel on Climate Change reports (e.g., IPCC, 2021) and, in particular, the panel's special report on climate change, desertification and land degradation (Mirzabaev and others, 2019). The AI classification system is simple and easily understood by scientific and non-scientific audiences, and it is extensively used in multisectoral indicator systems to monitor desertification (Sommer and others, 2011; Ferrara and others, 2012; Liu and others, 2015).

Using AI as a reliable indicator of current and future trends in aridity is controversial.

A reliable, comparable and universally accepted aridity indicator is considered essential for researchers, conservationists and others to better understand and compare aridity's response to the changing climate and to better anticipate impacts on ecosystems and populations throughout the world. An effective indicator can help ensure appropriate mitigating or adaptive responses to changing aridity, now and later this century. This is particularly relevant for drylands, which are prone to more severe climate change impacts than temperate or humid areas (Middleton and Sternberg, 2013; Huang and others, 2016, 2017b; Stringer and others, 2021) and which are inhabited by large populations, many of them living in developing countries (Dobie, 2001; Maestre and others, 2012).

However, recent studies have raised concerns regarding the limitations of predominantly climate-centric approaches, including the use of AI, that focus on precipitation and AED in aridity assessments. These studies argue that these approaches oversimplify the complexity of aridity by neglecting other crucial hydrological and biophysical factors, including evaporation rates, soil moisture and vegetation cover (Greve and others, 2019; Lian and others,

2021). Furthermore, these and other authors recognize that aridity is not solely dictated by climatic conditions, but involves intricate interactions between climate, hydrology, soil, biophysical factors and human activities (Figure 2). Importantly, separate research using AI versus approaches that include other hydrological and biophysical factors has revealed conflicting results. For example, studies using AI or other simple land-water-availability measures point to an increase in global and often regional aridity in future scenarios (Denissen and others, 2022). Other researchers that attempt to address complex biophysical mechanisms and interconnections suggest a decrease (Berg and McColl, 2021). This inconsistency erodes confidence in our understanding of current and future changes in aridity and, ultimately, contributes to uncertainty affecting policy or actions by governments and societies to ensure resilience against aridity's potentially devastating impacts.

The following sections explore the benefits and drawbacks of different approaches to assessing aridity. This examination is intended as a detailed rationale for the decision by this report to adopt the widely accepted climatic approach based on the aridity index (AI) to ensure consistency and comparability and to offer a more standardized foundation for evaluating the potential impacts of climate change on aridity conditions. At the same time, the approach provides the essential benefit of accounting for a full range of uncertainties in its estimates of aridity changes.

## A history of assessment approaches

Many indicators of aridity currently exist (e.g., Herschy and others, 1998; Kosmas and others, 1998; Stadler, 2005) (Table S1 in Supplementary Materials). In the early 1900s, the first scientific attempts to create indicators for aridity focused on precipitation as a key variable and included analyses of evapotranspiration (see Meng and others, 2004, for a detailed review). More than a hundred years later, the UNEP

(1992) formulated the aridity index (AI)—the most applied indicator for aridity at global scale—based on the same two parameters, precipitation and evapotranspiration.

The AI is used as an aridity indicator by many renowned publications, including the IPCC assessment reports (e.g., IPCC, 2023a) and the *World Atlas of Desertification* (e.g., Cherlet and others, 2018), as well as in highly cited global studies, such as those by Feng and Fu (2013), Zarch and others (2017) and Greve and others (2019). As discussed in section 1.3, depending on the method to obtain evapotranspiration, the AI could result in slightly different estimations of the extent of drylands (Lickley and Solomon, 2018) and new versions have been continuously proposed (e.g., Girvertz and Zganjar, 2014).

Many other climatic indicators for aridity are also currently in use (Ullah and others, 2022), sometimes in combination with drought indicators (Svoboda and Fuchs, 2016). Several simple climate-based aridity indices calculated from measures of precipitation and temperature have been in use since the 1920s and 1930s, including Lang's rain factor (Lang, 1920), De Martonne's aridity index (De Martonne, 1926 and 1942) and Emberger's pluviothermic index (Emberger, 1930). The Pinna Combinative Index (Zambakas, 1992) is a more recent and more sophisticated indicator along the same line. Stadler (1987) reports that evapotranspiration and precipitation were used in aridity metrics at the beginning of 20th century by several authors (e.g., Transeau, Vyssotsky, Oldekop). The approach was later adopted by Holdridge (1947), Penman (1948) and Prescott (1950), and it eventually resulted in the AI in use today (and defined by the UNEP in 1992). Other authors proposed indicators based on additional climatic variables. For example, solar radiation and evaporation latent heat (Budyko, 1951) were included in Budyko's framework for climate, water and vegetation interactions (Budyko, 1974).

Climate classification schemes, including those that describe aridity groups, have been in use for many decades and are still



employed in recent studies. For example, the Köppen-Geiger climate classification (Köppen, 1936) has been used in several global studies, including Kottek and others, (2006), Peel and others, (2007), Beck and others (2018) and Spinoni and others (2015). This classification scheme has been revised by Trewartha and Horn (1980) in its consolidated version and applied in other research (e.g., Belda and others, 2014; Remedio and others, 2019). Other examples of similar climate classification schemes include Thornthwaite's classification (Thornthwaite, 1948) and its revised versions (e.g., Feddema, 2005) and the Holdridge life zones (Holdridge, 1967), a scheme used by Spinoni and others (2021).

Other indicators of aridity reflect its impacts on soil and soil biodiversity—effects that are often severe (Maestre and others, 2015; Neilson and others, 2017; Moreno-Jimenez and others, 2019; Wu and others, 2021). The variety of these indicators, however, is smaller than those that track climate-based aridity metrics. The Soil Moisture Index (SMI), for example, is often used (Wang and others, 2019; Liu and others, 2020b; Qing and others, 2022), but it is usually applied in drought studies (e.g., Berg and Sheffield, 2018). SMI is also difficult to compute under future climate conditions, as it may require data about general soil characteristics (e.g., soil names or the composition of the soil cover) and in situ data for calibration and often involves complex modelling that can lead to divergent projections (Berg and others, 2017).

Alternative soil-related aridity indices include soil quality indices (Bastida and others, 2008; Paz-Ferreiro and Fu, 2016), mixed climate-soil indices (e.g., the Soil Aridity Index; Costantini and others, 2009) with a specific focus on wind erosion effects on soil texture (Zhibao and others, 2000; Borrelli and others, 2014) and vegetation-soil indices (Rondeaux and others, 1996; Gilabert and others, 2004). Vegetation-soil indices combine vegetation metrics, such as the Normalized Difference Vegetation Index (NDVI; e.g., Kriegler and others, 1969; Carlson and Ripley, 1997) with soil parameters. Examples are the Soil-

Adjusted Vegetation Index (SAVI; Huete, 1988) and its modified versions (e.g., MSAVI by Qi and others, 1994). However, large-scale studies dealing with vegetation and aridity need remote sensing data (Kimura and Moriyama, 2019; Prasetyo and others, 2020) that limits the analyses to the last three to four decades when this information became available. Similarly, modelled indicators, such as the Leaf Area Index (LAI), are needed for research exploring future projections (Zhang and others, 2021).

Still other aridity indicators focus on streamflow (Meira Neto and others, 2020), run-off (Zhang and others, 2019) and other complex water-related parameters (e.g., groundwater; Lloyd, 1986; Ranjan and others, 2006). Like the soil-related indices, these indicators often require complex and robust modelling and frequently need satellite data as input (Tweed and others, 2007). Characteristics of plants in natural conditions can also serve as simple indicators of changes in aridity.

Some aridity indicators attempt to include socioeconomic, soil, climate, vegetation and groundwater quality measures in a single indicator. An example of this approach is the Environmental Sensitive Areas (to desertification) Index used in the framework of the MEDALUS project (Kosmas and others, 1999) and further adapted to local studies (Symeonakis and others, 2016). Another multilayer indicator (i.e., based on climate, vegetation and soil quality data, with relevant use of ancillary satellite data) resulted from the DISMED project (Fons-Esteve and Paramo, 2003). This indicator was further improved and applied in various studies across the Mediterranean region (Imbrenda and others, 2014; Pravalie and others, 2017). Building on the outcome of those two projects, a third one (DIS4ME; Brandt and Geeson, 2015) collected more than 200 indicators to monitor desertification, with a special focus on involving local stakeholders in desertification and land degradation research (Geeson and others, 2015).

In light of these developments, a more comprehensive understanding of aridity has been proposed that considers the varied and complex biophysical mechanisms at play. This expanded view recognizes the interconnections between climate variability and the water and carbon cycles (Lian and others, 2021) and encompasses human-induced factors, land-use and land-cover changes and water management practices, which can exacerbate or mitigate aridity. This interdisciplinary approach, spanning climatology, hydrology, ecology, soil science and human geography, represents a paradigm-shift towards a more nuanced understanding of arid conditions and emphasizes the need to explore more holistic and integrative frameworks to understand and address aridity-related challenges.

### The challenge of complex aridity indicators

Nevertheless, while this broader perspective is important, several limitations and challenges exist that hinder a consideration of factors beyond climate characteristics. These complicate efforts to develop a more comprehensive global and regional assessment of spatial differences in aridity, current trends and future projections.

The first challenge lies in the intricate mechanisms that influence aridity conditions and that are determined by complex interactions between climate, soil and vegetation. These interactions involve different land-atmosphere feedbacks that alter the evapotranspiration and the partition between latent and sensible fluxes. This complexity is further compounded by the regional variability of soil and vegetation characteristics. The uniqueness of each region makes it challenging to develop standardized assessments that universally capture the diverse factors at play.

The second challenge relates to the diverse levels of human intervention and interaction with aridity-relevant biophysical factors.

Various human activities, such as land-use and land-cover changes as well as livestock pressure, can influence biophysiological processes in drylands, introducing variability that complicates a consistent and globally applicable assessment.

The third challenge stems from the scarcity of available hydrological information in most of the world's drylands, particularly pertaining to soil moisture, evapotranspiration and soil characteristics. Although modelling approaches can simulate hydrological variables (Padrón and others, 2020), the inherent uncertainties in these models, including those in Earth System Models (Ford and Quiring, 2019), limit the accuracy of assessments.

Finally, the diverse responses of vegetation to greater aridity and to increasing atmospheric CO<sub>2</sub> concentration pose a fourth challenge. Different physiological, phenological and morphological strategies employed by vegetation to cope with water deficits contribute to the complexity. The regional nature of dryland vegetation and the array of adaptive strategies make it exceptionally challenging to conduct an objective assessment that captures the full spectrum of responses.

### The advantages of climate variables

Aridity assessments that use climate variables present distinct advantages due to the availability of data and their spatial and temporal comparability. Additionally, numerous studies have established a robust correlation between soil nutrients, vegetation potential and climate aridity (Delgado-Baquerizo and others, 2013; Maestre and others, 2012). This correlation provides substantial support for grounding assessments of aridity trends and future projections in climate metrics. Climate aridity, being the fundamental driver of water limitation, serves as the origin from which all subsequent hydrological and biophysical mechanisms evolve.



By relying on climate metrics, such as precipitation, temperature and AED, aridity assessments gain a practical and widely applicable foundation. The use of climate variables facilitates a more comprehensive and globally consistent evaluation of aridity, making it a pragmatic approach for assessing the overarching water limitation that shapes various ecological and hydrological processes.

For future projections, some studies have raised concerns about the limitations of relying solely on data-driven, simplified, climate-based metrics (Greve and others, 2019; Lian and others, 2021; Scheff and others, 2022). The argument posits that the use of these climate metrics may overestimate aridity conditions compared to outputs from Earth System Models for vegetation variables, soil moisture, run-off and other relevant factors. The rationale is that, while AED might increase significantly in response to global warming (Scheff and Frierson, 2015), it does not necessarily result in increased aridity, because evaporation is constrained by limited soil water availability, reduced water demand, reduced plant transpiration due to elevated atmospheric CO<sub>2</sub> concentration and other factors (see Box 1).

In drylands, where water in soil and plants is inherently scarce, the limitation of evaporation is a common pattern. However, intensified AED could still introduce additional water stress, such as enhanced evaporation from water bodies and enhanced plant stress. Especially in water-limited regions, increased climate aridity, driven by reduced precipitation, heightened AED or a combination of both, could impose more pronounced ecological, agricultural and socioeconomic influences.

Variability in potential results between studies that use aridity assessments based on climate variables and alternative approaches that use correlations between hydroclimatic variables highlights the importance of adopting a widely accepted climatic approach—such as AI—when assessing projections of aridity under future climate scenarios. This approach ensures consistency and comparability, offering a more standardized foundation for evaluating the potential impacts of climate change on aridity conditions. At the same time, accounting for the full range of uncertainties in the estimated changes is essential.

## 1.4. METHODS

### Categorizing drylands and aridity classes

A main goal of this report is to quantify the past and projected future extent of drylands. Many different indicators are currently used to distinguish drylands vs. non-drylands (e.g., Huang and others, 2016; Berdugo and others, 2020; Ullah and others, 2022; see section 2.1), and these are often linked to drought (Svoboda and Fuchs, 2016) or to global warming (Fu and Feng, 2014; Greve and others, 2019).

In this study, the aridity index (AI) is used to categorize drylands and different aridity classes along an aridity continuum. Following the approach described in the second edition of the *World Atlas of Desertification* (WAD; Middleton and Thomas, 1997), this report uses AI values to distinguish five aridity classes: hyperarid ( $AI < 0.05$ ), arid ( $0.05 \leq AI < 0.2$ ), semi-arid ( $0.2 \leq AI < 0.5$ ), dry subhumid ( $0.5 \leq AI < 0.65$ ) and humid ( $AI \geq 0.65$ ). Some authors employ a slightly different classification, defining a dry class ( $0.5 \leq AI < 0.65$ ), a subhumid ( $0.65 \leq AI < 0.75$ ) and humid climate ( $AI > 0.75$ ; e.g., Spinoni and others, 2015).

The third edition of WAD introduced a sixth class for cold climates (annual PET < 400 mm; Cherlet and others, 2018), but here, cold areas are delineated according to temperature instead of PET. Thus, the Köppen-Geiger climate classification is used and assigns the cold (or polar) class designation to lands with annual mean temperature below 10°C (Peel and others, 2007; Beck and others, 2018).

In the analyses for this report, PET is calculated using the Hargreaves-Samani approach based on minimum and maximum temperatures (Hargreaves and Samani, 1985). This approach is generally considered more robust than the Thornthwaite method (Proutsos and others, 2021). Another method, the Penman-Monteith approach is more sophisticated (van der Schrier and others, 2011; Talebmorad and others, 2020) and may improve estimates, but it needs more climatic input data, which are not easily retrievable at high spatial resolutions, particularly for multi-scenario projections.

## Climate and population data

Calculating AI needs values for only two climatic variables, precipitation and PET, but estimating PET may require both minimum and maximum temperatures using the Hargreaves-Samani equation. As this study focuses on past aridity trends—including those attributable to human forcing—and future projections, two types of climate input data are used: i) reanalysis data for the period 1941–2022 and ii) modelled multi-scenario simulations for the period 1881–2100. The former is provided by the ERA5 Global Reanalysis (Hersbach and others, 2020) and the latter by the bias-adjusted ISIMIP3b (Lange, 2019; Cucchi and others, 2020).

ERA5 reanalysis data has been widely used in scientific publications that address aridity linked to climate change (e.g., Chai and others, 2021; Fang and others, 2022) and provides high-resolution (0.25°), gridded, hourly data from 1940 onwards, updated

to the previous month. Compared to other datasets, ERA5 performs well regarding both temperature (McNicholl and others, 2021) and precipitation variables (Hassler and Lauer, 2021), though its overall quality is lower over tropical areas, especially Africa (Steinkopf and Engelbrecht, 2022) and Colombia (Vega-Duran and others, 2021). However, these regions are very humid (Kottek and others, 2006), and, consequently, this quality difference does not affect the distinction between drylands and not drylands.

To analyse both attribution of past changes in aridity and projected changes, the ISIMIP3b bias-adjusted atmospheric climate dataset is used, because its latest version (Lange and others, 2023) includes daily data from 10 General Circulation Models (GCMs) designed with the specifics of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring and others, 2016). This dataset includes the historical-natural (hist-nat) runs (for six GCMs), together with five (plus two, see Table S2 in Supplementary Materials) Shared Socioeconomic Pathways (SSPs), covering any socioeconomic narrative within the framework of the IPCC. The total combination of GCMs and SSPs is 61, allowing a robust evaluation of the uncertainties in future aridity patterns.

To estimate the population located in drylands and in regions that show climate shifts between AI classes, three population datasets were selected. For the recent years, we use the United Nations WPP-Adjusted Population Density (v4.11; CIESIN, 2018, updated) from the Gridded Population of the World (GPWv4) dataset (Figure S1 in Supplementary Material). To look at past population change, we use the History Database of the Global Environment (HYDE v3.3; Klein Goldewijk and others, 2017 and updates). Finally, to explore future scenarios, we use the 1-km downscaled global database of population projections for five SSPs recently published by Wang and others (2022a). Population values were aggregated at the spatial scale of the aridity index (i.e., 0.25° or 0.5°) and at country and macroregional levels.



## Past and future estimations of arid areas and affected populations

This report first examines the current global and regional evolution of aridity and drylands from the early 20<sup>th</sup> century to 2020 (section 2.1). A global map shows AI changes over the period 1991–2020 with an estimation of the populations living within each AI class (section 2.2). To explore regional changes, a modified version of the official delineation of UNCCD regions (see <https://www.unccd.int/convention/regions>) is used to distinguish six broad macroregions: Africa, Asia, Latin America and the Caribbean (LAC), Europe, North America and Oceania. Section 2.3 describes the distribution of drylands and dryland inhabitants today.

Section 2.4 discusses the progressive shifts from less arid to more arid (and vice versa) AI classes at a global scale and in the hotspots of aridity changes. To detail the annual evolution of drylands, we extend the analysis to 1941–2020, and we investigate the number of people living within drylands from 1970 to 2020. The extent of drylands is again computed over the 30-year periods, this time moving by one year at each step: we consider 1941–1970, then 1942–1971 and so on. Additionally, we calculate the number of people living within drylands. To do that, for each 30-year period, we use the population of the last year in the interval. For example, for the climatological period 1941–1970, we use the population figures for 1970 and for the period 1942–1971, we use 1971 population figures and so on. We detail the evolution of drylands versus not drylands, and the corresponding population exposed, on an annual basis from 1971 to 2022.

In the scientific literature, the detection and attribution of extreme weather and climate events and their impacts is not yet well-understood (Hegerl and others, 2007). The theoretical background of these topics is still being developed (Hammerling and others, 2019), and their application in different sectors is becoming more frequent (Zhai and others, 2018). Following the guidelines by the CMIP6 Tier 1 Experiment

(see <https://wcrp-cmip.org/cmip-model-and-experiment-documentation/#es-doc>), the AI obtained with historical (hist) and with historical-natural (hist-nat) runs is compared to quantify the influence of human forcing on progressive changes in aridity (section 2.4).

Section 2.5 describes future projections of AI and populations, presenting results based on fixed periods (i.e., for the periods 2021–2050 and 2071–2100 relative to the baseline period of 1981–2010) and based on Global Warming Levels (GWLs) from 1.5°C to 4°C above the pre-industrial global temperatures, an approach used by Koutroulis (2019) and Spinoni and others (2021). The fixed period method uses different SSPs (except for those with few GCMs; these are left to the Supplementary Materials) to show how different emissions trajectories are likely to lead to different climate conditions within fixed time windows. The assumption behind the GWL method is that, at a given GWL, the world shows corresponding climatic features no matter which SSP led to that level of warming. In section 2.5, each output at global or macroregional scales is backed with statistics on the uncertainty and robustness of changes in AI.

The analyses focus on four Shared Socioeconomic Pathways, namely the SSP1-2.6 (based on sustainability), the SSP2-4.5 (the “middle-of-the-road” scenario), the SSP3-7.0 (with critical regional rivalry), and the SSP5-8.5 (global development still driven by fossil-fuel massive use). See Riahi and others (2017) for a thorough description of the details of the narratives. We discarded the SSP4-6.0 and two additional versions of the SSP1 (SSP1-1.9) and the SSP5 (SSP5-3.4ov) because the ISIMPI3b input data used for this study provided limited simulations. Results were considered “significant” if they showed agreement across more than two-thirds of the simulations used—that is, 10 for the historical part and for all the SSPs but the SSP2, which only has five models. Additional maps regarding the evolution of the AI for Global Warming Levels (from 1.5°C to 4°C) are left for Supplementary Materials.

## Literature review of aridity impacts, vulnerability and adaptation

A systematic literature review was used to explore previous knowledge about current and projected future impacts of aridity (Chapter 3) and about current vulnerability and adaptation needs (Chapter 4). This comprehensive and up-to-date review of the most relevant scientific and grey literature followed the established principles of a systematic review (Booth and others, 2012) to identify all possible publications relevant to aridity and aridification, research gaps and links between different areas of research. This literature was then further selected by relevance, regional scope, topicality and concordance with the scope of this report.

The review used major scientific databases, including Google Scholar, SCOPUS and Web of Science. It also examined reports published by relevant international organizations, including WMO, UNCCD, the World Bank, FAO and the IPCC. We divided the literature according to its relevance to three main subtopics: impacts, vulnerability and adaptation.

Topic and subtopic keywords included “aridity”/“aridification”, as well as “impacts”, “vulnerability” and “adaptation”. Complementary keywords to identify different environmental and socioeconomic factors affected by or relevant to aridity included “desertification”, “wildfires”, “water scarcity”, “ecosystems”, “poverty”, “health” and others. When no literature was found for a subtopic, region or combination of relevant keywords, the research was extended to related keywords (and concepts) such as “drought”, “climate change”, “warming” or “desertification”.

The review examined literature relevant to different time periods (including research exploring different periods of past observations and future projections) and to a variety of relevant spatial scales (i.e., from local and regional to global). Particular attention was paid to literature relevant to dry regions of the world and to recent publications. The review included only scientific and grey literature published in the English language.







# Chapter 2.

# CURRENT AND FUTURE TRENDS IN ARIDITY

## 2.1. THE TEMPORAL EVOLUTION OF ARIDITY

### Most land is drying

More than three-quarters of all land on Earth (77.6 per cent, Figure 5) experienced a drier climate during the three decades leading up to 2020, compared to the previous 30-year period (i.e., 1961–1990), according to an analysis conducted for this report. This widespread rising aridity increased the world's drylands by more than 3 per cent in recent decades compared to the earlier period (from 37.5 to 40.6 per cent, excluding Antarctica)—up approximately by 4.3 million km<sup>2</sup>, an area almost a third larger than the size of India, the world's seventh largest country.

The drying tendency—revealed in decreasing aridity index (AI) values across the two most recent 30-year periods (Figure 5) was particularly prevalent over Europe, the western United States, Brazil, Asia (especially eastern Asia) and central Africa. It affected almost all of Europe (95.9 per cent), while its impact on North America (affecting 68.9 per cent of the continent's land) was the lowest among world macroregions (Table 1).

Meanwhile, less than a quarter of global land (22.4 per cent) experienced a wetting tendency, including areas in central United States, the Atlantic coast of Angola and southeastern Pacific Asia (e.g., Malaysia, Indonesia and the Philippines). While potential evapotranspiration increased everywhere but in a few localized areas in the last decades, an increase in precipitation over

these areas (showing a wetting tendency) increased the AI values for these places.

### Drylands are expanding

The drying tendency pushed areas across aridity thresholds (i.e. from non-drylands to drylands or from less arid dryland classes to more arid classes) for 7.6 per cent of global lands, a vast area larger in total than the world's second largest country, Canada. Only 0.8 per cent of land on Earth shifted towards a wetter AI class, a change occurring almost nowhere in Europe (0.1 per cent). The cold aridity class, meanwhile, decreased by 1.2 per cent, mostly becoming humid (1.1 per cent).

Areas that were not drylands in 1961–1990 but changed to drylands in 1991–2020 are found in every macroregion, except Antarctica (Figure 3; Antarctica is not shown). Drylands are areas in the world where the amount of rain is <65 per cent of what can be potentially evaporated and comprise all lands with hyperarid, arid, semi-arid, dry sub-humid climates. Non-drylands with rain >65 per cent of potential evaporation are considered humid.

Areas that became drylands in recent decades are found in the western United States, and Mexico's Yucatan Peninsula (in North America); north-eastern Brazil and north-western Argentina (in Latin America



and the Caribbean); the Mediterranean region and north of the Black Sea (in Europe); the Sahel, the Rift Valley and north-eastern South Africa (in Africa); the border between Russia and Kazakhstan, few localized areas in north-eastern Siberia, large parts of Mongolia and north-eastern China (in Asia); and south-eastern Australia (in Oceania).

Among world nations, South Sudan and Tanzania have seen the largest portion of their land transformed to drylands from non-drylands, while China has seen the largest total area shift to drylands in the last three decades. Meanwhile, some small regions showed an opposite trend, shifting from drylands to non-drylands (i.e., to the humid class) in the Midwestern United States and southern Canada, north-eastern Angola and

south-western India. Local changes in aridity may differ from the global picture (with some of them showing opposite trends), highlighting the need for similar research exploring aridification at local scales.

A drying tendency (i.e., a change to a smaller AI value) does not always signify a complete shift to a drier aridity class. For example, the Republic Democratic of Congo, with its large tropical rainforest, remains almost entirely within the humid class, despite a widespread drying in the country from 1961–1990 to 1991–2020.

The global expansion of drylands (excluding Antarctica) from 1961–1990 to 1991–2020 was mostly due to a net exchange between two AI classes, from humid to dry subhumid

FIGURE 3

Upper panel: the difference between AI values over 1961–1990 and 1991–2020. Green means wetter conditions, brown drier conditions (Greenland is masked in the upper panel as the AI shows large variations due to snow, with no shifts from cold AI class). Lower panel: the shifts between AI classes in the above-mentioned periods. Black areas are the hotspots exposed to aridification.

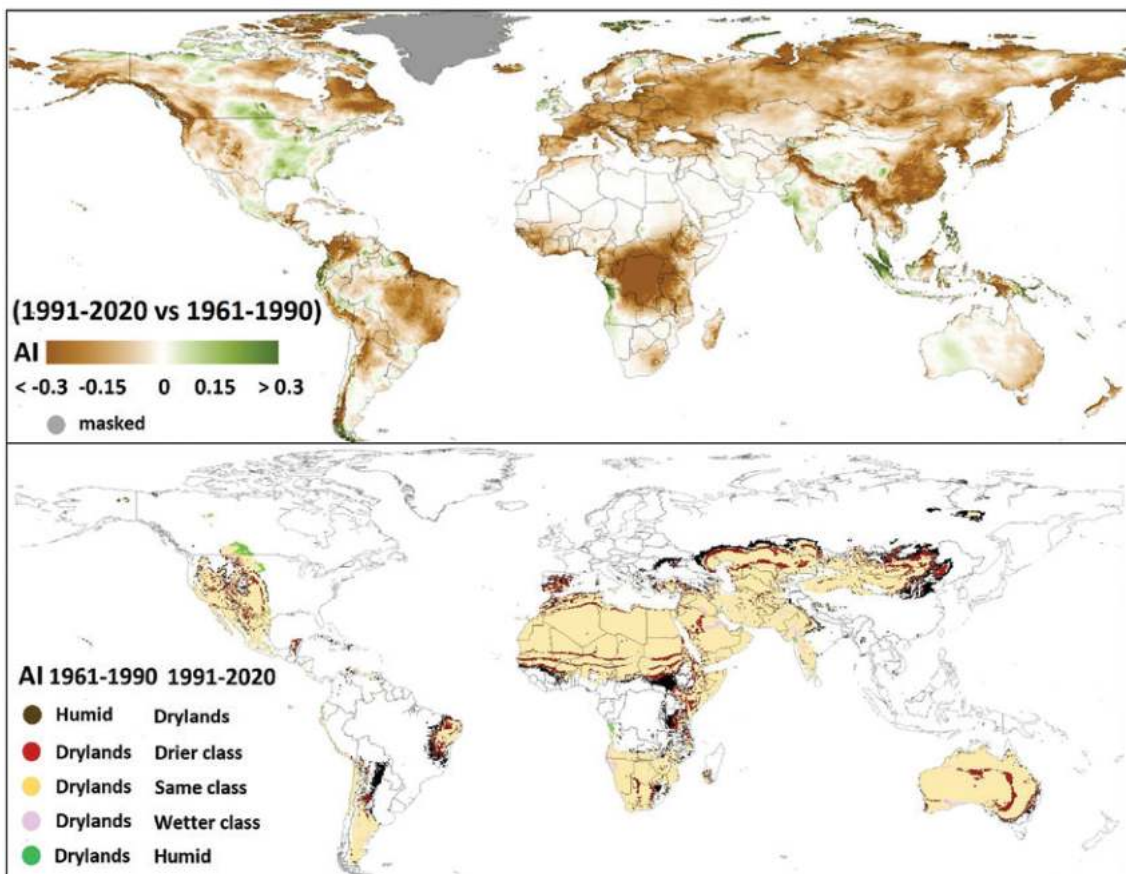
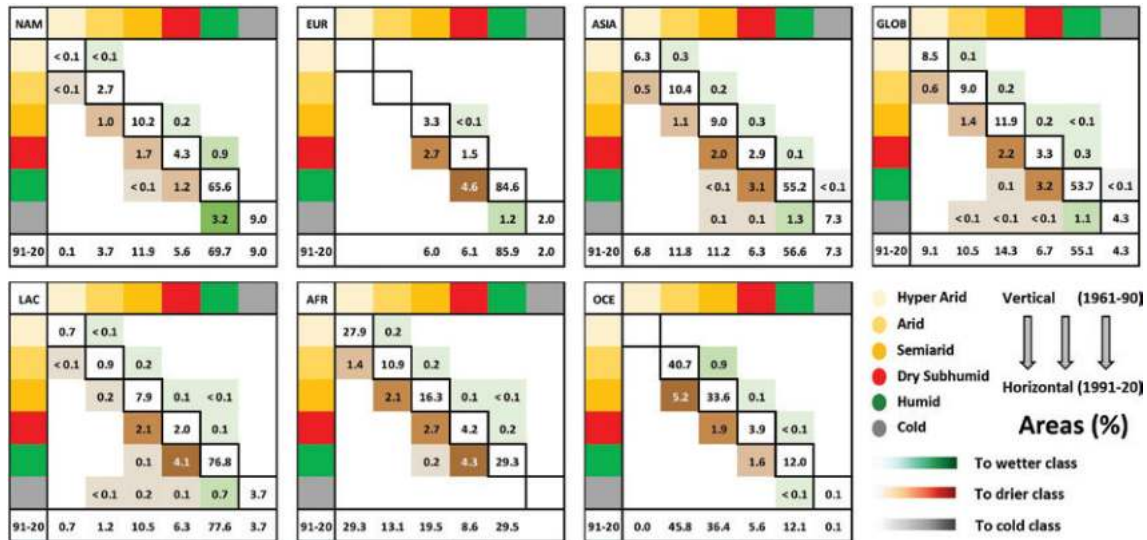




FIGURE 4

The percentage of macroregional and global lands changing AI class (or not changing, in the diagonals) from 1961–1990 to 1991–2020. Read the diagrams from vertical columns (AI class in 1961–1990) to horizontal rows (AI class in 1991–2020). Values coloured brown signify a shift towards drier conditions, green towards wetter conditions and grey towards the cold AI class. Antarctica is excluded from global statistics.



(3.2 per cent) and vice versa (0.3 per cent; Figure 4) according to the analysis. Other AI changes that contributed to dryland expansion included humid to semi-arid (0.1 per cent) and cold to arid, semi-arid or dry subhumid (0.2 per cent). Changes from drylands to non-drylands, meanwhile, include only shifts from semi-arid lands to humid class (< 0.1 per cent).

At a macroregional scale, the most frequent change of class—i.e., from humid to dry subhumid—exceeds 3 per cent in Latin America and the Caribbean, Europe, Africa and Asia. All AI shifts larger than 1 per cent are towards drier AI classes or from cold to humid classes. The largest shifts in AI class towards wetter conditions were changes from dry subhumid to humid classes in North America. Excluding the changes involving the cold AI class, the only AI value decrease large enough to cross two aridity class thresholds occurred in Latin America and the Caribbean (i.e., 0.1 per cent of the region’s land shifted from humid to semi-arid).

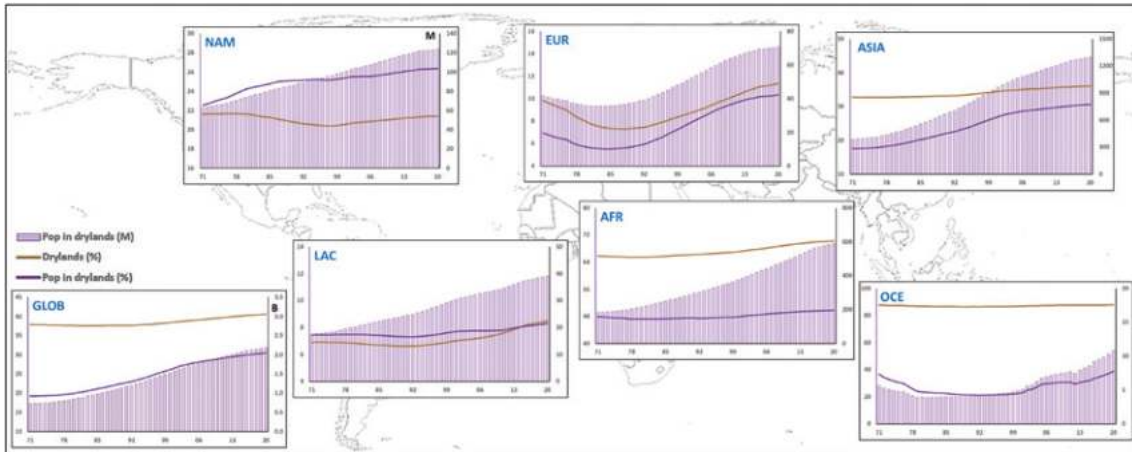
### Dryland expansion is recent

Much of the world’s dryland expansion appears to be recent. A separate analysis comparing global drylands using 30-year periods beginning each year since 1941 (e.g., 1941–1971, 1942–1972, 1943–1973, and so on) reveals that the global dryland area began increasing significantly in the 1990s (Figure 5).

The increase followed a relative plateau in dryland area expansion during periods leading up to the 1970s and 1980s—when drylands decreased slightly in the Americas (also in the 1990s for North America) and in Europe. The analysis also shows that drylands in North America were larger in 1941–1970 than they have been in more recent periods (despite the increase in drylands between 1961–1990 and 1991–2020).

FIGURE 5

The annual percentage of drylands and population in drylands from 1971 to 2020. Population totals (lilac bars) in million people but for global (billion people). The values are smoothed with an additional 10-year moving average. Global drylands are computed excluding Antarctica.



## 2.2. ARIDITY-AFFECTED POPULATIONS

### Dryland inhabitants have doubled

Twice as many people lived in drylands around the world in 2020 than lived there in 1990 (i.e., at the end of the most recent 30-year period compared to the end of the previous one), according to the analysis. The global population of dryland inhabitants grew to 2.3 billion in 2020, up from 1.2 billion three decades earlier (Table 1). That is, those living in drylands comprised almost a third of all people on Earth (30.9 per cent) in 2020, compared to just over a fifth (22.5 per cent) in 1990.

Most people living in drylands are found in Asia (1.35 billion people, about half of all dryland inhabitants in the world) and Africa (620 million people; close to half that continent’s population). The most densely populated drylands are in California (United States), Egypt (on the Nile River), eastern and northern Pakistan, large parts of India and north-eastern China (see Figure S1 in the Supplementary Materials). China, India, and

Pakistan are the Asian nations that together comprised about 50 per cent of all people in drylands in 2020.

Over the span of successive 30-periods from 1941–1970 to 1991–2020, the growth in the number of people living in global drylands significantly outpaced the geographic expansion of drylands (using the population figures for the last year in each interval; Figure 5). Nevertheless, the percentage of each of the world’s macroregions occupied by drylands is generally larger than the percentage of each macroregional population living there.

North America (including Mexico and its areas of densely populated drylands) is the one exception with a greater proportion of dryland inhabitants than the proportion of drylands across the macroregion. Latin America and the Caribbean also had a greater proportion of people living in drylands than its proportion of dryland area until about a decade ago, when

TABLE 1

The percentage of lands (at macroregional and global scales) showing drying tendencies (AI decreases) from 1961–1990 to 1991–2020, and the percentage considered as drylands for each of the two periods. The right column shows the population living in drylands in 1990 and 2020. Global statistics do not include Antarctica.

Region	Areas with AI decrease 1961–1990 v 1991–2020	Drylands		Population in drylands	
		1961–1990	1991–2020	1990	2020
NAM	68.9	21	21.3	25.7	26.4
LAC	82.1	14.3	18.6	14.9	16.2
EUR	95.9	7.3	12.1	5.7	10.7
AFR	88.4	66.2	70.5	47.2	49.6
ASIA	84	33.2	36.1	21.8	30.9
OCE	74.5	86.3	87.9	20.7	45.8
GLOB	77.6	37.5	40.6	22.5	30.9

dryland expansion exceeded the proportion of dryland inhabitants.

The large change within just a few decades likely reflects the expansion of drylands as well as technological progress that allows

more people to adapt to day-to-day life in dry and semi-arid landscapes. In north-eastern China, for example, large populations thrive in dryland megacities, such as Beijing and Tianjin, and in the highly populated dryland province of Hebei.

## 2.3. THE DISTRIBUTION OF ARIDITY TODAY

### Drylands found in every macroregion (except Antarctica)

Today, drylands represent more than two-fifths (40.6 per cent) of all land on Earth (excluding Antarctica; Figure 6). Drylands include 9.1 per cent of land classed as hyperarid, namely the Atacama Desert (Chile), the Sahara and Namib (Namibia) deserts in Africa, most of the Arabian Peninsula, sparse areas between Iran, Afghanistan and Pakistan, and the Taklamakan (China) and Gobi deserts (China and Mongolia). They also include areas considered arid (10.5 per cent of land), semi-arid (14.3 per cent) and dry subhumid (6.7 per cent).

Drylands exist in places throughout the world, including south-eastern United States, northern Mexico, north-eastern Brazil, Argentina, the Mediterranean region, the Sahel, the Horn of Africa, southern Africa, large parts of Central Asia, India, China and most of Australia. Nevertheless, more than half of all land is considered humid (55.1 per cent; 49.5 per cent if Antarctica is included in the global total), and the remaining 4.3 per cent (14.0 per cent including Antarctica) belongs in the cold class of the aridity index (AI), including all of Antarctica and Greenland, the Himalayan Plateau and areas at very high latitudes in the Northern Hemisphere.

FIGURE 6

Global map of six aridity index (AI) classes for 1991–2020. The boxes show the total percentage of global lands (and population) within each AI class and within drylands versus non-drylands. (Antarctica falls entirely in the cold class and is not included in this map or in the global percentages.)

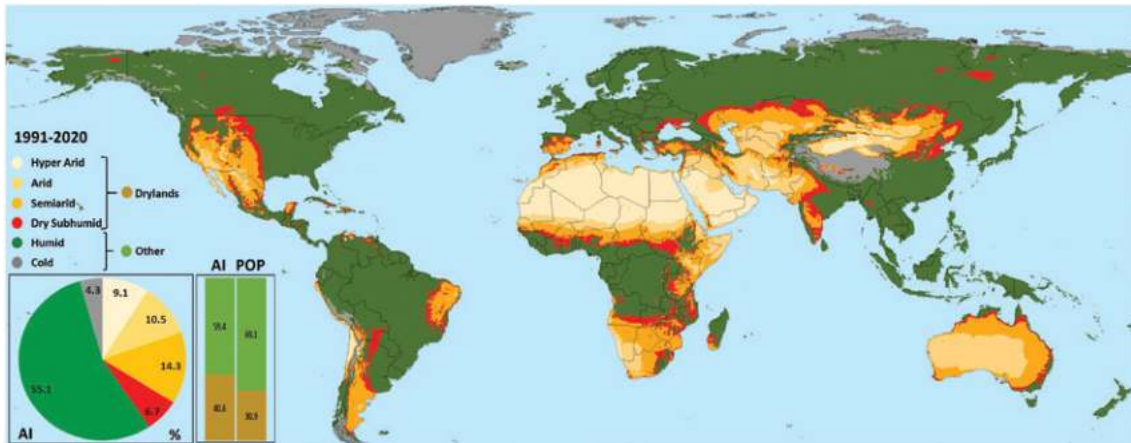
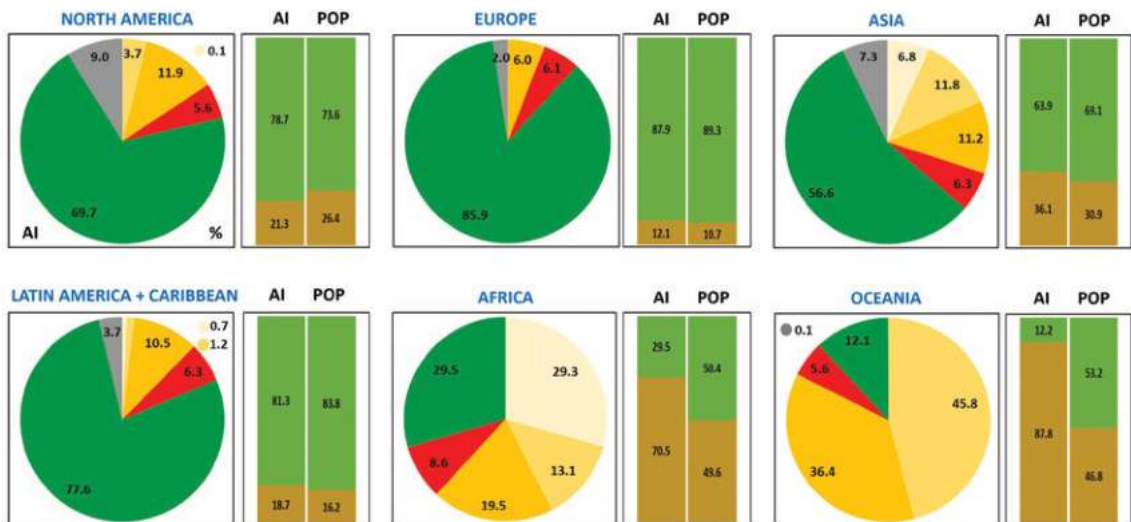


FIGURE 7

Regional percentages of lands within each aridity class and the percentages of land and population within drylands versus non-drylands. See Figure 3 for a description of colours and classes.



Oceania is the region with the largest fraction of drylands (about 88 per cent of the region's total lands, or 7 million km<sup>2</sup>), but none is in the hyperarid class. In absolute values, both Africa and Asia have a larger extent of drylands, covering 21.1 and 16.2 million km<sup>2</sup>, respectively. A smaller extent of drylands is present in North America (4.5 million km<sup>2</sup>,

Mexico included), Latin America and the Caribbean (3.5 million km<sup>2</sup>), and Europe (1.2 million km<sup>2</sup>). Europe's drylands currently cover approximately 12 per cent of the region's total lands, and the same percentage of the region's population lives in these dryland areas (Figure 7).

### Why results differ from IPCC report

The findings of this report show a smaller global extent of drylands than the IPCC's *Special Report on Climate Change and Land* (IPCC, 2019), which reported about 46 per cent of global land as drylands. The IPCC's number was derived from two published papers (Pravalié, 2016; Koutroulis and others, 2019), and its report labelled the figure as "low confidence". Both papers upon which the number was based used different input datasets, different time periods and slightly different approaches—in particular on the computation of potential evapotranspiration and on the thresholds used to define the cold areas. The IPCC's figure is also larger than most previous assessments that have usually calculated between 37 per cent and 42 per cent of global land as drylands (e.g., Safriel and Adeel, 2005, report 41 per cent).

In this report, a more robust approach is used, following the third edition of the *World Atlas of Desertification* (WAD; Cherlet and others, 2018) and using a slightly different threshold for PET than is used

by the IPCC-cited studies. Following the WAD methodology, global dryland coverage becomes 42 per cent of the planet's land surface. The approach of this report is in line with global climate maps and delineates cold areas using the Köppen-Geiger classification, a system that uses temperature, PET and precipitation values. This classification approach assigns the Tibetan Plateau and the Andes to the cold class, while the WAD considers such areas as drylands.

The methodology used in this report also results in larger percentages of global lands classified as hyperarid than those described in the IPCC report (8 per cent instead of 6-7 per cent), demonstrating that the main difference in these results is in the delineation of cold areas. Furthermore, changing the delineation for cold class areas (using PET thresholds) to boost the percentage of drylands to about 45 per cent results in an addition of only 0.3 per cent of the global population as dryland inhabitants. Importantly, this report emphasizes changes towards a drier climate and shifts from not-drylands to drylands, more than the size of absolute extent.

## 2.4. ATTRIBUTION OF ARIDITY CHANGES TO HUMAN-INDUCED CLIMATE CHANGE

### Climate change is main aridity culprit

Human-caused climate change is a likely culprit behind a 1.5 million km<sup>2</sup> expansion in the planet's drylands since early in the industrial revolution (i.e., 1850), further analysis done for this report reveals.

Using the ISIMIP3b dataset, historical simulations (hist) from six models that include impacts from human greenhouse gas emissions and climate change show 1.2 per cent larger dryland increases for the periods between 1850 and 1981–2010 than

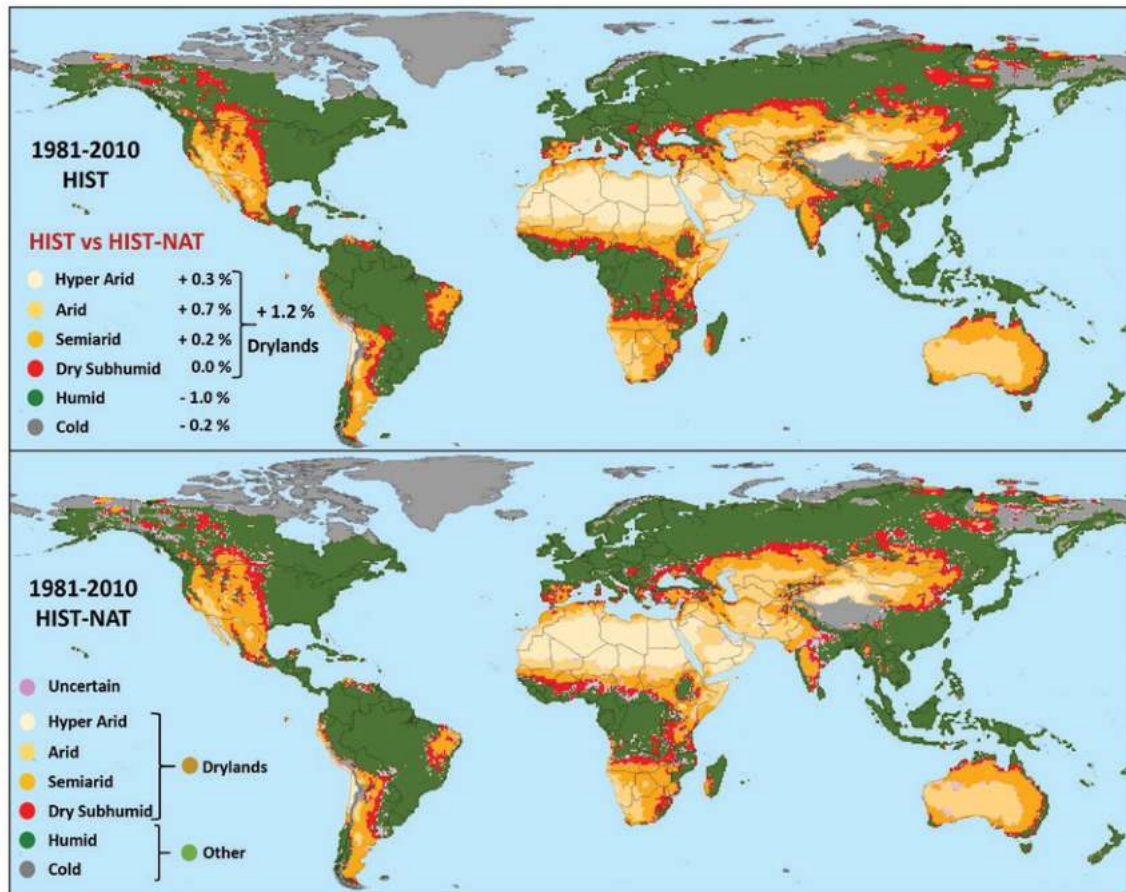
do historical-natural (hist-nat) simulations that consider only solar and volcanic impacts without human influence. The comparison between the two sets of simulations (i.e., hist vs. hist-nat) provides an estimate (although incomplete and for a limited number of models) of the role of human-induced climate change on the recent increase of drylands (Figure 8 and Figures S2–S3 and Tables S3–S4 in Supplementary Material).

Results suggest the larger expansion of the global drylands in 1981–2010 in the climate-change-altered historical simulations



FIGURE 8

Aridity index classifications around the world for the period 1981–2010, according to historical simulations (upper panel) and historical-natural simulations (lower panel). Pink areas (i.e., uncertain) represent lands where less than four models agree on the AI class. In the upper panel, the percentage values represent the global difference in each AI class between historical and historical-natural simulations.



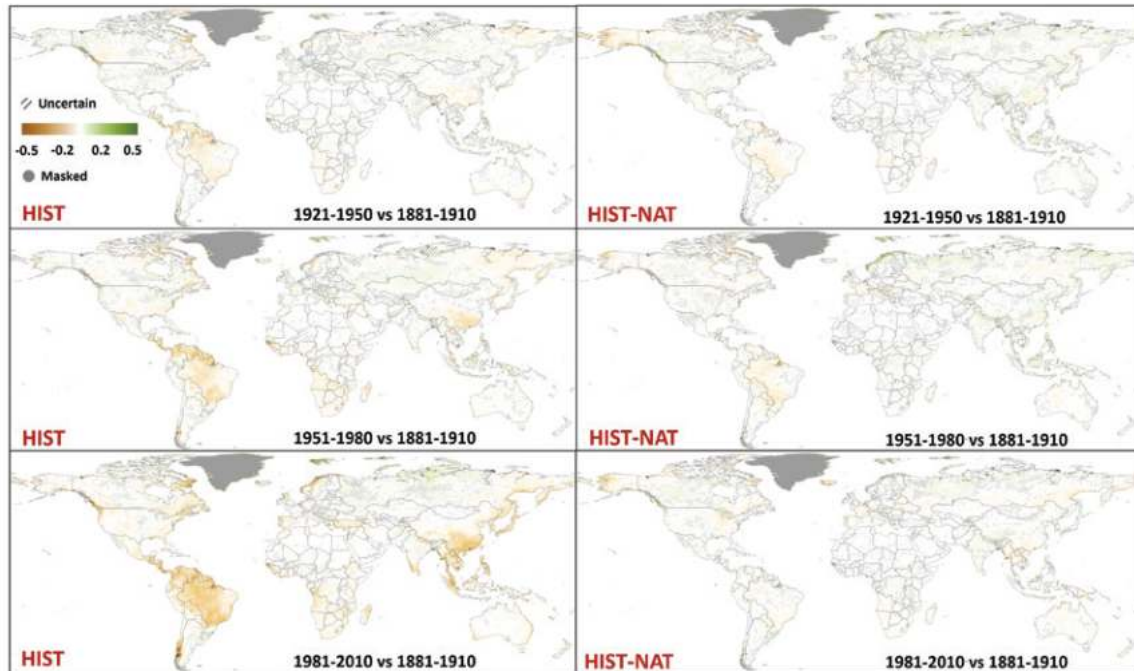
compared with the historical-natural approach is mostly due to greater arid areas (+ 0.7 per cent, with respect to the total lands) and smaller humid areas (–1.0 per cent, with respect to the total lands).

Large parts of Latin and Central America, sub-Saharan Africa and East Asia all show large areas becoming drier with time in the human-influenced historical simulations, compared to a reference period of 1881–1910 (Figure 9). Historical-natural

simulations, meanwhile, show smaller and more heterogeneous changes. Changes in this analysis were considered significant when at least four models out of six agree on the direction of the change or on the AI class. Otherwise, the change was classed as uncertain. The reference period 1881–1910 was chosen as the reference period typically used in global warming computations.

FIGURE 9

The difference between AI values averaged over 30-year periods and presented as the ensemble median for six models. “Uncertain” means that less than two thirds of models agree on the sign of such change. Left shows the historical simulations; right shows the historical-natural ones.



### Climate-related drying widespread by the 1980s

Human contributions to global drying first become apparent in the 1940s, when the historical and the historical-natural simulations start to diverge, according to the analysis. A progressive increase of drylands in the climate-affected historical simulation becomes particularly clear by the 1970s (Figure S4 in SM). For that decade, historical-natural simulations show an opposite, slight decrease compared to the reference period 1881–1910 (Figure 10, left panels). These results, however, should be interpreted with caution, as the historical-natural simulations do not show agreement as clearly as do the historical simulations.

A decade later, beginning in the 1980s and afterward, global drying in the historical simulations appears to be widespread—with exceptions across the mid-latitudes of

North America and Russia. The two sets of simulations clearly diverge in the 1981–2010 period, with more pronounced drying in the historical simulations appearing across the world’s tropical regions and throughout the Southern Hemisphere.

These changes, according to the analysis, also suggest that human-induced climate change is pushing more people to live in drier climate conditions. Both the historical and historical-natural simulations show a continuous increase in the percentage of people living in drylands since before the turn of the last century (Figure 10, right panels). The magnitude of this increase, however, is greater for the human-influenced historical simulations from 1951 onwards. This difference remains quite constant (ranging from 2 to 3 per cent) through time (see also Figure S5 and S6 in the Supplementary Materials), suggesting the world without

human-induced climate change (i.e., with no changes in the extent of drylands) would also see a progressive increase in dryland inhabitants—a consequence of population growth through the 21st century and of a likely non-negligible increase in population densities in the drylands of the western United States, sub-Saharan Africa and eastern China, among others.

Changes in aridity in the climate-altered historical simulations that consequently caused shifts in aridity classes occurred in large areas around the world—particularly over Brazil, the eastern Mediterranean region and mainland Southeast Asia. The historical-natural simulations, on the other hand, showed that changes in aridity classes solely driven by natural forces without human-caused climate change are very limited (and often uncertain; Figure 10). These suggest that, over the last century, only sparse areas in the Sahel, the Horn of Africa and north-eastern Asia would have become drylands without the influence of human-caused climate change.

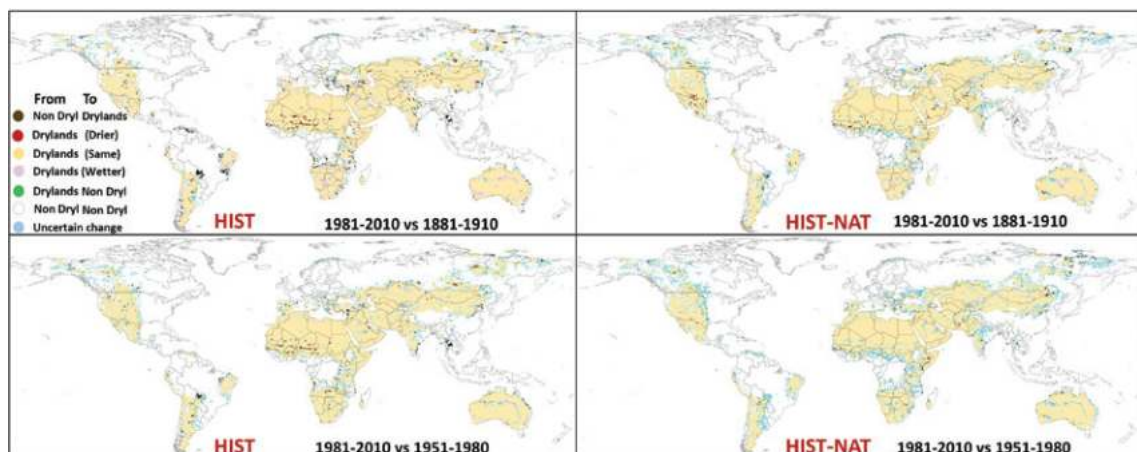
Note that the global extent of areas changed from non-drylands to drylands in Figure 10 is smaller than reported in the previous

analysis because of the different end periods considered for each. Figure 10 uses the period 1981–2010. The earlier reported result, on the other hand, uses end period of 1991–2020. The latter period includes the decade beginning 2010 when record-breaking high temperatures were frequent, resulting in higher PET values that were decisive for shifting AI classes. The difference may also reflect the distinct spatial resolutions (i.e., 0.5° for the Figure 10 simulations versus 0.25° for the previous analysis). The higher resolution of the previous analysis better captures local climate conditions, providing a more detailed delineation of dryland borders and a more accurate detection of non-dryland-to-dryland shifts.

### Drylands more vulnerable to climate change

Drylands are especially vulnerable to shifting from one aridity class to a drier class as a result of human-caused climate change, according to the analysis (see Figure S3, SM). Compared with results from models that exclude climate change effects (i.e., historical-natural simulations), historical simulations affected by human

**FIGURE 10** Changes between drylands and non-drylands and within dryland classes between 1981–2010 and 1881–1910 (upper parts) and between 1981–2010 and 1951–1980 (lower parts) for historical (left panels) and historical-natural simulations (right panels).



influence show more areas that were previously considered within a dryland class (i.e., hyperarid, arid, semi-arid, dry subhumid) shifted to a drier class (e.g., dry subhumid to semi-arid, semi-arid to arid). That is, human-induced changes appear to be forcing further aridification over these fragile ecosystems (Table 2; see Table S5 in the Supplementary Material for the uncertainties in the numbers).

These shifts affect both the extent of global drylands and the percentage of dryland inhabitants among populations in all macroregions and throughout the world for three 30-year periods (i.e., 1921–1950, 1951–1980, and 1981–2010) representing

the start, middle and end of the simulation runs (Table 2, Figure 11). Increases in global dryland inhabitants in the historical runs compared to the historical-natural simulations (around 3 per cent versus 1 per cent) are larger than the comparative changes in global dryland extent (0.8 per cent versus 0 per cent, respectively). All macroregions show more people living in drylands in historical versus historical-natural simulations, except for North America in 1921–1950 and Europe in 1951–1980 (a period in Europe characterized by positive precipitation anomalies).

TABLE 2

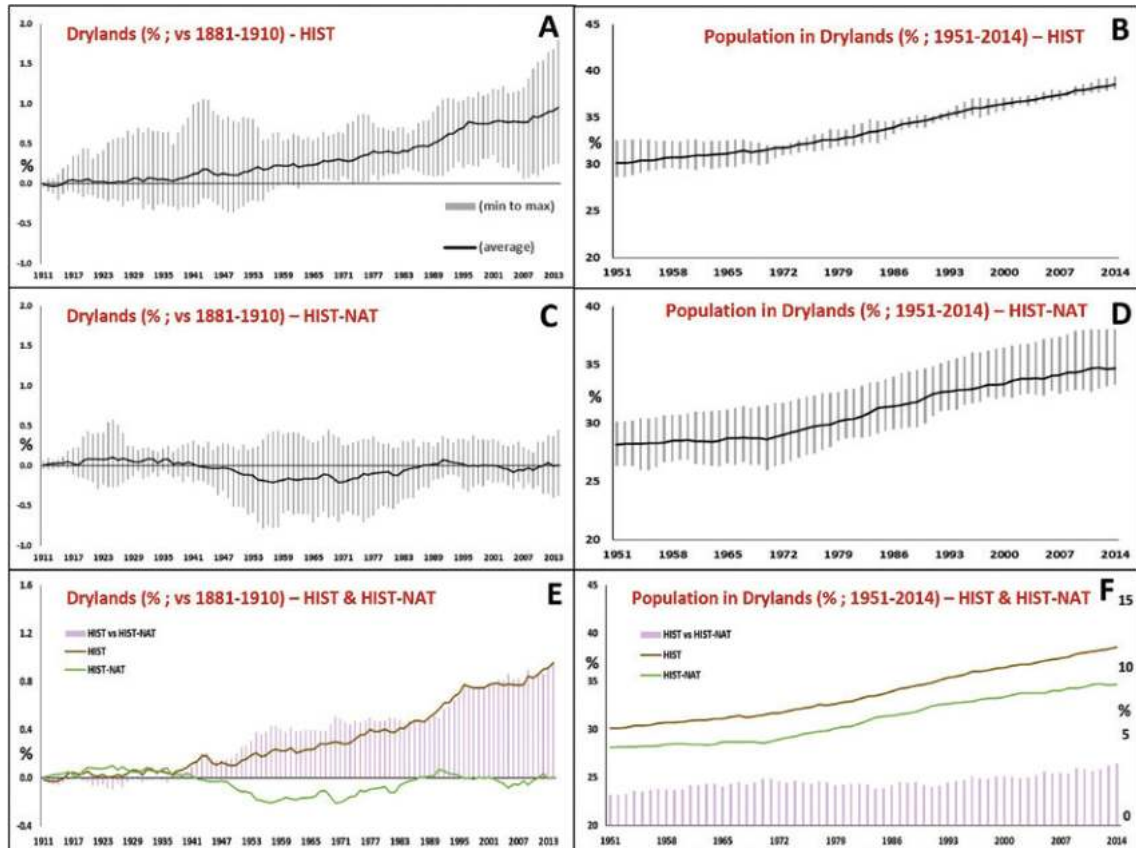
Changes in drylands extent (per cent) from 1881–1910 to three periods (upper panel), population in drylands (per cent) in three periods, for the six macroregions and at a global scale, dividing between historical (hist) and historical-natural (hist-nat) simulations. Red means drier, blue wetter and black no substantial differences between historical and historical-natural simulations. Globe includes Antarctica, where the cold AI class does not change between periods.

Drylands (%)	1881–1910 to 1921–1950		1881–1910 to 1951–1980		1881–1910 to 1981–2010	
	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	-0.4	-0.1	0.0	0.0	0.1	-0.4
LAC	0.6	-0.2	1.2	0.6	2.3	0.1
EUR	0.4	-0.2	0.1	1.2	1.1	0.3
AFR	0.4	0.3	1.1	-0.1	0.8	0.0
ASIA	-0.4	-0.1	0.0	0.0	0.5	0.3
OCE	0.5	0.2	0.2	0.1	0.7	0.4
GLOB	0.1	0.1	0.4	0.2	0.9	0.1
Population in drylands (%)	1921–1950		1951–1980		1981–2010	
	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	19.6	19.7	26.9	26.0	29.9	30.0
LAC	22.0	20.8	21.8	19.6	22.4	19.2
EUR	11.9	11.1	12.2	12.9	15.4	13.2
AFR	58.6	57.5	58.6	56.9	56.0	54.1
ASIA	34.3	32.3	35.7	32.1	40.1	36.5
OCE	34.1	30.8	32.9	31.0	31.2	30.7
GLOB	30.1	28.7	33.1	30.6	38.0	35.1



**FIGURE 11**

Left Panel: multi-model ensemble median for the percentage difference in the extent of global drylands relative to the reference period 1881–1910 according to (A) historical simulations; (C) historical-natural simulations; (E) historical versus historical-natural. Right Panel: the global annual population living in drylands illustrates change from 1951 to 2014, using historical (B) or historical-natural (D) simulations to delineate drylands and comparing both types of simulations (F). Min-max represent the models with lowest and highest values.



## 2.5. FUTURE ARIDITY TRENDS

### Global drying to worsen (except in Asia)

As much as 3 per cent of the world’s humid areas are projected to transform into drylands by the end of this century, if the world continues to drive economic development by burning large amounts of fossil fuels and accelerating climate change, according to an analysis conducted for this report.

This climatic drying reflects the potential consequences of a projected high-emissions future (SSP5-8.5) from among four anticipated greenhouse gas emissions and economic development pathways (i.e., Shared Socioeconomic Pathways, or SSPs) used to derive CMIP6-based aridity scenarios for this study. Aridity projections modelled for two other pathways—SSP2-4.5 (a “middle of the road” emissions and development pathway) and SSP3-7.0 (an emissions and development



pathway characterized by critical regional rivalries)—suggest a 2 per cent decline in global humid areas by 2100. A more optimistic pathway (i.e., SSP1-2.6, anticipating lower emissions and sustainable development going forward) suggests less change.

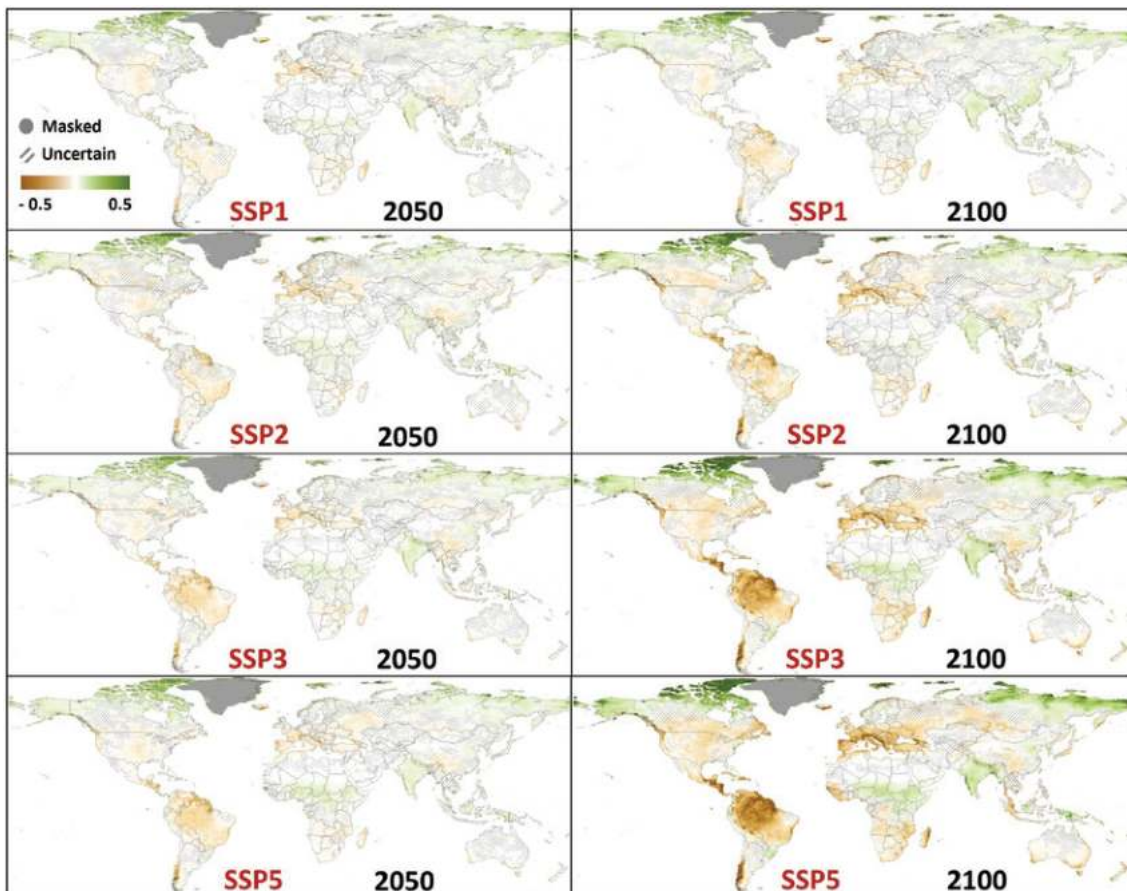
The expected increase in drylands does not mean extensive expansion of very dry areas known to be hyperarid and arid. These areas show limited expansion in the Americas, Africa (only in 2100) and Oceania (only for the SSP3-7.0 and the SSP5-8.5), while the extent of these areas will remain mostly unchanged in Europe and slightly smaller in Asia (Figure 12). Instead, the increase in drylands

is expected to reflect increases mainly in areas classed as semi-arid and dry subhumid in all regions of the world, except Asia (where precipitation is projected to increase, especially over India) and Oceania (where these areas are expected to expand by mid-century for SSP3-7.0 and the SSP5-8.5, but remain the same or shrink closer to 2100).

Regardless of the pathway, the analysis shows an increase in drylands (based on projected changes to AI values and aridity classes) projected for all regions of the world except Asia for the 30-year periods ending in 2050 and in 2100, compared to a three-decade reference period of 1981–2010.

FIGURE 12

Changes in the aridity index projected for the mid-century period of 2021–2050 (left panel) and the late-century period of 2071–2100 (right panel) relative to the reference period of 1981–2010, according to SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (in descending order). Values are computed as the median of the available simulations, and dashed lines represent areas where less than two-thirds of models agree on the sign of the change.



Drylands are projected to see the largest proportionate increase in Europe. If large-scale emissions and unsustainable development continue (i.e., SSP5-8.5), about 15 per cent of the region—including, especially, southern and eastern Europe—is expected to completely shift to a drier aridity class within the current century. This proportion could be as high as 21 per cent, if the uncertain shifts are included (see Table S6 in Supplementary Material addressing the uncertainties).

Depending on the SSP, future potential hotspots for aridification by the end of the century include most of the United States, Central America, the Amazon, Chile, the Mediterranean Region, Africa’s sub-Saharan Atlantic Coast, south-eastern Africa

(including Madagascar), southern Asia and southern Australia. These aridification hotspots show the largest projected changes in AI class from the recent past to future periods (Figure 13). In particular, the Midwestern United States, central Mexico, northern Venezuela, north-eastern Brazil, south-eastern Argentina, the Mediterranean region (including the Black Sea coastal region), large parts of southern Africa and the east and west coasts of southern Australia are projected to transform from non-drylands (i.e., humid) to drylands by 2100 for the SSP3-7.0 and the SSP5-8.5 scenarios (Figure 14).

This generalized trend of increasing aridification suggested by the various SSP scenarios is supported by assessments

**FIGURE 13** Change in the aridity index classes from 1981–2010 to 2021–2050 (left panel) and 2071–2100 (right panel), according to the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. See Figure 10 for the colour legend. Over light blue areas, the models show no agreement (i.e., less than two-thirds of models agree on such changes).

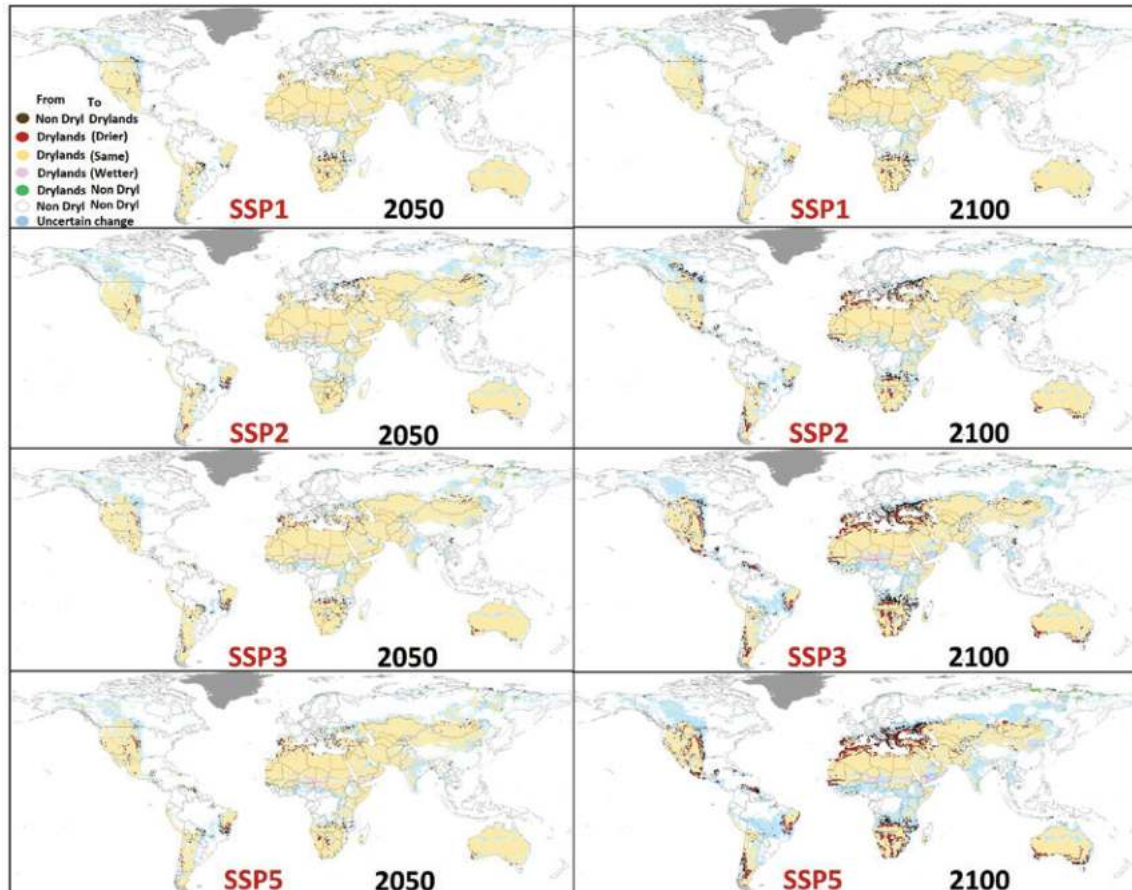
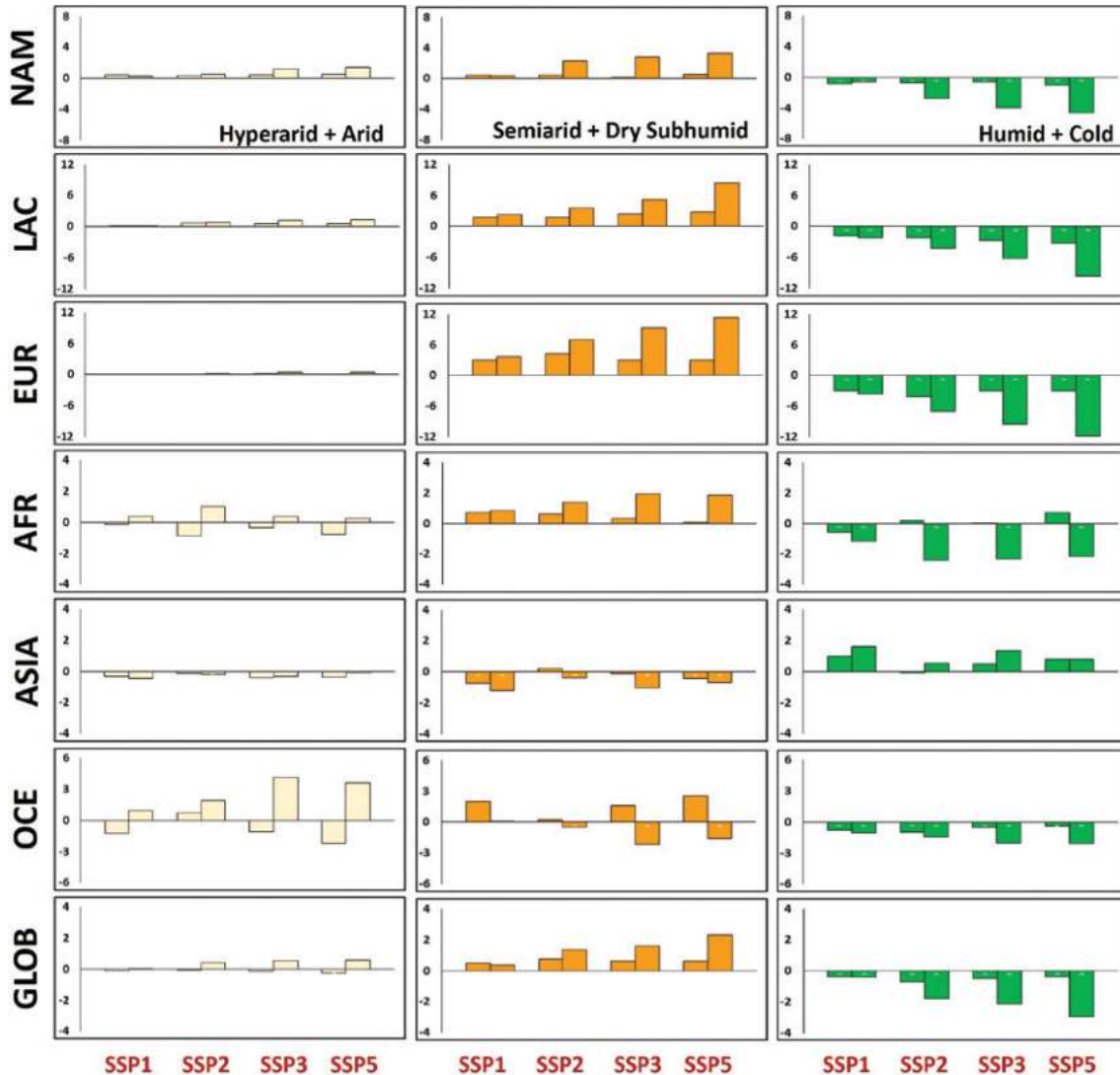


FIGURE 14

Regional and global changes (in per cent) of lands within aridity index classes for the mid century (2021–2050/left histograms for each SSP) and for the late century (2071–2100/right histograms for each SSP), according to SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.



of different global warming levels (GWLs), especially those predicting more significant temperature rises (Figures S7 and S8 in Supplementary Material).

### Future retreat of drylands unlikely

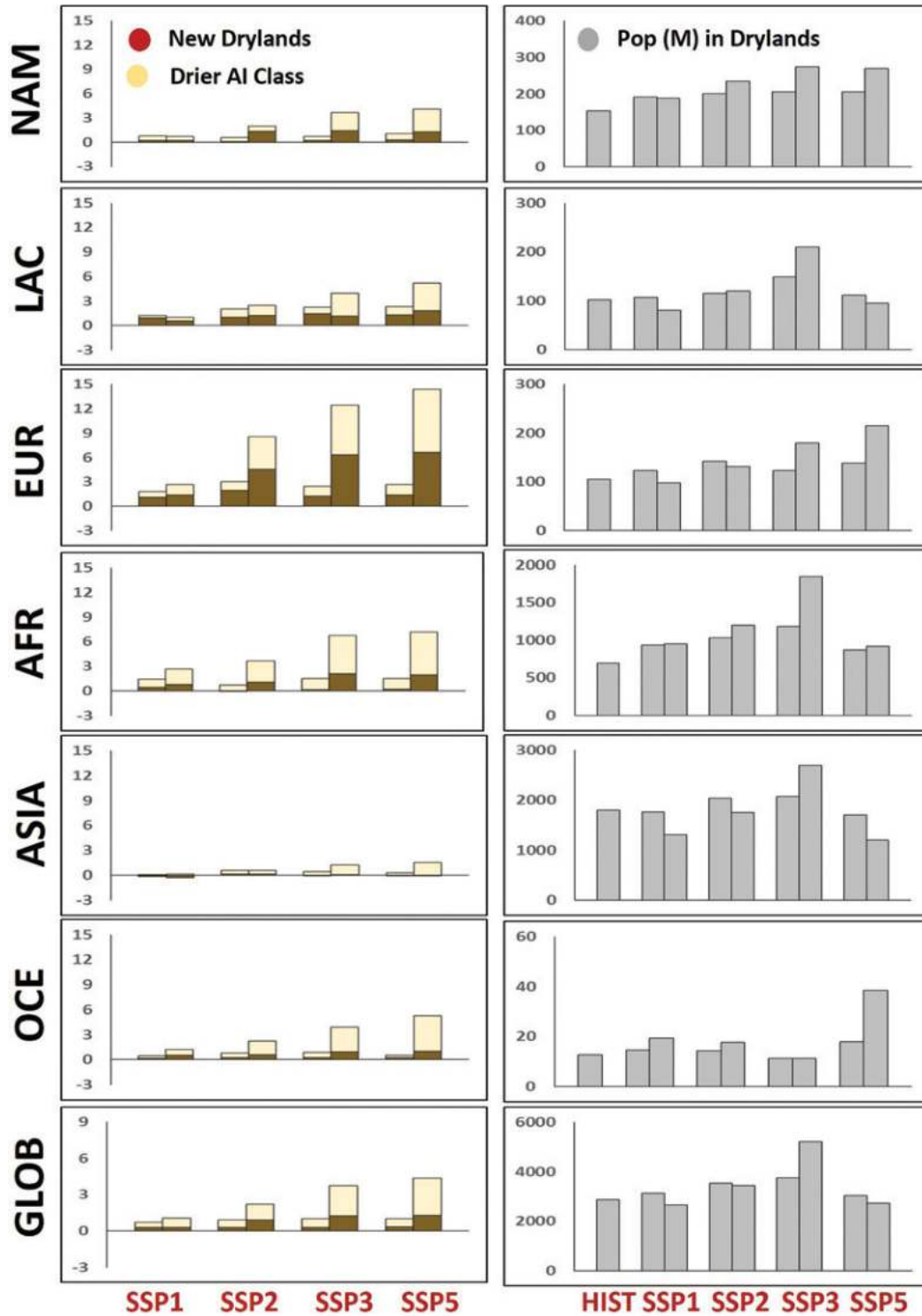
No region on the planet is projected to transition from historical drylands to future wetlands (although the future aridity status expected in some areas is uncertain). Thus, the models analysed for this study suggest that a possible retreat of drylands in the

climate-altered future appears unlikely (although models don't all agree on this outcome).

While drylands are not expected to transform into non-drylands and humid regions are expected to shrink, a number of places around the globe are nevertheless expected to become wetter than they are today. These areas include the very high latitudes in the Northern Hemisphere, Central Africa and India. Indeed, if emissions continue to soar and efforts to ensure sustainable development are ignored (i.e., SSP3-7.0 and

FIGURE 15

Regional and global changes from recent past (1981–2010) to the mid-century (2021–2050, left histograms for each SSP) and late-century (2071–2100, right histograms for each SSP) periods, according to four SSPs. Left panel: new drylands and shift to drier AI classes (per cent). Right panel: total population in drylands (in million people), including values for the recent past.





SSP5-8.5), both drying and wetting patterns across the planet are expected to grow more intense—with many previously wet areas becoming wetter and dry regions growing drier by 2100 (Figure 15).

### Billions more living in drylands by 2100

The population living in drylands could more than double—to more than 5 billion people—if climate change and human development follow a worst-case pathway through to the end of this century, according to projections developed for this report (Table S7 in Supplementary Material).

If emissions continue to soar and efforts to mitigate and adapt to climate change are mired in regional rivalries (i.e., SSP3), close to 40 per cent of the projected world population expected for this scenario could inhabit drylands and face significant risks from aridification by 2100. Even climate change trajectories based on relatively moderate emissions and development into the future (i.e., SSP2-4.5) will see the global dryland population climb to 3.5 billion by the century's end, according to the analysis.

North America, Europe and Africa are all projected to see growing numbers of people living in drylands throughout this century, regardless of which of the four emissions and development pathways lay ahead. In Europe, models assuming continued, large-scale fossil fuel use (i.e., SSP5-8.5) show the largest increase in dryland inhabitants by 2100 (i.e., the “worst-case” scenario), corresponding to the large projected increases in drylands in southern and eastern parts of the macroregion. Africa's worst-case scenario—projecting the largest increase in dryland inhabitants—follows the SSP3-7.0 pathway of high emissions, population growth and increased regional rivalries.

Oceania, currently the least populated of the world's macroregions, is expected to see its dryland population double by 2100, if growing global fossil-fuel use and unsustainable development follow a SSP5-8.5 trajectory. In Latin America and the Caribbean and in Asia, the largest increases in dryland inhabitants are projected only for SSP3-7.0, the pathway that projects the largest global population increase.

Climate change and development pathways that anticipate declining populations, on the other hand, are expected to mitigate the number of people at risk from aridification at the century's end. Future pathways for which global populations are projected to decrease beginning in the mid-century (i.e., SSP1-2.6 and SSP5-8.5) show only small increases in dryland inhabitants to about 2.5 billion in drylands in 2100. This analysis suggests shrinking global populations can offset increases in dryland extent from rising emissions and climate change and can slow increases in the numbers of people living in drylands.

Meanwhile, a trajectory that combines declining populations with low emissions and sustainable development (i.e., SSP1-2.6) is the optimal scenario for aridification risk to people in the 21st century. Global drylands are projected in this pathway to increase by as little as 0.5 per cent (with just 1 per cent of all areas shifting toward a drier AI class), a significantly smaller increase than in recent decades. The result is projected to be a limited or negligible increase in dryland populations in most regions of the world, with North America as the only exception. While numbers of North American dryland inhabitants may increase for this pathway, the trajectory remains the best-case scenario for the risks of aridification facing people who live there.









# Chapter 3.

## CURRENT AND FUTURE ARIDITY IMPACTS

Impacts from climate aridity are already being felt in drylands around the world. Climate aridity has widespread consequences over multiple biophysical and socioeconomic processes, often in the form of cascading impacts involving complex interactions among interconnected systems (Figure 16). Understanding, quantifying and assessing these impacts is essential to estimating the consequences of increasing aridity (driven by climate change) in the coming decades and to anticipating adaptation measures to reduce negative ecological and socioeconomic effects.

This section summarizes the findings of an up-to-date, systematic literature review conducted for this report to explore aridity's

most relevant current (Table 3) and future impacts (Table 4). Figure 13 illustrates how these impacts are distributed in regions across the globe.

This report recommends caution when interpreting aridity's future impacts, because the existing literature from which they are compiled (Table 4) does not always correspond to the future aridity scenarios derived from the projections analysed for this report (see Chapter 2). This is because the climate change scenarios and the generation of climate models used to project future aridity vary among the reviewed studies and those used in the projections. The findings presented below should be interpreted as plausible trends and subject to various degrees of uncertainty.

### 3.1. DESERTIFICATION AND LAND DEGRADATION

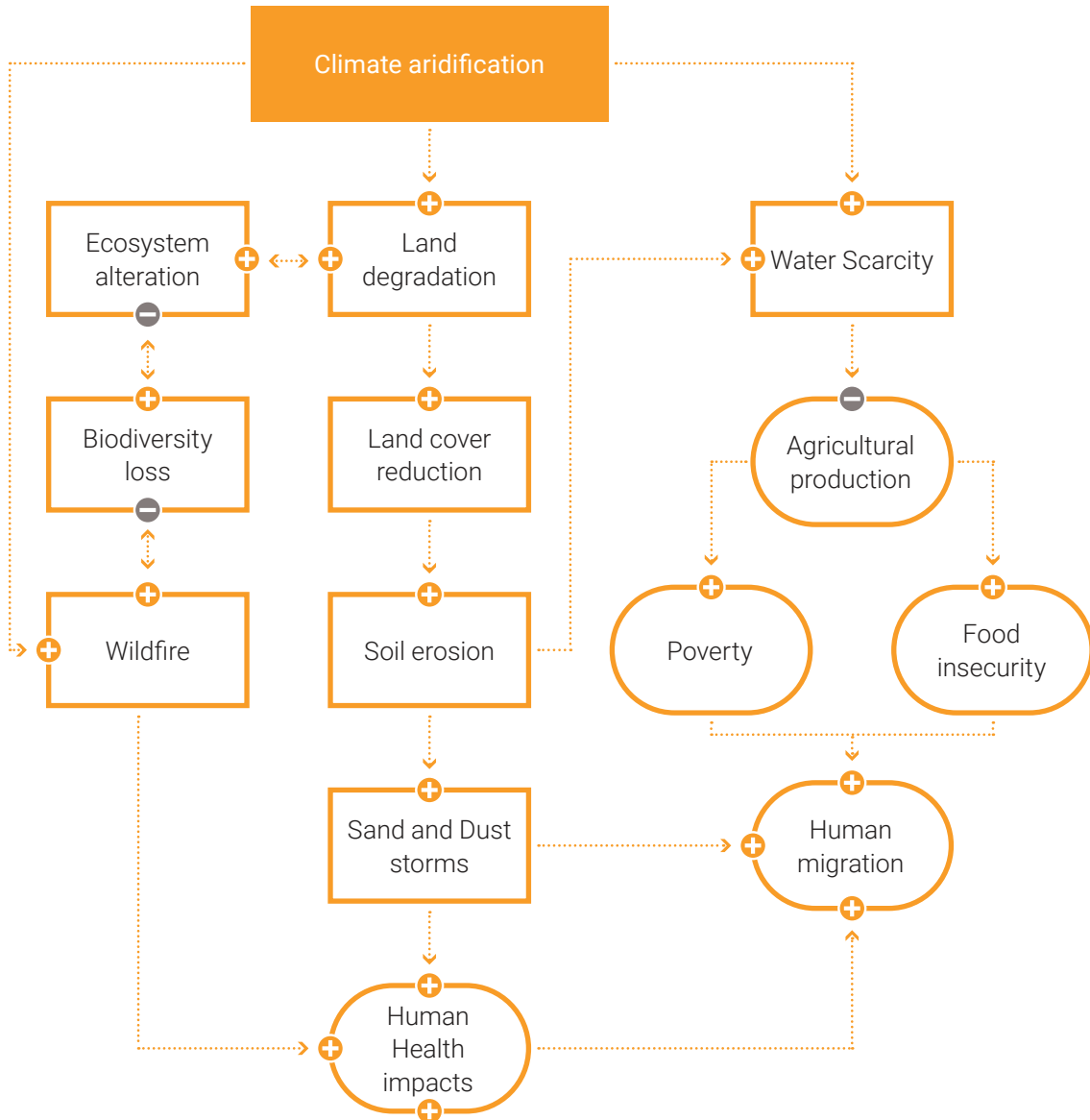
As much as 12.6 per cent of drylands around the world—an area (5.43 million km<sup>2</sup>) equal to more than half the size of the United States—has experienced desertification from the land-degrading effects of climate change and unsustainable land use in recent decades (from 1982 to 2015), affecting 213 million people living mainly in developing economies (Burrell and others, 2020).

Twenty-three per cent more global land is projected to be at “moderate” to “very high” risk of desertification in the years leading to

2100, compared with the period of 2000 to 2014, if large-scale fossil fuel use continues throughout this century (i.e., a worst-case RCP8.5 emissions pathway modelled in CMIP5 simulations; Huang and others, 2020). Eight per cent will be at “very high” risk, 5 per cent will be at “high” risk and 10 per cent more will be at “moderate” risk of desertification by late in the century. Under the moderate-emissions pathway RCP4.5, the area of all risk categories, except the low-level risk, will increase slightly by the century's end.

FIGURE 16

A diagram of cascading impacts and interactions among different socioeconomic and environmental processes affected by aridity. Arrows indicate the direction of the effect, and plus and minus symbols reflect whether the effect on these processes is increasing or decreasing in severity.



Desertification—a term that refers to land degradation in areas already considered to be drylands (UNCCD, 1994)—has affected the western United States, eastern Brazil, the Middle East, central Asia and Australia. Similar trends have been observed in a subset of drylands considered arid and semi-arid over a parallel period (1982–2016; Song and others, 2018), with hotspots of degradation found in south-western United

States, southern Argentina, Central Asia, Mongolia, China and Australia.

Other examples of areas experiencing desertification due to increasing aridity include the Horn of Africa and the Middle East, including Iran, Saudi Arabia, Jordan and Syria (Damberg and AghaKouchak, 2014; Mirzabaev and others, 2019; Pricope and others, 2013). In other regions (e.g.,

the Mediterranean region), the causes of desertification are less directly or solely attributable to rising aridity, because unsustainable land use may play a relevant role (Mirzabaev and others, 2019). Areas currently facing moderate to high risk of desertification in the future are found around deserts and barren lands, which account between 13 per cent and 7 per cent of the global land, respectively (Huang and others, 2020).

This aridity-driven desertification risk is expected to increase in the climate-altered future mainly in Europe, western Asia, northern China, the edge of the Sahel and Mexico (whereas the risk of desertification will eventually decrease in the Qinghai–Tibet Plateau and India). For Europe, a worst-case emissions pathway (RCP8.5) is expected to mean almost 11 per cent more of the continent will face desertification risks by the end of the 21<sup>st</sup> century, with large areas of Spain, southern Italy, south-eastern Europe and the Danube Delta all prone to different desertification risk levels (Spinoni and others, 2018). The Mediterranean, in particular, has been identified as a hotspot of climate change-induced aridification (Carvalho and others, 2022). At the country level, increasing aridity linked to climate change is considered the main driver of an expected 33.6 per cent expansion of land at risk from desertification in Serbia under moderate emissions (RCP4.5) and 51.7 per cent under high emissions (RCP8.5) by 2100 (Perović and others, 2021).

In Central Asia, on the other hand, projections suggest a warmer and wetter climate in the future, with the region's desert land area projected to decrease by 117,900 km<sup>2</sup> and 184,900 km<sup>2</sup> under late-century global warming scenarios of 1.5C and 2.0C, respectively (Ma and others, 2021). Likewise, China is expected to see areas at risk of desertification shrink with projected increases in rainfall (Xu and others, 2019), along with current and anticipated measures for the ecological protection of sensitive areas.

Climatic aridity has been identified as one of the five most important causes of land degradation (along with land erosion, salinization, organic carbon loss and vegetation degradation) throughout multiple ecosystems worldwide (Prävälíe, 2021). Land degradation, in turn, is recognized as one of the most significant environmental challenges facing societies today (Prävälíe, 2021), affecting almost a quarter of Earth's land and as many as 3.2 billion people, with severe implications for ecosystems and for its complex interactions with climate change (Olsson and others, 2019).

Land degradation affects the quality of land—that is, the layer of the terrestrial biosphere where ecological processes, natural resources and human settlements take place (adapted from Henry and others, 2018). Rising climatic aridity is directly connected to an increased vulnerability to land and vegetation degradation (Sun and others, 2023). This relationship, however, is nonlinear. Climatic aridity can cause abrupt changes to the structure and function of land-based ecosystems when it crosses cumulative thresholds in climatic aridity (e.g., certain AI values), resulting in a decline in soil fertility, productivity and vegetation cover (Berdugo and others, 2020, 2022) and ultimately causing land degradation.

Desertification has a complex relationship with rising greenhouse gas emissions and their impacts on climate change (Burrell and others, 2020). On the one hand, increasing climate aridity has a desertifying effect, degrading the productivity and ecosystem functioning of drylands. On the other hand, increasing atmospheric CO<sub>2</sub> concentrations have a fertilizer effect, contributing to an overall greening of Earth's land surface (Zhu and others, 2016).

## 3.2. SAND AND DUST STORMS

In some regions of the world where future rises in aridity are projected to increase desertification, sand and dust storms are expected to become more frequent and harmful. Sand and dust storms are strongly linked to aridity (or prolonged drought conditions), along with other factors that contribute to desertification and the loss of vegetation cover, such as unsustainable land use (Middleton, 2018; Reichhuber and others, 2019; UNEP and others, 2016).

In south-western United States, for example, premature deaths related to airborne dust are expected to more than double (i.e., up 220 per cent compared to 1986–2005 levels) by the century's end, if fossil fuel use continues unabated (Achakulwisut and others, 2019). With this

high-emissions SCP8.5 pathway, increases in fine and coarse atmospheric dust levels are projected to increase by 57 per cent, and 38 per cent, respectively, with expected hospitalizations to climb by 160 per cent, and health care costs will likely balloon by as much as \$47 billion per year (Achakulwisut and others, 2019).

In arid regions of the Middle East and Asia, on the other hand, atmospheric dust related to sand and dust storms for future climate change scenarios are projected to decrease. Models of global warming suggest that, for the remainder of this century, this decline is projected to continue for sand and dust storms linked to Mongolian cyclone activity (Li and others, 2022)—a decrease related to changes in atmospheric circulation and



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cyclone formation rather than to trends in climate aridity. Similarly, in West Asia and the Middle East, airborne dust is projected to decrease for the near future (i.e., to 2032) as climate change projections anticipate more soil moisture and lower wind speeds (Rabbani and Sharifikia, 2023).

Sand and dust storms are atmospheric events in which strong winds liberate sediment particles from the ground and transport them far distances (adapted from UNEP and others, 2016). These events, which can pose serious risks to populations, occur typically in arid and semi-arid regions where vegetation cover is scarce and the ground is more susceptible to sediment entrainment by the wind (Issanova and others, 2015; UNEP and others, 2016; Zucca and others, 2022). Thus, these storms are also tied to the regime of winds related to atmospheric circulation (Achakulwisut and others, 2017; Yang and others, 2008).

While climatic aridity is significantly correlated with quantities of atmospheric dust on a global scale (Mahowald and others, 2007), observed sand and dust storms around the world show no consistent

trends. At a regional level, however, opposite observed trends point to the complexity of the phenomenon. For example, increasing aridity recently reported in the Middle East has been tied to more frequent (Ebrahimi-Khusfi and others, 2022) and larger (Liu and others, 2016) sand and dust storms. Persistent drought conditions in the Sahel since the mid 1960s, meanwhile, have also preceded large increases in Sahel dust production (Ozer, 2003). Likewise, increasing aridity, combined with surface disturbance due to human land use, has been connected to windborne sediment transport over the Colorado Plateau of the United States in recent decades (Nauman and others, 2018).

These same factors have contributed to the increasing frequency of sand and dust storms in Mongolia, including a March 2021 storm that affected about 8,000 people, caused 10 deaths and left thousands of livestock missing (Han and others, 2021). However, in the arid regions of Central Asia and China, sand and dust storms have generally decreased in frequency, a shift explained by changes in regional and global atmospheric circulation (Indoitu and others, 2012).

### 3.3. ECOSYSTEMS AND BIODIVERSITY

More than a fifth of all land on the planet could experience abrupt ecosystem transformation in response to rising aridity by the end of the century, according to recent research (Berdugo and others, 2020). If CO<sub>2</sub> emissions continue to rise (i.e., RCP8.5 scenario), the research suggests aridity may pass key thresholds by 2100 that cause nonlinear changes in one or more of the ecosystem-defining features of plant productivity, soil fertility and plant cover and richness.

Other research suggests more than 55 per cent of all species among the world's mammals, reptiles, fish, amphibians

and birds could lose their habitat to unprecedented aridity—raising the risk of widespread biodiversity loss—if high greenhouse gas emissions continue to spur climate warming through to 2100 (i.e., SSP8.5; Liu and others, 2023a). Hotspots for this habitat loss are projected to include the arid regions of the west coast of Africa, west Australia and the Iberian Peninsula, but also humid regions such southern Mexico or the northern Amazon rainforest where many vertebrate species will experience aridity largely exceeding their niche limits.

Rising aridity related to climate change is altering the function and structure of dryland

ecosystems around the world (Berdugo and others, 2020). A significant number of studies highlight the threats of increasing global aridity to terrestrial ecosystem characteristics at different levels of the food chain, including risks to micronutrients in the soils (Moreno-Jiménez and others, 2019) that affect the microbiota (Maestre and others, 2015; Neilson and others, 2017), to grasslands (Brookshire and Weaver, 2015; Zhang and others, 2023a), to tree species (Allen and others, 2010; Vicente-Serrano and others, 2010; Williams and others, 2010), to overall plant productivity (Li and others, 2023) and to highly vulnerable vertebrates, such as amphibians (Shi and others, 2021).

Increased aridity has also been recognized as the main driver of river flow cessation and of the global prevalence of ephemeral rivers (Messenger and others, 2021). These impacts have implications for endemic fish

(Jaeger and others, 2014) and invertebrate communities living in these intermittent streams (Vander Vorste and others, 2021).

Increasing aridity into the future poses a significant threat to aquatic communities of dryland streams, including invertebrates and fishes (Crabot and others, 2021; Vander Vorste and others, 2021). If emissions continue to rise through to 2100 (i.e., a RCP8.5 scenario), for example, Jaeger and others (2014) project a 17 per cent increase in drying events in Arizona's Verde River in the United States with an 8–20 per cent decrease in the river's flowing portions. This is expected to substantially reduce hydrological connectivity and force fish to migrate to aquatic refuges, such as permanent streams.

Climate change-driven aridification has been linked to tree mortality, with



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contrasting evidence that rising temperature, atmospheric evaporative demand and low precipitation are the main drivers of tree deaths from water stress, reduced growth and reduced resilience to pests (Allen and others, 2010; Díaz-Martínez and others, 2023; Eamus and others, 2013; Forzieri and others, 2022; Grossiord and others, 2017; Maranz, 2009; Navarro-Cerrillo and others, 2022).

Nevertheless, forest ecosystems are considered especially sensitive to expected aridification under future warming conditions. More trees are projected to die in response to greater water stress during warmer droughts in combination with related wildfires and reduced resistance to pests and pathogens, and forests are expected to experience a progressive replacement by shrub species that are better adapted to drier conditions (Adams and others, 2017; Baudena and others, 2020; McDowell and Allen, 2015; Yi and others, 2022). In Australia, for example, a scenario of just moderate warming is expected to increase drought-related tree die-offs by 160 per cent, as the frequency of these extreme dry-weather events increases (Mitchell and others, 2014). Impacts are also projected to exceed the current tree mortality thresholds under a high-emissions scenario in the arid south-western United States by the 2050s (Anderegg and others, 2015).

### 3.4. WILDFIRES

Increasing aridity is expected to play a key role in larger and more intense wildfires in the climate-altered future—not least because of its impacts on tree deaths in semi-arid forests and the consequent growing availability of dry biomass for burning (Goodwin and others, 2021). For Europe, at least, the probability of these extreme fires is expected to more than double (i.e., reaching 0.45 compared to 0.19 as the historical baseline), if greenhouse gas emissions

The impacts of aridification on biodiversity can dramatically affect the structure and the fundamental processes of ecosystems (Berdugo and others, 2022; Shi and others, 2021). In drylands, aridity shows a strong negative correlation with species richness (García-Palacios and others, 2018). Importantly, aridity's impact on ecosystem function and structural attributes (e.g., plant species richness, fertility, soil organic carbon content, productivity, nitrogen content in leaves) is nonlinear, so that small increases in aridity that exceed particular aridity thresholds can lead to drastic changes in the values and characteristics of these attributes (Berdugo and others, 2020, 2022; Li and others, 2021a).

Even so, the extent of these ecological impacts from future aridity—and the chances of crossing aridity thresholds that transform ecosystems—is subject to debate. While some researchers predict climate-induced rising aridity will drive frequent nonlinear changes in ecosystems throughout the century (Berdugo and others, 2020), others suggest increased atmospheric CO<sub>2</sub> (from greenhouse gas emissions) could make plant water use more efficient and, in turn, reduce the likelihood of exceeding aridity thresholds (Keenan and others, 2020).

continue to climb (i.e., SSP8.5) by the end of the century (Grünig and others, 2023)

The Mediterranean region and the Amazon are expected to be particularly affected and are considered hotspots for climate-affected increases in fire weather—i.e., the hot, dry conditions in which wildfires propagate (Abatzoglou and others, 2019). For example, heat-induced fire-weather in the Mediterranean Basin is projected to



become 30 per cent more frequent by the last decades of this century (i.e., 2071–2100) in a high-emissions scenario (i.e., RCP8.5), and even moderate emissions (RCP4.5) will see a 14 per cent increase (Ruffault and others, 2020). Greece—which has suffered record-breaking wildfires in recent years—is expected to see up to 40 additional days of high fire danger by the end of the century (relative to the late 20th century; Rovithakis and others, 2022). Researchers warn that increases in aridity may critically reduce the resilience of Mediterranean forests against fires, leading to the potential transformation of post-fire ecosystems into open shrublands (Baudena and others, 2020).

More days of extreme fire weather are also projected in California by 2100 (Xu and others, 2020), resulting—under a high emissions scenario—in projected

increases in the area burned by as much as 74 per cent in the final decades of the century relative to recent decades (Westerling and others, 2011). Similarly, continued high CO<sub>2</sub> emissions (i.e., RCP8.5) are expected to result in significant increases in the risk of wildfires (relative to the risk in 2005) across all seasons in south and central Chile for 2050 and 2100 (Ciocca and others, 2023).

Wildfires and aridity are strongly interconnected. On the one hand, the occurrence and magnitude of wildfires depend largely on the same atmospheric variables—i.e., temperature, atmospheric vapour pressure deficit (VPD) and wind—that drive atmospheric aridity (Duane and others, 2021; Park Williams and others, 2014). On the other hand, wildfires can amplify the impacts of aridity on ecosystems and land degradation by reducing vegetation



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cover, increasing run-off and soil erosion and affecting soil microbial communities (Mirzabaev and others, 2019).

Wildfires also involve important feedback mechanisms with climate change, because of their direct impacts on CO<sub>2</sub> emissions and sinks and their impacts on albedo by removing vegetation cover or by depositing ashes over ice surfaces. These feedback mechanisms are considered a key element in understanding and mitigating anthropogenic global warming (Keywood and others, 2013; Liu and others, 2014; Stocker and others, 2021).

During the last decade, many severe and extreme wildfires have been documented particularly in semi-arid regions around the globe, such as those in Mediterranean-like climates, including California, Chile, southern Europe or south-east Australia (Brown and others, 2023; Ribeiro and others, 2020; Rodrigues and others, 2023; Tran and others, 2020; Bowman and others, 2019). While land management, urban expansion and other human causes can intensify the risk and exposure to wildfire (Hantson and others, 2015; Hawbaker and others, 2013; Sarricolea

and others, 2020; Siegel and others, 2022), increased or unusual atmospheric aridity (at various time-scales and linked to human-caused climate warming) is the underlying common factor for larger and more severe wildfires in semi-arid regions (Brown and others, 2023; Diffenbaugh and others, 2021; Williams and others, 2019; Xu and others, 2020).

Increasing aridity has been blamed for larger and more severe fires in Europe, with atmospheric moisture demand in that region correlating with wildfire severity and burned area (Grünig and others, 2023). Climate-related aridity increases observed in the south-west and western United States have also been connected to more severe and widespread wildfires in those regions (Overpeck and Udall, 2020). Likewise, the recent increase in the frequency of high-intensity wildfires observed in central Chile have been closely linked to a long-term decrease in precipitation over the last four decades, following intense heat waves and droughts linked to large climate variability factors, such as the El Niño-Southern Oscillation (González and others, 2018; Cordero and others, 2023).

### 3.5. WATER SCARCITY

More than two-thirds of all land on the planet (excluding Greenland and Antarctica) is projected to store less water by the end of the century, if climate change continues along a medium-high greenhouse gas emissions pathway (i.e., RCP6.0; Pokhrel and others, 2021). Climate-affected seasonal changes in precipitation and evaporation will also likely mean the disruption of regional and seasonal water availability in many areas around the globe (Konapala and others, 2020).

Increasing aridity is contributing to growing water scarcity, one of the main environmental issues threatening the socioeconomic

wellness of global societies and affecting between 1 and 2 billion people, mainly in drylands around the world (Právělie, 2016; Stringer and others, 2021).

Water scarcity—defined as “an excess of water demand over available water supply” (FAO, 2012a)—arises when insufficient water simultaneously fails to support both human and ecosystem water needs (Bond and others, 2019). Rising aridity (and desertification), resulting from climate conditions and their ecological impacts, is a primary driver of this imbalance between water needs and water availability (Bates



and others, 2008; Berghuijs and others, 2017; Gudmundsson and others, 2016). However, human factors, such as population increases, economic growth, unsustainable irrigation or insufficient infrastructure for water storage, often exacerbate water scarcity, especially in arid regions (Chitsaz and Azarnivand, 2017; Salehi, 2022).

Throughout the world, drylands of all aridity classes (i.e., hyperarid, arid, semi-arid and dry subhumid) saw their terrestrial water storage decrease by about 16 mm between 2002 and 2017 (Chang and others, 2020). In some regions, such as dryland areas in North America and the Middle East, this decline was mainly driven by climate—i.e., a growing imbalance between atmospheric demand (evapotranspiration) and precipitation. In other regions, such as Northern China, human water use appears

to have played a predominant role. Likewise, in separate research, a severe water crisis in Central Asia was found to have been mainly driven by population growth, increased irrigation, the expansion of cultivated areas and unsustainable management of transboundary rivers, with a less important contribution from climate change (Wang and others, 2022b).

Many arid and semi-arid regions of the world—including the Mediterranean, the Middle East, North Africa, Central Asia, India, the Horn of Africa or south-western United States—are projected to be increasingly exposed to water scarcity (measured as annual water resources per capita) by the middle of the present century—with different levels of risk depending on the warming scenario considered (Gosling and Arnell, 2016).



In the area comprising the Middle East and North Africa, annual water availability is expected to drop by 26 and 62 mm (relative to current levels) by 2100 under SSP2-4.5 and SSP5-8.5 scenarios, respectively (Ajjur and Al-Ghamdi, 2021). For Saudi Arabia, in particular, projected increases in atmospheric evaporative demand of 6 and 12 per cent by 2100 for scenarios SSP2-4.5 and SSP5-8.5, respectively, are expected to significantly affect agriculture in the country (El-Rawy and others, 2023). A consequent 12.4 per cent increase in crop water requirements (for the worst-case scenario) is expected to create water deficits of between 8 and 15 per cent for different crops, such as wheat, clover and maize.

Catchments in several semi-arid areas of the world show a tendency towards less run-off during the last decades, a decline considered closely related to diminished precipitation and increased evapotranspiration (i.e., climate aridification) in south and central Chile (Barrientos and others, 2023), in Spain, Italy, Greece, Turkey and other riverine Mediterranean countries (García-Ruiz and others, 2011) and in south-eastern Australia (Zhang and others, 2016a). Groundwater recharge is more sensitive to climate fluctuations in regions where potential evapotranspiration exceeds precipitation and where even slight climate aridification can drive substantial decreases in both groundwater levels and groundwater quality (particularly where seawater intrudes in coastal aquifers; Berghuijs and others, 2024).

Under future climate change conditions, the Mediterranean is widely regarded as a hotspot of reduced water availability as a result of intensified negative water balance (García-Ruiz and others, 2011; Mariotti and others, 2008; Schneider and others, 2013). Precipitation in the region is projected to decrease by 20 and 40 per cent with increases of about 15 per cent and 30 per cent in evapotranspiration for the 2081–2100 period under the RCP4.5 and

RCP8.5 emissions pathways, respectively (Carvalho and others, 2022). Water availability in the region's mountainous areas—such as the Pyrenees, the Alps or the Atlas Mountains—that serve as the headwaters for Mediterranean river networks could decline by as much as half as a result of reduced glacial meltwater and less seasonal accumulation of snow and ice (Carvalho and others, 2022).

Similarly, in the Andes mountains of South America—the source of water for vast arid and semi-arid areas of Chile, Bolivia and Argentina—annual run-off is projected to decline by 40 per cent by 2100 under a high-emissions climate scenario (i.e., RCP8.5; Bozkurt and others, 2018). Under scenarios in which moderate climate drying and warming leaves precipitation unaffected, stream flows are expected to decline by 2–11 per cent, while climate scenarios that reduce precipitation are expected to interrupt stream flows by more than a third (36 per cent) to more than a half (52 per cent; Slosson and others, 2021).

For El Kalb River in Lebanon, for example, river flows are projected to decrease by 28–29 per cent for the near future (i.e., 2021–2040) and by about 23, 28 and 45 per cent for the end of the century (i.e., 2081–2100) under RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively (Saade and others, 2021).

Increasing evapotranspiration and consequent water demands for irrigation exacerbate water scarcity by exposing groundwater resources to risks of depletion (Condon and others, 2020). Coastland aquifers of arid and semi-arid areas face the additional risks from sea water intrusion (Guyennon and others, 2017). In Jordan, for example, most groundwater basins are vertically and horizontally interconnected with different water quality horizons and with water salinity generally increasing at deeper layers. As a result, the increasing exploitation

of deep aquifers containing non-renewable fossil groundwater risks fresh groundwater seeping down and becoming salinized in the deep saline aquifers, depleting the deep groundwater and reducing the fresh groundwater in the overlying groundwater aquifers (Salameh and others, 2024).

Aridity also influences water availability indirectly through soil degradation. Degraded soils lose their capacity to hold water and favour surface run-off and erosion, which further limits available water in soils and aquifers (Liu and others, 2015b; Seeger and Ries, 2008; Sharma, 1998). However, the degree of severity and reversibility differs among these processes. In cases of drought or intense soil use, the impacts may be temporary. Impacts arising from aridity and desertification, on the other hand, are more likely to be irreversible. This distinction may be important to better understanding both the impacts of increased aridity and adaptation options (Bond and others, 2019; Pereira and others, 2009).

Water demand itself can be affected by aridification. Rain-fed agriculture is one of the main sources of livelihood in semi-arid regions, where crop production is strongly limited by water availability (Rockström and others, 2010). An increase in overall aridity in these regions can hurt local rain-fed

production and, while indirectly accentuating demand on both local and global markets, can increase pressure on irrigated production (FAO, 2012a). Moreover, higher temperatures and atmospheric evaporative demand can exacerbate the water requirements of irrigated crops—a phenomenon already observed in drylands of the Middle East (Chowdhury and others, 2016; Ragab and Prudhomme, 2002; Salman and others, 2020)—and can worsen the overall imbalance that drives water scarcity.

Throughout the Middle East and North Africa, which comprise the most water-scarce areas of the world (Roudi-Fahimi and others, 2002; Tropp and Jägerskog, 2006), a 75 per cent decline in water availability since the 1950s has accompanied growing populations, agricultural expansion and declining water availability (World Bank, 2009a). This reduced availability has been largely associated with aridification, in part due to the decline in precipitation in the area (Procházka and others, 2018) and to increased temperatures and evapotranspiration rates since the 1970s (Hamed and others, 2023). Higher atmospheric evaporative demand, in turn, has increased the consumption of water by agriculture to require up to 90 per cent of available water (Roudi-Fahimi and others, 2002).

## 3.6. AGRICULTURE, LIVESTOCK AND FOOD PRODUCTION

Aridity is considered the world's largest single driver behind the degradation of agricultural systems, affecting 40 per cent of Earth's arable lands—or about 5.7 million km<sup>2</sup>—and another 7 per cent, if the synergetic effects of soil erosion are added to the total (Právělie and others, 2021).

Human-caused climate change—and its impact on aridity—have already damaged agriculture and food production around the world (Ortiz-Bobea and others, 2021), and the problem is expected to worsen into the future—especially in sub-Saharan Africa, North Africa and the Middle East and South



Asia (World Bank, 2009a). Projections suggest that a climate-change-related increase in global arid area by 3.9 per cent by 2040 will mean losses of about 20 million tons of maize, 19 million tons of rice, 8 million tons of soybeans and 21 million tons of wheat (Malpede and Percoco, 2023).

In sub-Saharan Africa, for example, between 17 and 22 per cent of current crop production could be lost by mid-century due to the impacts of increasing aridity and temperatures in a moderate emissions scenario (Schlenker and Lobell, 2010). Rain-fed agriculture will be especially affected (Serdeczny and others, 2016). Yields of millet in the region have been projected to decline by a quarter within the same time frame, if greenhouse gas emissions continue to be high (Emediegwu and others, 2022), and in Kenya, maize production is projected to fall by as much as half by 2050, due to increased

atmospheric evaporative demand across the country (these projections, however, are considered highly uncertain; Herrero and others, 2010).

Meanwhile, Pakistan's arid and semi-arid areas are projected to see a 57 per cent decrease in per capita availability of wheat under a +3°C scenario for 2050 (relative to 2012; Hussain and others, 2018), and yields of pearl millet in the country are expected to drop by 7 and 13 per cent under RCP 4.5 and RCP 8.5 scenarios for 2040–2069, respectively (relative to 2015; Ullah and others, 2019).

Aridity's impacts on dryland agricultural production are highly dependent on the temporal and spatial distribution of precipitation, evapotranspiration and the availability of freshwater resources—factors affected, in turn, by aridity-driven



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land degradation and by decreasing water availability in the long term. Crop production in drylands is mostly based on rain-fed agriculture and is especially sensitive to climate fluctuations (Bates and others, 2008; Rockström and others, 2010).

While droughts often attract attention because their dramatic and sudden declines in water availability cause direct losses in food production and spikes in food prices (FAO, 2012b; Kim and others, 2019), aridification is subtler, and its direct effects on crop yields are harder to quantify. Globally, droughts have been reported to cause national crop yield declines of 9–10 per cent, and these impacts have been increasing in recent decades (Lesk and others, 2016). Similarly, aridity is considered one of the major crop stresses (along with ozone, pests, diseases and heat) on the global production of soya and wheat (Mills and others, 2018).

At a global scale, a country's proportion of hyperarid, semi-arid and arid land appears negatively correlated with its output of major crops, highlighting the fact that, even in regions where precipitation has increased, a higher atmospheric evaporative demand may negatively affect crop yields (Malpede and Percoco, 2023). Desertification—the degradation of drylands, often as a result of rising aridity—has also been linked to losses in agricultural productivity and incomes in many places around the world (Mirzabaev and others, 2019).

At the country level, aridity values (i.e., as measured by AI) have been clearly correlated with lower crop yields in Iran (Bannayan and others, 2010; Kouchak and others, 2023) and Botswana (Byakatonda and others, 2018). Elsewhere, however, increasing climate aridity has shown no impact on crop production. This may be linked to months when rainfall usually exceeds crop water demands to offset annual water deficits (as observed in Australia; Ludwig and others, 2009). It may also be related to the use

of improved crop varieties and improved management practices, such as the adoption of conservation tillage, crop rotations and increases in irrigated area (as seen in southern Africa; Nhamo and others, 2019). Irrigation, however, can also be affected by aridification. For example, recurrent droughts in nut producing areas of California have already resulted in trees being removed due to lack of access to irrigation water (Keppen and Dutcher, 2015; Reisman, 2019).

While climate warming is projected to threaten future farm production, especially in places prone to land degradation and extreme weather events, such as drought, floods or windstorms (IPCC, 2022; Mirzabaev and others, 2019), rising greenhouse gas emissions can also positively affect crops, thanks to the fertilizing effect of increasing CO<sub>2</sub>. In Morocco, for example, a projected 7–30 per cent decline in wheat yield by mid-century is expected to be directly offset by a CO<sub>2</sub> fertilizing effect that will improve yields by 7 and 13 per cent for RCP4.5 and RCP8.5 scenarios, respectively (Bouras and others, 2019). A similar effect was shown for grain yields in Jordan (Dixit and others, 2018). This beneficial effect could also reduce water requirements by 13 to 42 per cent in response to the shortening of the growth cycle.

Even so, a meta-analysis by Knox and others (2012) examined the negative impacts of climate warming and the beneficial effects of CO<sub>2</sub> in 50 published studies and concluded that mean crop yield will decrease by 8 per cent across Africa and South Asia by 2050—with differences depending on the crop and the warming scenario considered. In any case, the fertilizing effects of CO<sub>2</sub> are influenced by significant uncertainties (see Box 1), making it difficult to assess the overall impact.

Generally, insufficient crop yields make countries in drylands highly dependent on food imports to ensure food security (FAO, 2020). These countries face additional food security risks when increases in



food prices make imports prohibitive (Christoforidou and others, 2023) or when food production crises, such as those during severe droughts, make these imports unavailable (Hameed and others, 2020). The socioeconomic and health impacts of these food crises are aggravated under conditions of increasing aridity.

Aridity's impacts on livestock have not been well researched, but the effects of rising aridity on rangeland vegetation have been shown to be consequential. In eastern Ethiopia, for example, research that tracked the aridification of the region for six decades between 1944 to 2004 showed a significant degradation of rangeland vegetation (Kassahun and others, 2008). This, in turn, diminished the grazing/browsing capacity of the region and significantly altered the livestock species composition—favouring more camels and small ruminants and fewer cattle and donkeys. The result was reduced overall food production and increased poverty.

Meanwhile, high aridity—with its absence of fertile soils and water resources to sustain crop production—can contribute to making pastoralism a critical activity for the livelihoods of rural dryland households. Intense grazing in drylands, in turn, can cause vegetation and land degradation, synergistically driving desertification and more climate aridification (e.g., Carboni and others, 2023, Oñatibia and others, 2020, Velasco Ayuso and others, 2019; Zhang and others, 2023a).

Climate aridification may also affect livestock production in the future by altering the quantity and quality of forage and available water, increasing heat stress and creating other climate conditions to which a region's livestock species may not be currently adapted (Thorton and others, 2009; Rojas-

Dawning and others, 2017; Rahimi and others, 2021). In semi-arid Australia, for example, simulations of future sustained lower amounts of precipitation and increases in its inter-annual variability led to declines in dry matter forage, in herd stocking rates, in livestock sales and in herd mortality (Godde and others, 2019).

Similarly, in Israel, a projected 20 per cent decline in precipitation (along with an increase in its inter-annual variability) was expected to significantly affect net primary production of herbaceous ecosystems, with vegetation of arid and semi-arid sites showing the highest sensitivity to future changes in climate (Golodets and others, 2015). These climate impacts on the vegetation of arid lands may be exacerbated by the effects of unsustainable grazing, which, in turn, can seriously aggravate future husbandry activities in drier climates (Cipriotti and others, 2019).

The limited research on climate impacts on livestock to date has mostly focused on the effects of droughts rather than on aridification. During a 2011–2012 drought in Mexico, for example, cattle populations declined significantly—but not those of sheep or goats—with an almost complete recovery to previous levels after the drought was over (Murray-Tortarolo and Jaramillo, 2019). Similarly, a drought in South Africa from 2015 to 2016 saw livestock losses of 43 per cent of all cattle and 29 per cent of goats (Vetter and others, 2020). While goat numbers recovered within three years of the drought, cattle numbers did not. In principle, the impact of aridification on livestock is expected to be less shocking than the effects of droughts, but these impacts may result in more structural changes for livestock farming, given the long-term nature of this climatic condition.

## 3.7. POVERTY

Rising aridity has been blamed for a 12 per cent decline in gross domestic product (GDP) recorded for African countries between 1990–2015 (Malpede and Percoco, 2021a). Among Asian nations, aridification—which has a greater impact than precipitation or temperature alone—is considered responsible for a 2.7 per cent GDP drop over the same period.

While few climate-model projections directly link future aridity to poverty, climate drying in the future is nevertheless expected to make poverty more acute, resulting in losses in GDP growth of about 16 and 6.7 per cent in Africa and Asia, respectively, under the modest-emissions RPC4.5 scenario for 2079 (Malpede and Percoco, 2021b). Other global projections suggest that—unless measures for eradicating multidimensional poverty are applied—climate change could increase the number of people living in poverty by between 35 million and 122 million people by 2030, especially in arid regions of the Sahel, eastern Africa and South Asia (Bangalore and others, 2016). However, these figures include the overall impact of expected climate change on the economy, without distinguishing the particular impacts of climate aridification.

Rising aridity affects economic wealth mainly among rural farmers and pastoralists in arid regions, contributing to income losses from poor crop and livestock husbandry linked to land degradation/desertification and water scarcity (Nkonya and others, 2011). In arid, semi-arid and dry subhumid regions of Africa, for example, 40 per cent of the 240 million agriculture-dependent people are estimated to be living below the extreme poverty line (Cervigni and Morris, 2015).

The relationship of aridity and poverty, however, is not straightforward, and efforts to link the two have resulted in contradictory findings. For example, Malpede and Percoco

(2021) found that each standard deviation drop in the AI (i.e., indicating rising aridity) was associated with a decline in the GDP per capita of between 1.9 and 4.1 per cent in Africa and Asia. Similarly, Barrios and others (2010) concluded that declining rainfall in sub-Saharan Africa during the last decades had an important impact on economic growth and suggested that if rainfall had remained at previous levels, the gap in GDP per capita relative to other developing countries would be between 15 and 40 per cent lower than it is now.

Mirzabaev and others (2023) also found that lands that had experienced three decades of degradation—often associated with aridification—showed a 4.8-fold reduction in crop-season farm profits compared with farms that had experienced no land degradation in arid Central Asia. Traore and others (2014), on the other hand, found that poverty rates in West Africa were independent from the latitudinally distributed AI, with some of the highest rates of poverty found in both high aridity (e.g., in the Zinder Region of Niger) and low aridity (e.g., Kwara State in Nigeria) areas.

Scientific projections directly linking future aridity and poverty under climate change scenarios are frequently uncertain, but declining crop yields as a result of climate change can result in higher food prices and increased poverty in drylands (Hallegatte and Rozenberg, 2017; Hertel and others, 2010).

Droughts are more abrupt and sudden than aridification, and their direct effects on poverty—from sudden crop failures that trigger inflation and decrease household consumption—are easier to quantify (Makoka, 2008). For example, a moderate drought in Ethiopia, such as the drought of 2002, can increase poverty rates from 30 to 36 per cent (Hill and Porter, 2017). In Somalia, a severe drought in 2016 and

2017 increased poverty in that country by 9 per cent. In one study projecting future drought impacts for 16 developing countries (including Zambia, Mexico and Bangladesh), for example, anticipated increases in the

intensity of extreme dry events by 2080 (under the SRES A2 scenario) are projected to lead to an average rise of extreme poverty by 0.53 percentage points relative to current levels.

### 3.8. HUMAN HEALTH

While global projections predict that climate change—and its impacts on heat, malnutrition, malaria and diarrhoeal diseases in Africa and Asia—could result in more than 250,000 deaths by 2050 (compared to a 1960–1990 reference period; WHO, 2014), isolating future health impacts from aridity alone are more difficult to project.

Deaths from climate-related temperatures are expected to climb between 3 and

13 per cent in Central America, Southern Europe and South-East Asia by the end of the century, if greenhouse gas emissions remain high (i.e., RCP8.5 scenario; Gasparrini and others, 2017). In the Mediterranean Basin, meanwhile, the populations of African nations and countries along the eastern Mediterranean coast are at highest risk of climate change-related impacts on health, especially associated with extreme heat and vector and water-borne diseases that are



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often associated with aridification (among other factors; Linares and others, 2020).

Isolating human health impacts strictly linked to aridity from those tied to other consequences of climate change (e.g., floods, droughts, heatwaves, hurricanes) or to climate-relevant socioeconomic factors (e.g., wealth, population growth, spending on education, health and social care, social interactions, migratory dynamics) is complex (Carleton and Hsiang, 2016; IPCC, 2022; Phalkey and others, 2015). For example, health impacts are often the result of rising aridity's effect on other processes discussed above, such as premature deaths related to airborne dust from increasing sand and dust storms (Achakulwisut and others, 2019).

Impacts from increasing aridity—especially those resulting from aridity's economic effects, water scarcity, land degradation and insufficient food production—have been linked to human health and increasing rates of morbidity and mortality, especially among the most vulnerable populations, such as children and women.

Declines in food production related to aridity and water scarcity have been linked to malnutrition and related health conditions, especially in children. In Africa, for example, aridity has been associated with childhood wasting in West Africa (Curtis and Hossain, 1998) and childhood stunting—a sign of malnutrition—in Nigeria (Ahmed and others, 2023), Ghana (Aheto and Dagne, 2020), Ethiopia (Ahmed and others, 2021) and Uganda (Ssentongo and others, 2020). Arid conditions are also connected to reduced birth weight in Africa (Davenport and others, 2017; Grace and others, 2015), while increases in birth mortality have been linked to the scarcity of rainfall in other arid regions, such as north-east Brazil (Rocha and Soares, 2015).

One study explicitly exploring future drying and warming—assuming climate change pushes global temperatures to 2°C above pre-industrial levels—suggests childhood

stunting will increase by an average 3 per cent in sub-Saharan Africa (unless socioeconomic development improves to mitigate the warming and drying impact; Davenport and others, 2017). More broadly, severe child stunting is projected to increase by as much as 55 per cent in sub-Saharan Africa and 62 per cent in South Asia by 2050, as a result of the wider impacts of climate change under a medium emissions scenario (SRES A2)—assuming increasing global temperatures and evapotranspiration and regional changes in precipitation (Lloyd and others, 2011).

Increasing aridity and desertification can also affect health by reducing the availability of micronutrients, such as copper, molybdenum, zinc and iron—a key element in human diets—in drylands around the world (Moreno-Jiménez and others, 2019). These can affect food production and human health, directly (Thompson and Amoroso, 2010).

Rising aridity that contributes to water scarcity often forces local people to use water that is poor quality or polluted (Peletz and others, 2016; Pereira and others, 2009). Drinking polluted water can involve digestion of heavy metals and other toxic elements, increasing risks of cancer, cardiovascular diseases and other illnesses (Madilonga and others, 2021; Reimann and others, 2003). Fecal contamination of water is also a common problem for low-income countries facing water scarcity (Debela and others, 2018; Pereira and others, 2009). In Afghanistan, for example, aridity has been empirically linked to occurrences of diarrhoeal diseases (Anwar and others, 2019). A higher prevalence of diarrhoea under long-term drought conditions has also been reported for other middle- and low-income countries (Wang and others, 2022c). In Iran, lower precipitation during warm months was found to be statistically correlated with cholera infection rates (Asadgol and others, 2019).

Aridity's effects on human health can also be indirect. In drylands, for example, limited



access to water and a lack of infrastructure often require carrying water from long distances, a task traditionally designated to women and children (Sorenson and others, 2011; Yadav and Lal, 2018). This activity is associated with musculoskeletal disorders, including spinal, lumbar, head or neck pain (Geere and others, 2018; Geere and others, 2010; Patil and Sangle, 2022). It also poses a serious threat of sexual and physical violence for women, a risk that is accentuated during drought episodes (Chigusiwa and others, 2023; Tallman and others, 2023). In the sub-Saharan countries of Africa, for example, the HIV infection rate has been shown to rise by about 11 per cent following every recent drought episode—likely as a result of drought-induced economic impoverishment forcing women to undertake or increase remunerated sexual intercourse (Burke and others, 2015).

The health consequences of aridity-related water scarcity have been described in the context of the early years of the COVID-19 pandemic, when recommendations for more preventative hand washing and overall domestic hygiene caused an average 10 per cent increase in household water consumption around the world (Abderrahmane and Zineb, 2022). For areas with water scarcity, this increased water demand put additional pressure on water resources and increased risks of related health effects for rural populations (Rafa and others, 2020; Terrell 2020; Feizizadeh and others, 2021; Pacheco-Treviño and Manzano-Caramillo, 2024). This connection serves as a warning of the need to consider the link between water scarcity and vulnerability to health impacts in future pandemics.

Another adverse health impact from aridification emerges from its influence on atmospheric dust concentrations and on the occurrence of sand and dust storms (Middleton, 2017). In the United States, for example, sand and dust storms have been directly linked to hospital admissions for respiratory conditions (Ruble and

others, 2020). In China, the risk of death from multiple conditions between 2013 and 2018 (in a sample of almost 1.5 million deaths) increased by 3.5–12.5 per cent as a consequence of the health impacts from sand and dust storms (Zhang and others, 2023b).

Concentrations of fine dust that exceed levels safe for human inhalation (WHO, 2021) can expose people to spores, pollutants, bacteria or fungi carried along with the dust (Kellogg and others, 2004). These can cause cardiovascular and respiratory diseases, lung cancer and acute respiratory infections, increasing risks of premature death (UNEP and others, 2016). In Kuwait, for example, high dust concentrations have been correlated with bronchial asthma, acute respiratory infections and increased mortality rates during dust storms (Al-Hemoud and others, 2018). Intensified dust storm activity in south-western United States—consistent with aridification—has been temporally and spatially correlated with indices of valley fever, an infectious disease caused by soil-dwelling fungus (Tong and others, 2017).

Health impacts from aridity-related sand and dust storms can be far-reaching. Sand and dust storms in the Sahara Desert, for example, have been linked to health problems and increased mortality in faraway Spain (Díaz and others, 2017), while dust storms generated in the deserts of Central Asia have registered health effects in distant Taiwan (Chen and others, 2004).

Health impacts linked to aridity can also arise from aridification's role in creating conditions for wildfires—events that can directly cause death during the event or can increase morbidity afterwards as a result of environmental pollution (Li and Banerjee, 2021; Thomas and others, 2017). For example, half of all reported air-pollution-related deaths following California's large wildfires in October 2017 were directly attributable to the wildfire smoke (O'Neill and others, 2021).

Strong relationships have also been found between increases in air pollutants and respiratory illnesses after wildfires in the United States and Australia (Liu and others, 2015c). Wildfire smoke has been shown to affect general respiratory health, asthma, chronic obstructive pulmonary diseases,

risks of respiratory infections and risks of death from all causes (Reid and others, 2016). Wildfire exposure is also considered a culprit in a variety of cardiovascular, ophthalmic and psychiatric problems (Finlay and others, 2012; Chen and others, 2021).

## 3.9. HUMAN MIGRATION

Environmental changes—especially climate fluctuations or extreme weather—have long been considered important drivers of human migration (Anderson and Silva, 2020; Bohra-Mishra and others, 2014; Cai and others, 2016; Hoffmann and others, 2021; Klepp, 2017; McLeman, 2011). In drylands, the environment plays a crucial role, because erratic rainfall, land degradation or chronic water shortages impose harsh constraints for economic development and force people to migrate (Neumann and others, 2015; Reynolds and others, 2007). These environmental pressures on migration, however, are often also influenced by complex interactions with socioeconomic, political, demographic or cultural factors (Jónsson, 2010; Massey and others, 2010).

Rising aridity and drought are considered significant factors affecting fast-increasing rates of human migration around the world—particularly in the hyperarid and arid areas of Southern Europe, the Middle East and North Africa and Southern Asia (Hoffman and others, 2023).

Almost five times more people are projected to migrate in response to more frequent and more intense water shortages by the end of this century, if international efforts fail to curb rising greenhouse gas emissions (i.e., RCP 8.5; Smirnov and others, 2023). Even with current international climate policies to curb emissions (i.e., RCP 4.5; corresponding to the targets of the Paris Agreement), about twice as many people as today are expected

to move from their place of origin by 2100 (Smirnov and others, 2023).

Aridification—and its impacts affecting poverty and limited access to food and water—can spur millions of people to abandon their homes and communities to seek a better life elsewhere. Increasing aridity has been empirically linked to out-migration in dozens of countries around the world—with a “high consistency in the effects of water stress and dryness on human mobility” (Hoffmann and others, 2023).

Examples of apparently aridity-driven migration have been reported in many regions. In Brazil, for example, periodic droughts and desertification between 1960 and 1980 have been blamed for the emigration of more than 3 million people (Leighton, 2016). Declining rainfall in Mexico has also been linked to migration into the United States from rural Mexican communities that depend on rain-fed agriculture (Munshi, 2003).

In the Sahel region of Africa—a hotspot of desertification since the mid 20th century (Hein and De Ridder, 2006)—generations of herders, farmers and even fishermen adopted seasonal and circular migration as an adaptive strategy in response to the extreme seasonality of rainfall and periodic droughts (McLeman and Hunter, 2010; Romankiewicz and Doevenspeck, 2015). However, this approach proved inadequate when precipitation in the region declined by

an unprecedented amount from the 1950s to 1980s and severe droughts recurred throughout the 1970s and 1980s (Biasutti and others, 2019; Held and others, 2005).

These impacts—along with significant long-term drying from sustained increases in temperature and evapotranspiration—resulted in massive displacements of millions of people (Grolle, 2015; Pedersen, 1995) in response to large losses of livestock and devastating famines (Greve and others, 2014; Pearson and Niaufre, 2013). In the United States, the “dust bowl” crisis during the 1930s is also widely considered an episode of human migration resulting from environmental collapse related to desertification (Hornbeck, 2023).

Despite a clear link between rain deficits and migration, the large array of other factors that can drive human mobility make the future impacts on migration of climate change complicated (IPCC, 2022; Piguet and others, 2011) and, in particular, make the future effects of aridification difficult to estimate and little studied. For African drylands, for example, the amplifying effect of climate

change on the aridity-related drivers of migration (e.g., water scarcity, ecosystem collapse, desertification, agricultural failure) complicate efforts to estimate future migration under various warming scenarios (Hoffmann, 2022; Thalheimer and others, 2021).

Meanwhile, the impacts of aridity and other environmental pressures on human migration are often heavily influenced by other political and socioeconomic processes (Romankiewicz and Doevenspeck, 2015; UNEP, 2011), and these, in turn, often reflect the long-term alteration of the response capacities of affected rural communities to environmental changes (Pearson and Niaufre, 2013). Political instability and armed conflict are sometimes considered the main drivers of migration, especially in areas with the greatest population mobility, such as the Middle East and North Africa and throughout sub-Saharan Africa (Abel and others, 2019; Adaawen and others, 2019; Neumann and others, 2015). However, instability and conflict are also often intricately linked to aridity and other environmental stressors (Figure 17).



FIGURE 17

A map of aridity-related impacts based on the literature review. Each pictogram indicates a study that describes an impact; no pictogram does not indicate a lack of impact, but, rather, that no research has been published on that topic.

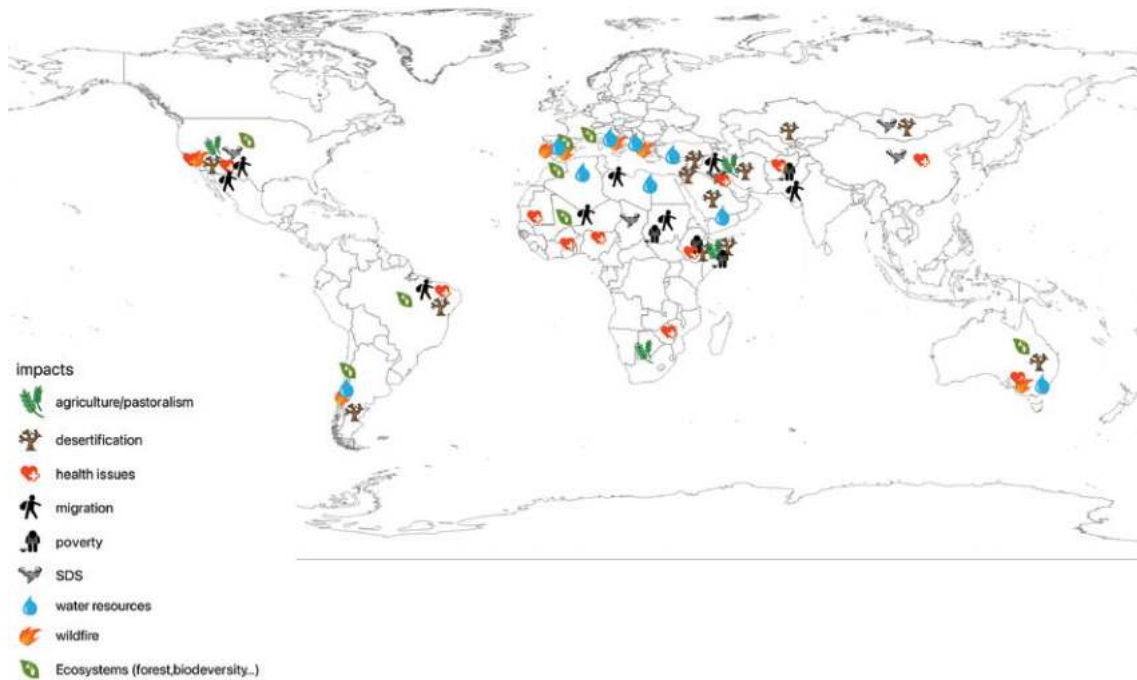


TABLE 3

Summary table of the most relevant studies of aridity impacts on several socioeconomic and environmental processes. These studies were selected from the reviewed literature based on the spatial scope of the research, the quality of the journal and the level of linkage found between aridity and the affected process.

Type of aridity impact	Spatial scope	Title	Authors	Year
Desertification	Global	Desertification vulnerability under accelerated dryland expansion	Sun and others	2023
	Global	Anthropogenic climate change has driven over 5 million km <sup>2</sup> of drylands towards desertification	Burrell and others	2018
Sand and Dust Storms	Middle East	Climate, not conflict, explains extreme Middle East dust storm	Parolari and others	2016
	Mongolia	Sandstorms and desertification in Mongolia, an example of future climate events: A review	Han and others	2021
Ecosystems and Biodiversity	Global	Global ecosystem thresholds driven by aridity	Berdugo and others	2020
	Global	Terrestrial biodiversity threatened by increasing global aridity velocity under high-level warming	Shi and others	2021
	Global	Increasing aridity reduces soil microbial diversity and abundance in global drylands	Maestre and others	2015

(Continued)



TABLE 3 (continued)

Type of aridity impact	Spatial scope	Title	Authors	Year
Wildfires	Global	Global increase in wildfire risk due to climate-driven declines in fuel moisture	Ellis and others	2022
	California	Observed impacts of anthropogenic climate change on wildfire in California	Williams and others	2019
	Australia	High-severity wildfires in temperate Australian forests have increased in extent and aggregation in recent decades	Tran and others	2020
Water Resources	Global	Climate change impacts on water security in global drylands	Stringer and others	2021
	Global	Groundwater recharge is sensitive to changing long-term aridity.	Berghuijs and others	2024
	North America, Middle East, North China	Why Is the Terrestrial Water Storage in Dryland Regions Declining? A Perspective Based on Gravity Recovery and Climate Experiment Satellite Observations and Noah Land Surface Model with Multiparameterization Schemes Model Simulations	Chang and others	2020
Agriculture and food security	Global	Aridification, precipitations and crop productivity: evidence from the aridity index	Malpede and Percoco	2023
	Iran	Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran	Bannayan and others	2010
	Botswana	Influence of climate variability and length of rainy season on crop yields in semiarid Botswana	Byakatonda and others	2018
Poverty	Africa/Asia	Long-term Economic Effects of Aridification on the GDPs of Africa and Asia	Malpede and Percoco	2021
	Africa/Asia	Trends in Rainfall and Economic Growth in Africa: A Neglected Cause of the African Growth Tragedy	Barrios and others	2010
Health	Afghanistan	Diarrhea Patterns and Climate: A Spatiotemporal Bayesian Hierarchical Analysis of Diarrheal Disease in Afghanistan	Anwar and others	2019
Health	West Africa	West Africa Spatial Analysis Prototype Exploratory Analysis: The Effect of Aridity Zone on Child Nutritional Status	Curtis and Hossain	1998
Health	Spain	Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions		
Migration	Global	Climate Change, Aridity, and Internal Migration: Evidence from Census Microdata for 72 Countries	Hoffmann and others	2023
	Global drylands	Environmental drivers of human migration in drylands – A spatial picture	Neumann and others	2015

TABLE 4

Summary table of the existing studies of future risks related to aridification under climate change conditions, sorted by the aridity impacts projected for several socioeconomic and environmental processes. These studies were selected from the reviewed literature, based on the spatial scope of the research, the quality of the journal and the level of linkages found between aridity and the affected process.

Type of aridity impact	Spatial scope	Title	Authors	Year
Land degradation/ desertification	Global	Global desertification vulnerability to climate change and human activities	Huang and others	2020
	Europe	Is Europe at risk of desertification due to climate change	Spinoni and others	2018
	Central Asia	Projections of desertification trends in Central Asia under global warming scenarios	Ma and others	2021
	China	Assessing the spatial-temporal pattern and evolution of areas sensitive to land desertification in North China	Xu, D., and others	2019
Ecosystems and biodiversity	Global	Global ecosystem thresholds driven by aridity	Berdugo and others	2020
	Global	Future Increase in Aridity Drives Abrupt Biodiversity Loss Among Terrestrial Vertebrate Species	Liu, X., and others	2023a
	Western United States	Temperature response surfaces for mortality risk of tree species with future drought	Adams and others	2017
	Global	Tree mortality in a warming world: causes, patterns, and implications	Yi and others	2022
Wildfires	Europe	Increasing aridity causes larger and more severe forest fires across Europe	Grünig and others	2023
	Mediterranean Basin	Increased likelihood of heat-induced large wildfires in the Mediterranean Basin	Ruffault and others	2020
	California	Climate change is increasing the likelihood of extreme autumn wildfire conditions across California	Xu, Q., and others	2020
Water scarcity	Global	Global terrestrial water storage and drought severity under climate change	Pokhrel and others	2021
	Global	A global assessment of the impact of climate change on water scarcity	Gosling and Arnell	2016
	Mediterranean Basin	Mediterranean water resources in a global change scenario	García-Ruiz and others	2011
	Mediterranean Basin	Aridity and desertification in the Mediterranean under EURO-CORDEX future climate change scenarios	Carvalho and others	2022
	Middle East and North Africa	Evapotranspiration and water availability response to climate change in the Middle East and North Africa	Ajjur and Al-Ghamdi	2021
Agriculture and livestock production	Global	Aridification, precipitations and crop productivity: evidence from the aridity index	Malpede and Percoco	2023

(Continued)

TABLE 4 (continued)

Type of aridity impact	Spatial scope	Title	Authors	Year
	Sub-Saharan Africa	Robust negative impacts of climate change on African agriculture	Schlenker and Lobell	2010
	Morocco	Assessing the impact of global climate changes on irrigated wheat yields and water requirements in a semi-arid environment of Morocco	Bouras and others	2019
	Jordan	Decadal analysis of impact of future climate on wheat production in dry Mediterranean environment: A case of Jordan.	Dixit and others	2018
	Africa/Asia	Climate change impacts on crop productivity in Africa and South Asia	Knox and others	2012
	Australia	Climate change and variability impacts on grazing herds: Insights from a system dynamics approach for semi-arid Australian rangelands	Godde and others	2019
	Israel	Climate change scenarios of herbaceous production along an aridity gradient: vulnerability increases with aridity	Golodets and others	2015
Poverty	Global	Climate change through a poverty lens	Hallegatte and Rozenberg	2017
	Africa/Asia	By 2079, aridification will have reduced the GDPs of Africa and Asia by 16% and 6.3%, respectively	Malpede and Percoco	2021a
	Global	Climate volatility deepens poverty vulnerability in developing countries	Ahmed and others	2009
Health	Global	Climate change, crop yields, and undernutrition: Development of a model to quantify the impact of climate scenarios on child undernutrition	Lloyd and others	2011
	Mediterranean Basin	Impacts of climate change on the public health of the Mediterranean Basin population - Current situation, projections, preparedness and adaptation	Linares and others	2020
	Sub-Saharan Africa	Child health outcomes in sub-Saharan Africa: A comparison of changes in climate and socio-economic factors	Davenport and others	2017
	United States	Effects of Increasing Aridity on Ambient Dust and Public Health in the U.S. Southwest Under Climate Change	Achakulwisut and others	2019
Migration	Africa	Contextualizing Climate Change Impacts on Human Mobility in African Drylands	Hoffmann	2022
	Africa	Advancing the Evidence Base of Future Warming Impacts on Human Mobility in African Drylands	Thalheimer and others	2021
	Global	Climate Change, Drought, and Potential Environmental Migration Flows Under Different Policy Scenarios	Smirnov and others	2023

## **Box 2. Case study: A catastrophic sand and dust storm in Mongolia and East Asia (based on Han and others, 2021)**

In March and April 2021, Mongolia suffered a massive and persistent sand and dust storm that caused extensive, nationwide damage and significantly deteriorated air quality over large areas of East Asia, including Northern China, Japan and South Korea. The triggering cause was the Mongolian Cyclone, which produced a significant drop in atmospheric pressure (980 hPa) leading to strong winds over the eastern Gobi Desert (Filonchik, 2022). While these winds were considered the proximate culprit, researchers believe constant desertification across the region during the last decades is the underlying reason for the frequent occurrence of sand and dust storms that culminated in the 2021 event.

High winds and a dust cloud rapidly spread over the South Mongolian Plateau, the Loess Plateau, the North China Plain and the Korean Peninsula, reaching an area of about 450,000 km<sup>2</sup>. As of March 16, 2021, impacts to Mongolia of the sand and dust storm included 10 deaths (including one child), 1.6 million missing livestock and other impacts affecting an estimated 8,000 people and 2,000 households across 14 provinces. The severity of the event prompted the Mongolian government to declare it “catastrophic”.

Although this event was unprecedented in its scale, sand and dust storms are not rare in the region and are the main source of common “yellow dust” intrusions in East Asia. These intrusions are responsible for severe impacts on human health and widespread damage to agriculture and livestock. Climate aridification has played a pivotal role, along with Mongolia’s 1992 shift to a market-oriented economy and higher economic growth. These economic changes have fueled an intensification of agriculture, overgrazing and extensive mineral extraction that have resulted in intense land degradation. Meanwhile, the annual mean air temperature in Mongolia rose by 2.24°C from 1940 to 2015, accompanied by a 7 per cent decrease in annual precipitation, leading to increased aridity nationwide and more frequent droughts. Between 1987 and 2010, more than a quarter of lakes larger than 1.0 km<sup>2</sup> dried up on the Mongolian Plateau, and the decrease in soil moisture has activated a feedback loop, resulting in an even hotter and drier climate. Elevated temperatures, diminished precipitation and land degradation have collectively fostered a persistent drying trend, affecting more than three-quarters of Mongolia’s land area with drought and desertification.

The 2021 sand and dust storms brought global focus to ecological issues that have been accumulating for decades in Mongolia. Urgent and collaborative efforts are required from policymakers, local residents and scientists from both the local and global research communities to address the significant and rapidly worsening ecological challenges in Mongolia.

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**Box 3. Case study: Aridity as a driver of diarrhoeal diseases in Afghanistan**  
(based on Anwar and others, 2019)

Acute diarrhoea—a common health condition that is a leading cause of sickness and death in countries with poor water sanitation and treatment facilities—has a spatial and temporal distribution around the world that can be linked to several climatic variables. Its association with temperature and precipitation, however, is less straightforward. For example, bacterial diarrhoea has been associated with warmer temperatures, but viral diarrhoea exhibits negative associations with temperature. Both positive and negative associations have been found between diarrhoea and precipitation (Carlton and others, 2016; Guzman Herrador and others, 2015).

In Afghanistan, a country with high aridity and low economic development, diarrhoea is the second most prevalent disease and causes an estimated ~20 per cent of illnesses reported among children under five and 11 per cent of illnesses across all age groups attending health facilities (Anwar and Burnham, 2016). Research suggests that rising incidences of diarrhoea are closely correlated with increases in aridity (i.e., as measured by the AI) and temperature during the summer months in central, northern and western parts of the country (Anwar and others, 2019). These findings are consistent with results from other settings with a dry climate. In the absence of information about the specific etiologic agents of diarrhoea in their study, the authors hypothesize that warm and dry weather is associated with increased survivability of viral and bacterial pathogens and with more exposure to contaminated food and water. Association between diarrhoea rates and concurrence of warm and dry conditions has also been reported in Botswana (Alexander and others, 2013) and elsewhere. Aridity has also been suggested to facilitate communicability of other infections, such as plague (Yue and Lee, 2018).

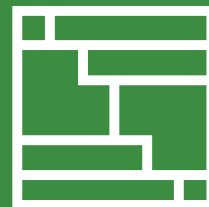
This example highlights the role that aridity can play in human health, especially in poor, arid countries, and suggests a need for considering the potential impacts of climate change in public health assessments and policies.

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# Chapter 4.

# ARIDITY ADAPTATION AND FUTURE APPROACHES

Reducing the vulnerability of ecosystems and populations to increasing aridity requires both broad, large-scale measures related to mitigating global climate warming and more regional or local approaches focused on vulnerable communities in the most affected countries.

While the severity, distribution and trends affecting aridity depend on physical interactions between the atmosphere, oceans and land surfaces, aridity's impacts on environmental and socioeconomic processes—now and into the climate-altered future—are nevertheless influenced by the conditions and measures that make societies and the environment more or less vulnerable.

Key priorities to ensure adaptation to rising aridity include assessing vulnerabilities to

aridity, understanding the enabling conditions for adaptation to aridity and developing adaptive strategies for aridity, including both transformational and incremental approaches and sectoral approaches that address food production, livestock farming and water management.

Adaptation to aridity requires a multifaceted approach, encompassing financial support, strong governance, capacity-building and effective monitoring. Tailored regional strategies, combined with large-scale transformational actions, can enhance resilience to arid conditions. Further research on the socioeconomic impacts of aridity is imperative to develop comprehensive and informed adaptation policies.

## 4.1. ASSESSING VULNERABILITIES TO ARIDITY

Research exploring the vulnerability and resilience of environmental and socioeconomic processes and systems to impacts from rising aridity is limited. However, three important characteristics are known to substantially affect these challenges: the scale and nature of land use and land degradation, levels of poverty and demographic features.

### Prior land degradation

Whether or not land has previously suffered from unsustainable land use or from degradation—either as a result of climate change or as a consequence of non-climate impacts—can substantially affect the vulnerability of land to the effects of aridity. Prior land degradation and desertification can leave areas vulnerable to crossing key

aridity thresholds that lead to dramatic, nonlinear changes to soils, vegetation and ecosystems (Berdugo and other, 2020; Sun and others, 2023). The degree of this vulnerability ranges from low (i.e., at risk is the loss of soil fertility alone) to high (i.e., the risk is overall land degradation). Rapid population growth and unsustainable farming practices are important causes of land degradation (Middleton, 2018; Reichhuber and others, 2019). These causes interact with climate and other environmental factors (e.g., pests and diseases) to increase the vulnerability of populations to reduced agricultural yields or reduced water availability (Padgham and others, 2015). Historically, populations facing high aridity and limited water resources have developed livelihoods adapted to these conditions, including farming rain-fed crops and pastoralism (Rockström and others, 2010). While these approaches have allowed these people to cope with harsh environmental conditions, an excessive dependence on these activities can also contribute to vulnerability to increasing aridity or to climate shocks, such as floods and droughts (Leichenko and Silva, 2014), resulting in massive declines in crop yields or cattle losses.

### Poverty

Poverty and limited economic resources can significantly increase vulnerability to climate change (e.g., Adger and others, 2003; Eriksen and O'Brien, 2007; Tucker and others, 2015), and this vulnerability is similarly applicable to aridity and its environmental and socioeconomic impacts (Mirzabaev and others, 2019). People with limited wealth are more susceptible to climate stresses, because they lack resources to recover from climate shocks, such as droughts (Leichenko and Silva, 2014). They face climate risks because their livelihoods generally depend on climate sensitive sectors, such as agriculture and pastoralism. Poor people also generally have low-income jobs with little protection against climate disruptions, tend to live

in areas with higher exposure to climate extremes, have less access to knowledge and information about adaptation and have few livelihood options. This vulnerability of impoverished people to climate impacts is exacerbated by other factors that are also linked to poverty, such as poor health, a lack of political voice and limited access to technologies and networks (Tucker and others, 2015). In the same way, aridity and desertification have disproportionate impacts on those whose poverty restricts their access to health care or to those who are forced to migrate when alternative livelihood options are not possible (Greene, 2021; Linares and others, 2020; Mirzabaev and others, 2019).

Poverty has a complex relationship with land degradation, which is frequently associated with rising aridity. This relationship is often characterized as a “self-reinforcing, downward spiral”, in which poverty is seen as a consequence and a cause of land degradation (Barrett and Bevis, 2015; Rodrigo-Comino and others, 2022; Winslow and others, 2004). In this view, poor agricultural households are assumed to be unable to cope with sustainable land management, increasing the risk of land degradation. However, this narrative is subject to debate (Scherr, 2000). For example, Mirzabaev and others (2023) showed that the poor households of Central Asian countries applied more sustainable land management practices than richer farm households, because less-wealthy farmers depend more on land and its use for their livelihoods. On the other hand, Rodrigo-Comino and others (2022) showed that the risk of desertification from aridification and unsustainable land practices in southern Italy, where 20 per cent of people are poor, can be twice the risk in the country's northern regions, where poverty affects less than 10 per cent of the population.

### Demography

Population growth and overpopulation exacerbate vulnerability to climate hazards



by increasing the exposure to risk and by creating more pressure on the land and resources to overcome climate challenges (Scovronick and others, 2017; Sun and others, 2023). These population pressures also likely contribute to risks from rising aridity. The threat of desertification—often closely linked to aridification—is worsened by overpopulation in the drylands of Africa, South-East Asia and South Asia (Sun and others, 2023). Structural characteristics of populations—including the percentage of rural versus urban inhabitants, of the numbers of refugees, the literacy rate and the life expectancy—can be considered proxy variables for gauging vulnerability to drought (Carrão and others, 2016), and they are valid as measures of risk from long-term climate aridity.

Other demographic characteristics that increase the vulnerability of populations to climate impacts include gender inequity and age (Carleton and Hsiang, 2016; IPCC, 2022). For example, women and children face greater risks of poor health or gender-based violence from water scarcity (Geere and others, 2010; Sorenson and others, 2011; Tallman and others, 2023), which is often associated with climate warming and rising aridity. These risks reflect the increased need, in the face of limited water, to carry water long distances and to suffer muscle

and skeletal issues and more frequent sexual assaults as a result. Women are similarly at higher risk of sexually transmitted diseases when economic hardship from droughts or water scarcity compel them to practise prostitution (Burke and others, 2015).

Still other characteristics of populations are recognized for their impacts on vulnerabilities related to rising aridity in Asia and Africa (Anugwa and others, 2023; Rao and others, 2019; Yadav and Lal, 2018). These include the proportion of the population with limited control of land, with high household work burdens, with high levels of responsibility for agricultural production and with a lack of access to formal education. These features make women more vulnerable to the effects of water scarcity and agricultural failure resulting from droughts and aridification. In many poor countries, children are the most vulnerable to health risks from undernutrition (Serdeczny and others, 2016; Venkat and others, 2023) that are often a result of agricultural and economic impacts from rising aridity. Other poverty-related issues, such as limited access to health care and undereducation, affect climate vulnerabilities for children, whose risk is further exacerbated in countries in which they comprise a large proportion of the population (Bartlett, 2009; Cooper and others, 2019).

## 4.2. ENABLING CONDITIONS FOR ADAPTATION TO ARIDITY

Just as vulnerabilities to aridity reflect the particular circumstances of different ecosystems and societies, factors that contribute to the efficiency and suitability of measures to adapt to rising aridity also vary from one place to another. Enabling conditions that play an indispensable role in fostering successful adaptation include availability of financial resources, the presence of favourable governance

structures, the existence of education and capacity-building and the effectiveness of monitoring and reporting mechanisms.

### Financial Resources

Adequate financial resources ensure that communities and institutions have the necessary means to address the

multifaceted challenges posed by aridity. These investments in adaptation strategies are most effective when they prioritize approaches that benefit the widest possible range of sectors. Financing should also ensure that adaptation measures not only address the direct challenges posed by aridity but also contribute to broader development goals, such as poverty alleviation, food security, food safety and ecosystem conservation. Increasingly, the private sector and international aid are becoming key sources for this adaptation funding.

The private sector is now widely recognized as a central actor in adaptation efforts that make societies more resilient to climate change (Pauw, 2015). However, unlike technologies and products aimed at mitigating climate change (e.g., clean energy projects), adaptation measures rarely offer

adequate direct incentives to the private sector (Timilsina, 2021). In sub-Saharan Africa, for example, inadequate incentives combined with limited access to financial products and services means small and medium-sized enterprises struggle to cover the high capital costs of investing in both short- and long-term adaptation projects (Crick and others, 2018). This is aggravated by the large gap in time horizons anticipating climate change impacts and by business investments that look for quick returns and short-term growth.

International aid is another source of adaptation funding, especially for nations without adequate financial resources or technical and institutional capacities to launch adaptation projects on their own. International funding currently plays a pivotal role in financing climate change adaptation activities around the world (Füssel



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and others, 2012; Robinson and Dornan, 2017) through various channels, including multilateral development banks, the United Nations Development Programme, the United Nations Environmental Program, active participation by donor countries, the private sector (e.g., World Bank Group) and philanthropic organizations (Timilsina, 2021). In Africa, for example, an international funding initiative known as the African Water Facility was established in 2004 to mobilize financing for water-resource development activities across the continent. The initiative receives contributions from multilateral financial institutions, foundations and African governments, and from 2006 to 2018, has committed approximately GBP 162 million (about \$210 million) to 117 projects in 52 countries (Timilsina, 2021).

### Governance structures

Robust governance structures are essential for effectively coordinating adaptation initiatives in response to climate change and aridification. Good governance involves the creation and implementation of policies that address climate change impacts and that foster collaboration, coordination and coherence among both public and private institutions engaged in climate adaptation. Multi-stakeholder partnerships can coordinate actions across various scales and develop integrated approaches to overcoming project barriers (Crick and others, 2018). In Africa, for example, partnerships known as PREPARED (Planning for Resilience in East Africa through Policy, Adaptation, Research, and Economic Development) and Coping with Drought and Climate Change in Zimbabwe leverage the knowledge, expertise and resources of diverse sectors to identify gaps in participation, resources and learning (Crick and others, 2018). Governance that involves local and regional entities in decision-making ensures that adaptation efforts are inclusive, holistic, context-specific and responsive to the unique challenges faced by different geographical areas.

Robust governance structures also provide financial support and promote capacity-building, education, knowledge integration and skills essential for addressing the challenges related to aridification. Governments can initiate and support training on the use of new technologies, promoting sustainable practices and establishing early warning systems and emergency response protocols. Governance structures that support education and awareness programmes—which have been instrumental to informing local communities in Kenya and India about the impacts of droughts (Udmale and others, 2014; Wens and others, 2022)—are critical to building an enabling environment for effective adaptation strategies in response to aridification (Feinstein and Mach, 2020; Jellason and others, 2022). Investing in education and capacity-building programmes helps societies prepare for impacts from future aridification with sustainable adaptation practices. Including indigenous local knowledge and involving local communities in adaptation planning and projects are also vital, especially when these include incorporating traditional knowledge related to drought and desertification (Filho and others, 2023).

### Monitoring and reporting mechanisms

Robust aridity monitoring and reporting mechanisms are needed to ensure accountability and to track progress (Berrang-Ford and others, 2019). Regular assessments of adaptation activities offer insights into their effectiveness, identifying successes, challenges and areas that require additional attention. Adaptation reporting helps keep corporate and other stakeholders informed (Street and Jude, 2019) and facilitates the alignment and integration of actions within existing risk management and governance structures. For policymakers, reporting enhances an understanding of local and regional climate risks and actions to allow their integration into national-level

assessments and adaptation planning processes. Transparent and comprehensive reporting contributes to a collective understanding of the effectiveness of adaptation measures and encourages continuous improvement, fostering a culture of learning and adaptation within communities and institutions alike.

Nevertheless, notable gaps exist in the scientific literature addressing the socioeconomic impacts of aridity and the vulnerability of societies to climate

aridification. Existing research predominantly focuses on severe climate-related shocks, such as droughts and floods, while slower, sustained, long-term socioeconomic impacts from aridification are less well known. Empirical and modelling research on socioeconomic impacts and vulnerabilities associated with prolonged aridification could help foster a more informed and resilient population and ensure societies can effectively tackle the challenges of climate change.

### 4.3. ADAPTIVE STRATEGIES FOR ARIDITY

#### Transformative vs. incremental approaches

Adaptation to climate change has traditionally focused on progressive and incrementally more intensive activities to reduce the impacts of climatic variations and extremes and to maintain the essence and integrity of affected societies and environments (Brooks and others, 2017; Kates and others, 2012). On the other hand, transformative approaches—that is, activities that can be “adopted at a much larger scale or intensity, are truly new to a particular region or resource system, or transform places and shift locations” (Kates and others, 2012)—are increasingly seen as appropriate when the risk and vulnerability of ecosystems and societies are particularly large in scale (Kates and others, 2012; O’Brien, 2016; Tàbara and others, 2019).

Incremental adaptation includes practices such as regreening degraded landscapes and implementing sustainable land management to progressively reduce vulnerability to climate-affected rises in aridity. These can reduce risks from desertification by regreening to establish vegetation cover that will reduce wind speed, prevent erosion by stabilizing the soil and increase soil moisture (O’Connor and Ford, 2014). Similarly, targeted forest restoration

can mitigate drought risk by enhancing evapotranspiration in afforested areas to potentially enhance precipitation over nearby drier areas (Tuinenburg and others, 2022). In China, for example, the Three North Shelterbelt Development Program (TNSDP) is a progressive afforestation programme in the country’s drylands and is considered the largest environmental programme in the world (Li and others, 2012).

Other similar, government-planned environmental protection programmes include the Beijing-Tianjin Sand Source Control Programme (BSSCP), the Nature Forest Conservation Programme (NFCP) and the Grain to Green Programme (GTGP; Zhang and others, 2016b). Evidence suggests these initiatives have helped accelerate a large-scale greening in the drylands of China (Li and others, 2021; Zhang and others, 2016b) and have effectively reduced desertification, decreased sand and dust storms, increased carbon sequestration and cooled surface temperatures, among other benefits (Zhang and others, 2016b). Even so, these programmes have also been criticized for planting “thirsty trees” (Cao and others, 2010) in low-precipitation regions, risking further reductions in water resources (Sun and others, 2006) and threatening the structure and function of existing ecosystems (Ma and others, 2013).



Another incremental greening adaptation effort in the Sahel region of Africa began in response to ongoing desertification in rural areas of southern Niger (Partey and others, 2018). Beginning in the 1980s, the region's farmers—who faced productivity losses from growing land degradation and declining woodlands following droughts and population growth—developed a farming technique that incorporated the growing of selected native tree species that had previously been removed from agricultural lands (Kates and others, 2012; Partey and others, 2018). The technique, which came to be known as “farmer managed natural regeneration”, ensures new trees are scattered among the fields to provide animal fodder and fuel, while preventing erosion and protecting crops from wind and evaporation. So far, the approach has resulted in about 200 million new trees in Niger (Toungiani and others, 2009). It has also increased soil fertility, provided substantial amounts of biomass for household energy (i.e., charcoal and firewood) and contributed to food security for about 2.5 million people (Garrity and others, 2010; Partey and others, 2018).

Many incremental approaches to adaptation to aridity incorporate the conceptual framework and principles of sustainable land management (SLM) to help progressively reduce vulnerability. SLM combines technologies, policies and activities that integrate socioeconomic and environmental aims to simultaneously improve productivity, reduce risk, protect the potential of natural resources, prevent the degradation of soil and water, ensure economic viability and encourage social acceptability. In recent decades, incremental adaptation approaches that include SLM have helped global nations affected by desertification fight land degradation by increasing land productivity while improving ecosystems and livelihoods, promoting water-use efficiency and fortifying soil fertility (Liniger and others, 2011).

Unlike incremental approaches, transformational adaptation measures involve changes in the fundamental attributes of

affected systems (Brooks and others, 2017). Many large-scale adaptation efforts, such as the Great Green Wall initiative and other large-scale afforestation programmes, can be considered transformational approaches if they aim to transform ecosystems and societies to enhance their resilience and provide potentially transformative benefits.

The Great Green Wall initiative (Mbow, 2017) is a transformational adaptation effort in the face of rising aridity that aims to halt the advance of desertification and extend greening efforts along the 8000 km length of the pan-African Sahel Belt, from Djibouti to Senegal. The initiative has been successfully implemented in Burkina Faso, Ethiopia, Nigeria, Senegal and Sudan (see <https://www.unccd.int/our-work/ggwi/impact>) and has resulted in millions of plants seeded, thousands of hectares reforested and restored, hundreds of kilometres of windbreaks created and thousands of jobs generated. The Great Green Wall initiative followed from the incremental greening efforts initiated by farmers in Niger and is considered an example of incremental adaptation that became transformative as it gained in popularity and became widespread across more than 5 million hectares of climate-resilient greenbelt (Kates and others, 2012). Even so, the initiative is not without critics. In a study of its impacts in semi-arid regions of Senegal, for example, Hermann and Tappan (2013) reported an overall reduction in species richness among woody plants, a loss of large trees, an increasing dominance of shrubs and an overall shift towards more arid-tolerant species. Using long-term remote sensing data, Dardel and others (2014) found a dominant and regional trend toward greening, but with local spots where degradation prevails. O'Connor and Ford (2014) argue that the project should ensure more international support to local communities and should shift from planting trees to shrubs, which are more adapted to arid conditions, grow faster and could provide a basis for silvo-pastoral livelihoods based on honey production.

However, because of the slow and scattered implementation of SLM practices in different countries (Kust and others, 2017) and because of the urgency of actions needed to mitigate the effects of climate change, the UNCCD adopted, as a sustainable development goal, the novel concept of Land Degradation Neutrality (LDN) defined as “a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems”. LDN is accompanied with a set of indicators to evaluate the state of degradation of land and is aimed to serve as an operational platform to promote and guide transformative policies and practices to halt land degradation. Adaptation to aridity, as well as to climate change extremes, requires action guided by policy and informed by knowledge. In this regard, further actions that could enhance governance, practice and information are badly needed (see Chapter 5).

### Sectoral adaptation approaches

Increasing resilience and adaptation to aridity and desertification typically requires approaches that consider particular sectors and that can be adapted to the specific geographical and socioeconomic characteristics of affected territories. These approaches are important for an effective mitigation of the risks to ecosystems and populations from increasing aridity. Key sectors for consideration include food production, livestock farming, water management and education.

**Food production** adaptation measures are essential to ensuring the food security of populations affected by aridity or by other climate stressors, such as recurrent droughts or floods. Adaptation measures to increase the resilience of crop production to climate change impacts are considered equally valid for protecting against the effects of increasing aridity. These measures include crop and water management, livelihood

diversification and protection against losses, such as index-based insurance (IPCC, 2022; Kates and others, 2012). The development of water-efficient varieties of crops is considered a promising adaptation approach. For example, the Water-Efficient Maize for Africa project (Lumpkin and Armstrong, 2009) is a private-public partnership for creating drought- and pest-resistant maize hybrids to be used by smallholder farmers of sub-Saharan Africa (Oikeh and others, 2014). While final results and impacts of this project are yet to be assessed, partial economic assessments indicate increasing productivity, improved incomes and reduced poverty (Marechera and others, 2019).

Adaptation that relies on monocultures of drought-resistant crops requires caution, however, because the approach may lead to genetic homogenization, loss of biodiversity and reduced resilience to pests and diseases. Monoculture has been shown to increase susceptibility to disease (He and others, 2019), while polyculture crops can significantly suppress disease spread (Zhu and others, 2000, Armengot and others, 2020). To conserve biodiversity (Zuppinger-Dingley and others, 2014; Venter and others, 2016) and improve sustainable food production, polycultures are recommended as an effective adaptation strategy for increasing drought resilience (Adamczewska-Sowińska, 2020).

Another adaptation approach involves developing crop systems with different phenologies, such as planting crops like sorghum instead of maize that require water when it is available and that avoid water demands during dry seasons (Yahaya and Shimelis, 2022). This approach can benefit from the land use management approach known as agroecology, which is defined as “an integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems” (FAO, 2018). Agroecology contributes to food system transformations that improve food production, nutrition, biodiversity

and soil fertility. By saving water and promoting drought-adapted crops and crop diversification, agroecology has proved an efficient adaptation approach to cope with dry conditions (HLPE, 2019).

Similarly, sustainable irrigation is an adaptation approach that diversifies crop production and makes it less vulnerable to climate variability. The approach is an alternative to conventional large-scale irrigation practices that are common in dry regions. Despite short-term economic benefits, conventional large-scale irrigation has shown that it can have enormous, detrimental and long-term environmental impacts. One example of this is the paradigmatic desiccation of Aral Sea and the large-scale land degradation of its basin (Stringer and others, 2021). On the other hand, sustainable, local-scale irrigation measures—such as drip irrigation that delivers water slowly to the roots of plants to minimize evaporation—are seen as the best solution for producing high-value vegetables while saving water in areas with low water availability (Partey and others, 2018; Wanvoeke and others, 2016). For example, a control experiment in a semi-arid area of Zimbabwe showed that drip irrigation could substantially increase crop yields (i.e., by up to 100 per cent) in comparison with yields from rain-fed fields, while substantially reducing water use (i.e., down by 80 per cent) compared with conventional irrigation practices (Maisiri and others, 2005).

The success of sustainable irrigation, however, depends on the individual circumstances. For example, drip irrigation may require capacity-building and training to ensure adequate application. In some cases, the use of efficient irrigation systems to reduce water consumption may lead to an increase in irrigated lands and, paradoxically, a subsequent increase in water consumption. The approach may also reduce aquifer recharge (Jin and others, 2018; Pool and others, 2022) or cause soil salinization, especially under arid conditions (e.g., Wang and others, 2019).

Crop insurance against weather-induced losses is an adaptation approach that has been long available in developed countries, but it has only been adopted in African countries, for example, in the last two decades (Johnson, 2021; Kates and others, 2012). Index-based insurance can reduce the vulnerability of smallholder farmers and democratize the assumption of risk (Johnson, 2021) by basing indemnification on environmental variables rather than on quantities of direct losses. While recognizing the potential of this insurance as an adaptive response to climate change in developing countries, some experts warn of issues of power, social inequality or differential access of rural communities concerning the adoption of indexed insurance. Many of these experts call for intervention by development practitioners and policymakers to ensure that the outcomes are more equitable and have greater potential for inclusion and fairer distribution (Fisher and others, 2019).

**Livestock and pastoral farming** approaches provide adaptations to climate aridification through adaptive practices, such as changes to livestock species compositions and changes in grazing practices. For example, the use of species that are better adapted to hotter and drier conditions can reduce losses in the face of climate change (IPCC, 2022). Switching from cows to goats for dairy production can ensure livestock are more resilient to heat stress and adapted to desert environments (Silanikove and Koluman, 2015). In southern Ethiopia, pastoralists have used species diversification, including changing from cattle to camel management, as an adaptation strategy to the severity of recurrent droughts. Compared to cattle, the camels were found to withstand the harsh environmental conditions and were better adapted to the changing ecology of rangeland vegetation in the face of aridification, while maintaining the potential for milk production (Wako and others, 2017). The success has led to increasing camel numbers in southern Ethiopia. Likewise, in Kenya, pastoralists have diversified their herds and changed their patterns of

livestock mobility as long-term adaptations to increasingly arid conditions (Opiyo and others, 2015). Goats, in particular, are considered by some to be ideal animals as livestock in the face of climate change due to their high thermal and drought resilience, their ability to survive on limited and low-quality pastures and their high resistance to disease (Nair and others, 2021).

In regions with highly seasonal and interannual climate variability, pastoralists have historically adapted to long dry periods by migrating with their herds to locations where forage was not affected by drought. Since the mid-twentieth century, however, this type of nomadism has been constrained by changes in land policies, by changes to land tenure or by political conflicts—particularly in Africa and Asia (Godde and others, 2020; Stringer and others, 2021). Policies and measures that facilitate pastoral mobility can help these livestock farmers adapt to the expected increase in climate variability and the harsher conditions expected in tropical drylands. In a recent review of responses to climate change by African indigenous communities, Filho and others (2021) found livestock and crop diversification, temporary migration and mixed cropping among the most common adaptation practices to cope with aridity and drought conditions.

**Water management** adaptation measures in the water sector are vital for ensuring food and water security in regions affected by aridification. Given the large dependence of rain-fed agriculture for crop production in drylands, rainwater management is considered crucial for increasing agricultural productivity without compromising water availability for other sectors (Rockström and others, 2002). Two types of these rainwater management strategies are used as adaptation approaches by crop farmers in Kenya. The first uses rainwater harvesting (blue water) from roofs, pits and storage structures. It also aims at soil moisture replenishment (green water) through harnessing, channelling, conserving, terracing, retention ditches or otherwise

optimizing rainfall and surface flows within the soil profile (Recha and others, 2016). The second water management adaptation approach involves harvesting water contained in fog droplets as a low-cost and sustainable solution to cope with water scarcity in drylands where fog is a recurrent phenomenon (Ismail and Go, 2021). Rainwater harvesting techniques and anti-erosion measures are reportedly used by farmers in Burkina Faso following seasons of crop failure to improve soil fertility, water retention and the efficiency of organic and mineral fertilizers (Barbier and others, 2009; Zampaligré and others, 2014). These include techniques known as “zai” and “half-moon” that involve digging pits in the ground to retain rainwater for long periods and seeding crops in them or building stone bunds to promote soil retention and water infiltration. Partey and others (2018) reviewed the use of these techniques by smallholder farmers in several countries of the Sahel and found improved crop productivity and increased water-use efficiency for crops, such as sorghum, millet and maize, especially during dry spells. Traditional local practices for groundwater use in drylands, such as the use of *qanats* in Iran or the *tula wells* in southern Ethiopia, also provide sustainable water management that preserves cultural identities and rural livelihoods (Stringer and others, 2021). These, however, can be difficult to implement in other locations or at larger scales.

For dryland countries with advanced economies (e.g., Israel, Australia, Saudi Arabia or the United States), adaptations to aridity often involve technological solutions to cope with water scarcity, such as seawater desalination or intelligent irrigation systems based on evapotranspiration controllers (Al-Ghobari and Mohammad, 2011; Slater and others, 2020). Stringer and others (2021) suggest that these technologies require adequate “institutional setups, economic incentives, political will, and greater levels of state investment than is feasible in low-income economies” and, consequently, can increase inequalities within and between



nations. High-cost and technological techniques may also include the exploitation or “mining” of non-renewable and fossil groundwater from deep aquifers, dramatically affecting the quality of more superficial fresh groundwater reservoirs and raising questions about their environmental and social sustainability (Salameh and others, 2024; Aghamir, 2024). Technology is also used to respond to and reverse groundwater depletion and contamination by employing a set of techniques collectively known as managed aquifer recharge (MAR) (Dillon and

others, 2019). These are especially useful for managing irrigation water supplies in arid and semi-arid climates. While these techniques have shown potential to alleviate and reverse water crises (Zhang and others, 2020), they can also result in adverse environmental impacts, such as shifting river flows (Yaraghi and others, 2019). Dillon and others (2019) recommend that “countries need governance frameworks strengthened to ensure that MAR is sustainable and protects groundwater quality and generates benefits

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#### **Box 4. Adapting to water scarcity for farmers in semi-arid Chile** (based on Roco and others, 2016)

Large parts of Chile are characterized by arid and semi-arid conditions and by high levels of climate variability resulting from the influence of the El Niño Southern Oscillation and the Pacific Decadal Oscillation phenomena. These phenomena produce multi-year droughts and pose risks to the availability of freshwater. Meanwhile, agriculture in the country has shifted to producing vegetables and fruits that consume large quantities of water to meet the winter market demand of the northern hemisphere. Similarly, grapes for the production of Chilean wine put additional pressure on water resources. Roco and others (2016) surveyed Chilean farmers about their perceptions of water availability in the face of climate fluctuations and about the adaptation strategies in response to water scarcity in two river basins of central Chile. These river basins are characterized by a Mediterranean-type climate (i.e., it demonstrates a bimodal rainfall-temperature regime) that is also semi-arid (i.e., annual precipitation ranges from 100 mm on the coast to 300 mm at the top of the Andean mountains). They also face an intense use of water for agriculture. The farmers reported that they perceived climate, droughts and associated water scarcity as the main stressors facing their agricultural production over other socioeconomic factors, such the volatility of prices, lack of labour or lack of institutional support. Although the majority (93 per cent) expect climate changes in the future, only 32 per cent reported having implemented adaptation measures to deal with climate-driven water scarcity. Those measures were classified in four categories: 1. the rationalization of water use at the farm level; 2. the use of water accumulation infrastructure; 3. the modernization of irrigation systems; and 4. the use of partnership strategies. Several factors affected the adoption of these strategies. For example, female farmers were more willing to implement irrigation and infrastructure modernization; the largest producers were less likely to implement associative actions; access to credit positively influenced the use of irrigation technologies; and access to internet and weather information was associated with water rationing, partnerships and water accumulation infrastructure. This case study highlights the complex interconnections between climate, production systems, perception, economics and sociodemographic structures relevant to adaptation to the consequences of aridity. Even so, this case study reflects farmer perceptions of adaptation strategies in a survey conducted in 2013, prior to the impacts from a megadrought that hit Chile during 2010–2018 (Garreaud and others, 2019). This significant event has notably changed peoples’ perceptions of drought and adaptation investment (Cortina and Madeira 2023).

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for all members of groundwater-dependent communities, particularly during drought”.

Another sustainable, cost-effective water management approach to aridity adaptation is the treatment and reutilization of greywater. Greywater is wastewater generated from domestic activities without fecal contamination, such as laundering, dishwashing or bathing. Leas and others (2014, and references therein) report that this adaptation solution is used only at low levels in countries across the Middle East and North Africa, despite the consensus among governments that recycled greywater is a sustainable solution to water scarcity in low-income rural communities. The authors attribute this low implementation to two main factors: costs and uncertainty. The costs of recycling greywater involve costs for infrastructure, costs for treatment facilities and costs to households. These require greater involvement by governments and partnering organizations to convince smallholder farmers to adopt the approach. Uncertainties concerning the health implications of using wastewater for irrigation may also contribute to low implementation—despite guidelines established by international and national agencies, based on threshold levels of risk for specific biological, physical and chemical indicators (Leas and others, 2014). In one study in central Israel, rates of gastrointestinal disease and other illness among people using greywater did not differ from those of a control group—although the research revealed large variability in water quality among water samples taken (Busgang and others, 2015). In the drought-prone, semi-arid area of Ceará, Brazil, meanwhile, families that reused greywater for agriculture reported higher incomes (i.e., by 22 per cent) and higher levels of sustainability compared to the families that did not use recycled wastewater in times of drought.

**Education** and access to information comprise another sector-based approach to adaptation in the face of rising aridity. Education is considered a key and

transversal measure to reduce vulnerability to environmental shocks, because educated and informed societies are better prepared to respond to disasters, suffer lower negative impacts and are able to recover faster than societies with less education (Muttarak and Lutz, 2014). A lack of education is recognized as a common structural cause of poverty and inequality in many arid regions of the world (Omoniyi, 2013; Yadav and Lal, 2018). It is also a factor that contributes to vulnerability to climate distress, especially among women and children. Promoting education positively impacts all levels of society, and these impacts can improve adaptation to increasing aridity. In sub-Saharan Africa, for example, improving the educational status of mothers has been shown to mitigate the negative effects of warming and drying on child stunting (Davenport and others, 2017). In Nigeria, children whose mothers received a formal education were found to be less likely to be stunted compared to their counterparts (Ahmed and others, 2023). Opiyo and others (2015) reported that sending children to school to acquire education and training helped facilitate income diversification for pastoral households in northern Kenya. Interviewed pastoralists viewed education as a long-term adaptation strategy and believed education could help family members find jobs in the modern and urban economy.

Investing in universal primary and secondary education around the world is the most effective strategy for preparing to cope with impacts of future climate warming, according to a review of natural disaster research since the 1980s (Striessnig and others, 2013). The finding addresses the public debate about where funds for adaptation to climate change should be allocated and whether money should be invested in improving infrastructure and agricultural practices or whether it should go to empowering people through education and health (Muttarak and Lutz, 2014). Lutz and others (2014) suggest that public investment in universal education in poor countries should be seen as a top priority for enhancing the adaptive capacity of societies to face future climate change.

General knowledge and awareness of the effects of climate change, including those from drought and aridity, is also important (Jellason and others, 2022; Sani and others, 2018; Wens and others, 2022). Awareness extends beyond acknowledging environmental changes and encompasses an understanding of the interconnectedness between human activities and the changing climate. Farmers, for instance, benefit from an awareness of altered growing seasons, unpredictable precipitation patterns and increased likelihood of extreme weather events. Climate information services (CIS) are an essential tool for sustainable agricultural practices, especially for the rain-fed agriculture that is common in dryland countries (Partey and others, 2018). Climate information services are considered a mainstream strategy for climate risk mitigation (Lodoun and others, 2014; Wanders and Wood, 2018), and they ensure farmers are well-informed about accurate weather predictions, the frequency of diverse meteorological phenomena, climate trends and patterns, intensity and frequency of droughts and floods, etc. This information enables farmers to plan their agricultural activities effectively and efficiently (Partey and others, 2018). In central-western India, for example, CIS along with remote sensing have been used to help farm-scale irrigation

and water management (Roy and others, 2023). In Burkina Faso, farmers using CIS were found to need fewer inputs (e.g., organic manure, fertilizers) in cowpea and sesame production systems compared with those not using CIS (Ouedraogo and others, 2015). Millet growers in Niger, meanwhile, saw an increase in incomes by 1.8–13 per cent in more than 75 per cent of cases when they began using 10-day forecasts to help direct their farming decisions, rather than using seasonal forecasts alone.

Early warning systems constitute another effective awareness tool to minimize the potential effects of aridification (Turp and others, 2019; Wens and others, 2022), especially when impacts are the result of sudden aridity-related events, such as sand and dust storms (Wu and others, 2021). Early warning systems effectively provide information about the onset, progression, extent and intensity of drought conditions, and they can help to anticipate adaptation measures (Fragaszy and others, 2020; Senay and others, 2015). These characteristics of early warning systems can be equally valid in contributing to a better understanding of aridification and to improving and accelerating decision-making processes to combat aridity's impacts in the most vulnerable territories.



### **Box 5. Adaptations to aridity by agropastoralist women in Namibia** (based on Hazel and others, 2021)

In drylands with subsistence economies, women often carry the burden of household chores. They are directly responsible for supplying water, often by carrying it from long distances, and for fulfilling the nutritional, material and hygienic needs of their children and other household members. In the drylands of Kaokoveld in Namibia, women constitute the pillar of a subsistence economy based on herding (mainly cattle) and on the small-scale cultivation of maize. The social structure is strongly grounded in the freedom of women to choose and maintain different sexual partners, before and alongside marriage. This polygamous behaviour is thought to be an ecological strategy for adapting to aridity; it allows the securing of resources and strengthens the social fabric by linking people through emotional bonds and reproduction (Scelza and others, 2020) in an environment that requires frequent dispersal and mobility (Low, 2019). As climate models predict a temperature increase of 4°C and a decrease of annual rainfall by 60–80 mm by the end of the 21st century, however, both the subsistence economy and the sociosexual network may be threatened by environmental shifts and increasing aridification. Hazel and others (2021) conducted a survey to investigate the resilience of women and their capacity to secure resources in the context of increasing unpredictability due to climate change. During the survey period (2009–2016), the researchers found a decrease in the average number of sexual partners, a decline that the interviewed women said was linked to drought. The decrease in sexual partners did not, however, appear to influence the provision of resources, indicating that the relationship between partner concurrency and resource security is complex and highly non-linear. The statistical analysis differentiated two groups of women according to the strategy they adopted for securing resources during droughts. One group turned their subsistence labour into a market resource by trading or selling livestock for cash or other products. The other group increased their effort to produce direct subsistence resources, such as livestock, maize and other crops. A sociodemographic analysis revealed that the adoption of market strategies was most common among married women (including monogamous and polygamous), whereas the preservation of subsistence labour was prevalent among women who had suffered child mortality. Unlike men, only a small portion of women had enough cattle to sell or trade, and goats were the largest contributor to women's access to market resources. Although goats have smaller market value than cattle, they were revealed to be a more flexible commodity to obtain critical resources, especially during droughts, when cattle die and crops fail. The agropastoralist women of northern Namibia have shown the potential for adaptation to aridity and occasional droughts, yet increasing arid conditions may eventually overwhelm the adaptive capacity and jeopardize husbandry practices in this region.

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# Chapter 5.

# POLICY PROPOSALS FOR STRENGTHENING ARIDITY MANAGEMENT AND SUSTAINABLE LAND USE

## PREAMBLE TO POLICY PROPOSALS

The Science-Policy Interface (SPI) of the UNCCD recognizes the pivotal role of global policymakers in steering the world towards sustainable resource management in the face of rising aridity and its challenges, including land degradation. *Visionary leadership and proactive governance can help ensure the success of transformative scientific endeavours aimed at safeguarding our planet's natural resources and ecosystems while ensuring sustainability of socioeconomic development.* The authors of this report urge decision makers across the globe to embrace and implement the five integrated policy areas and their policy recommendations set out below (Figure 18). These recommendations are crafted to catalyse aridity adaptation and drought mitigation, aligning closely with the aspirations of the United Nations sustainable development goals (SDGs) and enhancing the resilience of both human and natural systems against the threats of land degradation and climate change.

By spearheading initiatives that amplify awareness and systematically tackle the multifaceted impacts of aridity, policymakers can pave the way for holistic development strategies and position aridity management

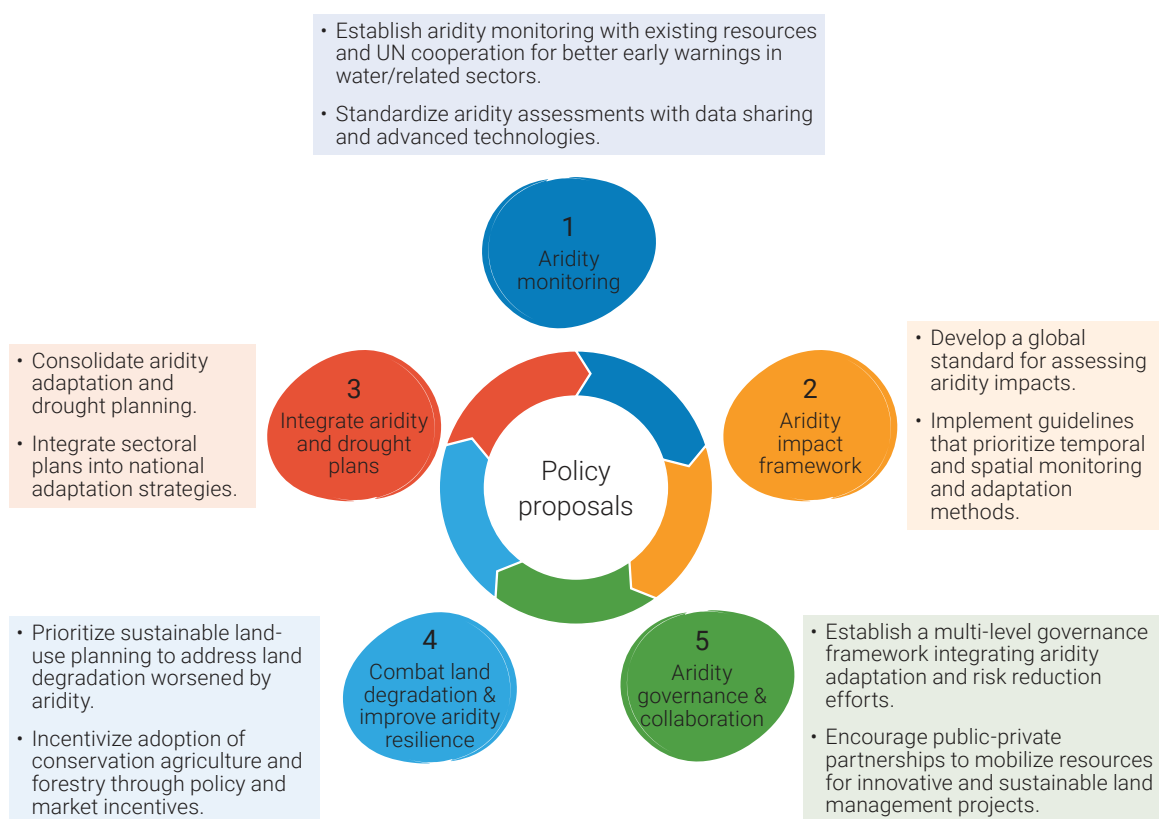
as integral to achieving overarching environmental, social and economic objectives. This leadership is indispensable for cultivating a comprehensive and integrative response to aridity that transcends sectoral boundaries and ensures that both public and private resources are mobilized toward the common goal of advancing SDGs and sustainable land systems through the strategic integration of aridity management into overarching LDN and drought-monitoring frameworks.

These policy proposals are intended as a blueprint for a sustainable future in which proactive aridity and drought resilience measures are undertaken in synergy with measures that cut greenhouse gas emissions, reduce land degradation, safeguard livelihoods, protect ecosystems and simultaneously encourage development for communities.

### **1. Strengthen aridity monitoring and threshold identification:**

Integrate an aridity-monitoring system into existing drought-monitoring frameworks to identify critical ecological and socioeconomic thresholds. This system

**FIGURE 18** Five integrated policy areas—and the policy recommendations they include—for addressing the challenge of current and future rising aridity.



will enhance early warning capabilities for water-related sectors using existing drought observatories and leveraging the UN Early Warning for All initiative for improved global cooperation. Facilitate establishing a standardized approach for robust aridity assessments, enabling timely responses to critical conditions of water stress. Foster collaboration by systematically sharing data (with a focus on interoperability) and best practices to enhance regional and local aridity monitoring and evaluation. Consider leveraging advanced technologies, such as artificial intelligence for predictive analysis (with an emphasis on creating robust, artificial-intelligence-ready data sets), and highlight successful examples. The relevant information generated for this report is included in an Aridity Visual Information Tool, available at [https://global-aridity-](https://global-aridity-monitoring-system.csic.es)

[monitoring-system.csic.es](https://global-aridity-monitoring-system.csic.es). The tool provides a monitoring feature that updates the aridity index annually to help assess long-term changes in aridity.

**2. Adopt a global-to-local aridity impact standard:**

Develop a global standard for assessing the socioeconomic and environmental impacts of aridity. This global standard will facilitate consistent and cross-regional analysis of aridity impacts, enabling (with appropriate support) effective adaptation strategies and promoting resilience among vulnerable communities, particularly in shared river basins and watersheds. Guidelines should emphasize temporal and spatial monitoring to adapt methods in response to climatic, environmental and socioeconomic changes.

This global-to-local, hierarchical approach could facilitate a unified understanding of aridity, enable evidence-based and tailored adaptation strategies and promote inclusivity in addressing aridity impacts. It could also help to integrate, where possible, indigenous knowledge and community-led monitoring efforts to ensure the cultural sensitivity of the standard and to ground it in local realities.

### **3. Integrate aridity adaptation and drought planning into National Adaptation Plans:**

Consolidate aridity adaptation and drought planning into a unified strategy both internationally and under National Climate Adaptation Plans to reduce the compound effects of climate change. Emphasizing community involvement and capacity-building should also be a priority to foster sustainable water and land management practices. A robust monitoring framework for aridity-specific indicators will ensure the efficiency and sustainability of adaptation measures, aligning with overarching national and regional climate adaptation strategies. Leverage adaptive management practices that have been effective in diverse ecological zones, such as water-saving technologies and practices used in agriculture, and advocate for flexible funding mechanisms to support these strategies using robust evidence of their success and scalability.

### **4. Implement comprehensive and integrative strategies to combat land degradation and enhance drought and aridity resilience:**

Emphasize existing and emerging land-use planning and sustainable land-use practices to combat land degradation exacerbated by drought and aridity. Incentivize the adoption of conservation agriculture and forestry to maintain ecosystem services, underpinned by policy incentives, market incentives and emerging technologies for predictive analysis and strategy optimization. Advocate for integrating comprehensive land-use planning that weaves together environmental, social and economic strands. Promote soil conservation through

sustainable practices, such as agroforestry, organic farming, agroecology and/or climate-smart agriculture. Implement terracing, reforestation and other measures to enhance soil and forest health. Support these actions with financial incentives tied to environmental performance (within both the public and private sectors), encouraging a broader adoption of sustainable practices. Push for the development and use of emerging technologies (i.e., artificial intelligence and digital twins) and traditional knowledge systems for precise land management. Similarly, establish a global repository of case studies on successful land restoration efforts, providing a blueprint for addressing land degradation and fostering resilience. This implies strengthening networks of field meteorological stations—currently scarce in dryland regions—integrating soil and hydrogeological survey data into 3-D models to evaluate flood risks and hydrological disruptions and regulating the exploitation of deep aquifers that contain non-renewable and fossil groundwater.

### **5. Promote cross-sectoral aridity governance and collaboration through the UNCCD LDN mechanism:**

Enhance the UNCCD land degradation neutrality (LDN) multilevel governance framework to integrate aridity adaptation and risk reduction, drawing on the principles of the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC). This enhanced framework should continue to foster international collaboration, ensuring that initiatives are synergistically aligned with existing agreements, such as the CBD's Global Biodiversity Framework and Sustainable Development Goal 15.3. Encourage robust public-private partnerships to mobilize resources for innovative and sustainable land management projects, aligning with the objectives of LDN targets. This cooperation is vital for the development and implementation of technologies and conservation practices that support risk

reduction and adaptation to rising aridity. International cooperation and local capacity enhancement are pivotal, as are sustainable financing mechanisms and communication and outreach to the general public. By connecting global decision makers, civil society and practitioners, an integrative LDN governance framework can advance the adoption of best land practices and encourage active participation in global initiatives. This approach will leverage the

strengths of programmes such as the Global Environment Facility (GEF) and the Green Climate Fund (GCF), ensuring that efforts to combat aridity and land degradation are well-supported and aligned with broader environmental and climate goals. It can also help to attract substantive global financing mechanisms to assist with adaptation efforts in areas already being affected by increased aridity.



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# Supplementary Materials

TABLE S1

A list of aridity indicators currently in use or frequently used in the past. This list is not complete, as a very long list of indicators are applied at local scales, often in adapted versions of those included here.

Type	Indicator	Inputs	Reference	Recent use	Advantages	Limitations
Climate	Lang rain factor		Lang, 1920	Ashraf, 2014	Easy to compute	Based only on temperature and precipitation
	Koppen aridity index		Koppen, 1923	Quan, 2013	"	"
	De Martonne aridity index (DM)		De Martonne, 1926	Tabari, 2014	"	"
	Reichel aridity index	T, P	Reichel, 1928	Perez-Mendoza, 2014	"	"
	Emberger pluviothermic index		Emberger, 1930	Derdous, 2021	"	"
	Pinna Combinative Index		Zambakas, 1992	Baltas, 2007	"	"
	Holdridge PE index		Holdridge, 1947	Pan and others, 2000	Easy to compute	PET only includes T as input
	Thornthwaite humidity index		Thornthwaite, 1948	Lorencone, 2022	"	"
	Penman PE index	P, ET (PET)	Penman, 1948	<i>Used as PET in aridity indices</i>	FAO official method	Arbitrary parameters and too many input data
	Prescott Index		Prescott, 1950	Wang, 1918	Easy to compute	Low performance in semi-humid and humid areas
	UNEP Aridity Index (AI)		UNEP, 1992	Zomer, 2022	Reference indicator for global studies	PET estimated in multiple ways
	Aridity Index Plus		Girvetz, 2014a	Girvetz, 2014b	Updated AI with CW deficit/surplus	Based on the same inputs as reference AI
	Budyko dryness index	SolarRad, LatHeat	Budyko, 1951	Gao, 2008	Included in Budyko's framework	Often diverges from other aridity indicators
Palfai Aridity Index	T, P, Groundwater	Palfai, 1995	Dragota, 2011	Based also on groundwater	Laborious computation, groundwater data needed	

Type	Indicator	Inputs	Reference	Recent use	Advantages	Limitations
Climate Classification	Thornthwaite Classification	P, PET	Thornthwaite, 1948	Elguindi, 2014	Combines moisture index and aridity index	Usually replaced by Koppen-Geiger classification
	Koppen-Geiger Classification (KG)	P, T	Koppen, 1936	Beck, 2018	Makes use of monthly T and P	Arbitrary division between macro-classes
	Koppen-Trewartha Classification (KT)	P, T	Trewartha, 1980	Belda, 2014	More refined classes than KG	Builds on KG and uses the same inputs
	Holdridge Life Zones	P, PET, bioT	Holdridge, 1967	Spinoni, 2021	Classes reflect vegetation responses to climate	Uses a logarithmic scale and a complex system
Soil	Soil Moisture Index (SMI)	In situ data or modelled	Review in Su, 2014	Quing, 2022	Estimates water content in soil layers	Needs in situ data or models, better for drought studies
	Surface Soil Moisture (SSM)	"	"	Lian, 2021	Easier to compute than Soil Moisture	Needs in situ data or models, one soil layer only
	Soil Aridity Index (SAI)	Climate and soil inputs	Costantini, 2016	Costantini, 2016	Combines climate and soil parameters	Empirical approach and needs soil parameters
Vegetation	Normalized Difference Vegetation Index (NDVI)	Spectral reflectances	Kriegler, 1969	He, 2019	Estimate vegetation greenness	Needs remote sensing inputs, needs robust modeling for projections
	Leaf Area Index (LAI)	Processed satellite imagery	Review in Fang, 2019	Huang, 2020	Estimates total green leaf per area	Same as NDVI, might need more modeling
	Satellite-based Aridity Index (SbAI)	LST, SolarRad	Kimura, 2019	Niu, 2022	Uses climate parameters estimated by satellite sensors	Needs remote sensing, not yet applied for projections
Composite	Soil-Adjusted Vegetation Index (SAVI)	NDVI, Soil brightness	Huete, 1988	Ren, 2018	Combines vegetation with soil brightness and slope	Simple soil parameters, complex modeling for projections
	Modified SAVI (MSAVI)	SAVI and Veg param	Qi, 1994	Ahmad, 2012	Improves SAVI with refined soil functions	Same problems of SAVI, more complex
	Temperature-Vegetation Soil Moisture Dryness Index (TVMDI)	Climate, veg, soil inputs	Amani, 2017	Wang, 2020	Includes climate, vegetation and soil estimations	Limited application, mostly in East Asia
	Temperature Vegetation Precipitation Dryness Index (TVPDI)	SM, NDVI, P, LST	Wei, 2020	Yao, 2023	Similar to TVMDI but with precipitation	Limited application and similar to TVMDI
	Temperature-sun-induced chlorophyll fluorescence-water balance dryness index (TSWDI)	Climate, veg, soil inputs	Liu, 2023	Liu, 2023	Another evolution of TVMDI	One of the evolutions of TVMDI-like indicators, more complex
Environmental Sensitive Areas (to desertification) Index (ESAI)	Multiple methods	Kosmas, 1999	Symeonakis, 2016	Includes inputs from various sectors	Complex methodology, cannot be applied globally	



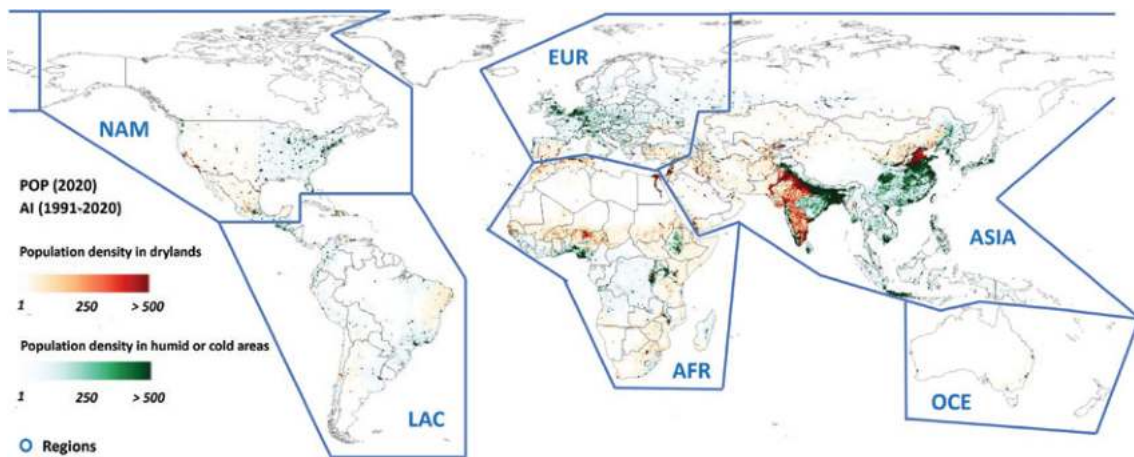
TABLE S2

The combination of SSPs available for each of the 10 GCMs in the ISIMIP3b bias-adjusted climate dataset. Hist starts in 1850 (1881 in this study) and ends in 2014. Hist-nat starts in 1850 (1881 in this study) and ends in 2020. Ssp534ov starts in 2040 (2041 in this study) and ends in 2100. All other SSPs start in 2015 and end in 2100.

GCM	hist	hist-nat	ssp119	ssp126	ssp245	ssp370	ssp460	ssp534ov	ssp585
CAN-ESM5	✓	✓		✓		✓		✓	✓
CNRM-CM6	✓	✓		✓		✓			✓
CNRM-ESM2	✓			✓		✓		✓	✓
EC-EARTH3	✓			✓		✓			✓
GFDL-ESM4	✓	✓		✓	✓	✓			✓
IPSL-CM6A	✓	✓	✓	✓	✓	✓	✓	✓	✓
MIRO-C6	✓	✓		✓		✓			✓
MPI-ESM1	✓			✓	✓	✓			✓
MRI-ESM2	✓	✓	✓	✓	✓	✓	✓	✓	✓
UK-ESM1	✓		✓	✓	✓	✓		✓	✓

FIGURE S1

Population density (inhabitants/km<sup>2</sup>) in drylands (brown) and non-drylands (green) in 2020. The blue lines divide the six macroregions used in this report.



**FIGURE S2** Difference between AI (averaged over 30-year periods and presented as the ensemble median of the six models as in Figure 9) in historical simulations versus historical-natural simulations.

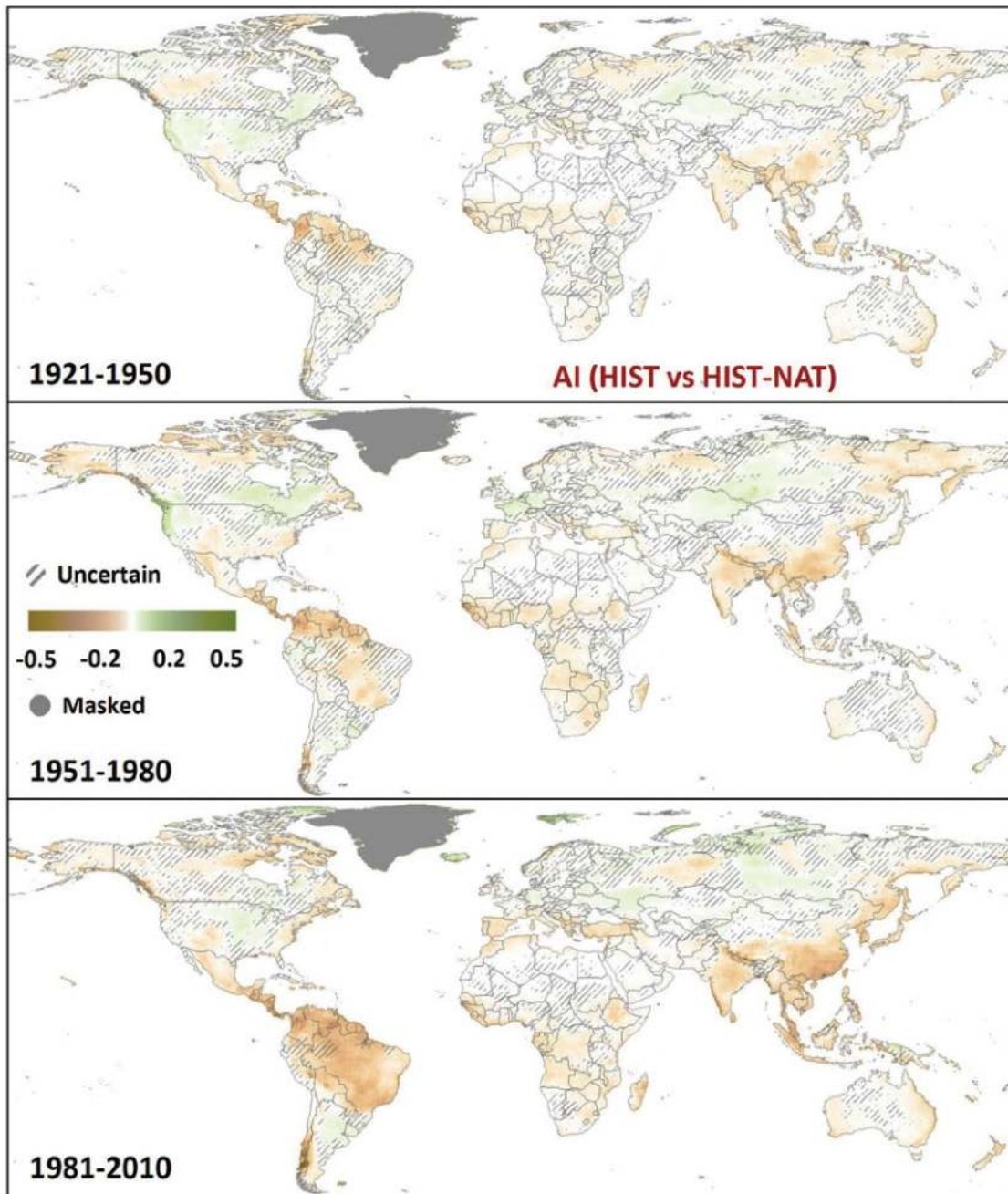
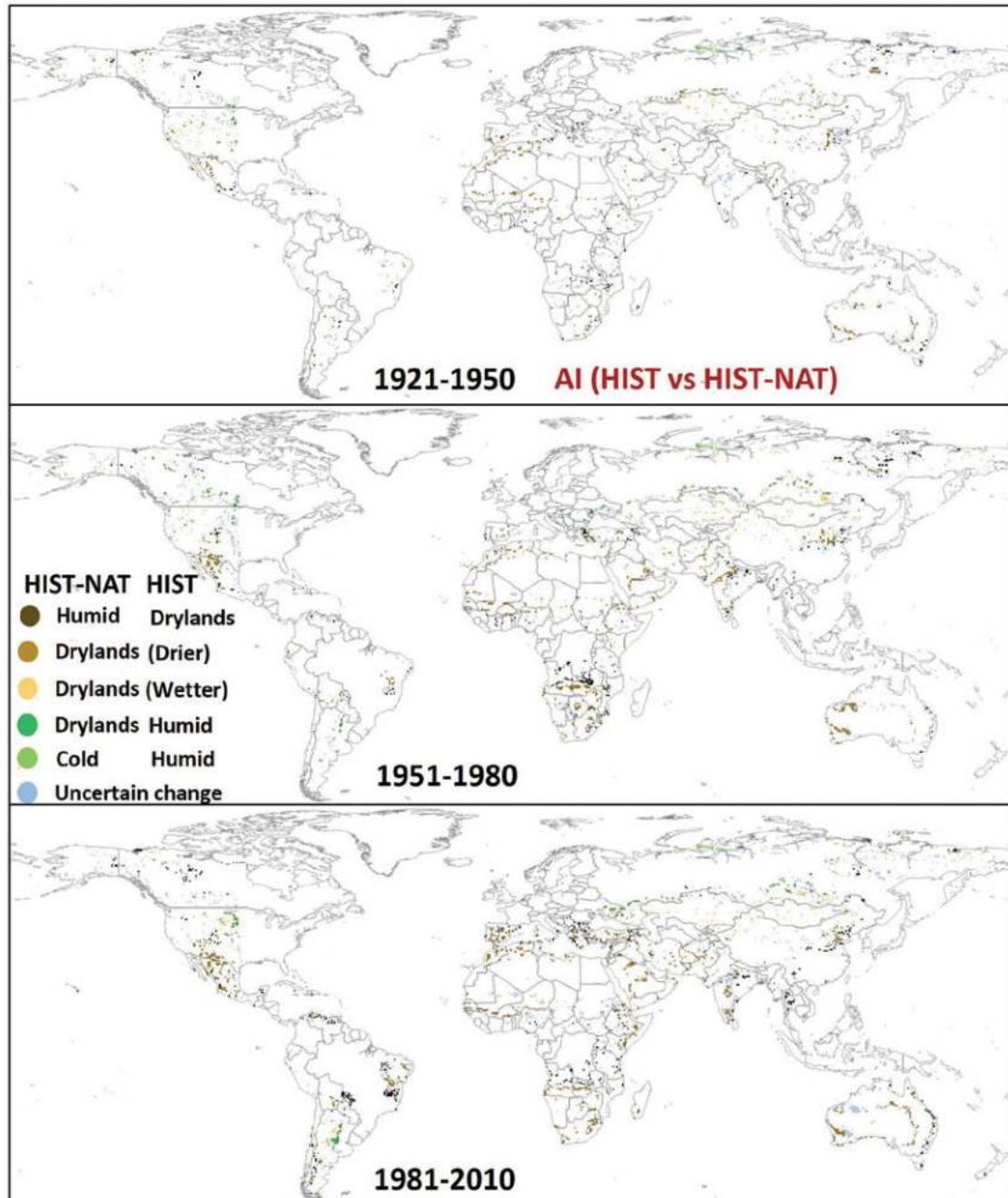


FIGURE S3

Differences between drylands and non-drylands and between AI classes within drylands in the historical and the historical-natural simulations in 1951–1980 and 1981–2010. The colours in the legend are different from those in Figure 10 in the report main text because this figure compares simulations and not evolution over time.



**TABLE S3** Percentage of lands classified as drylands by less than two-third of models (i.e., defined as “uncertain”) and of the populations living in these “uncertain” lands.

Drylands	1881–10		1921–50		1951–80		1981–10	
Uncertain Areas (%)	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	0.7	0.6	1.3	2.1	1.5	1.8	0.5	1.4
LAC	0.5	0.5	1.1	1.8	1.0	1.6	0.4	1.2
EUR	0.3	0.4	1.2	1.0	0.6	1.6	0.5	0.6
AFR	0.8	1.0	2.6	4.5	2.0	4.6	0.9	3.7
ASIA	0.7	0.5	2.3	2.2	2.1	2.4	0.9	2.7
OCE	0.4	0.8	3.4	3.7	2.7	2.9	1.2	3.8
<b>GLOB</b>	<b>0.5</b>	<b>0.5</b>	<b>1.8</b>	<b>2.4</b>	<b>1.6</b>	<b>2.4</b>	<b>0.7</b>	<b>2.2</b>
Population in Uncertain Areas (%)			Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM			1.2	1.4	2.0	1.0	0.2	2.0
LAC			1.6	1.8	0.8	1.5	0.2	1.1
EUR			1.0	1.1	0.4	1.3	0.7	0.4
AFR			3.7	6.5	2.2	6.4	0.6	4.9
ASIA			3.3	3.8	2.8	3.6	1.3	4.1
OCE			7.5	1.5	0.4	0.5	0.1	2.0
<b>GLOB</b>			<b>2.6</b>	<b>3.2</b>	<b>2.2</b>	<b>3.2</b>	<b>0.9</b>	<b>3.5</b>

TABLE S4

Changes between drylands and non-drylands and between AI classes within drylands (i.e., toward drier or wetter AI classes) between 1881–1910 and 1981–2010 (upper part) and between 1951–1980 and 1981–2010 (lower part). Yellow means drier, green wetter and white no substantial differences between historical and historical-natural simulations. GLOB includes Antarctica, where the cold AI class is included for this section but does not change between periods. The colours of the classes are the same shown in Figure 10.

From 1881–10 to 1981–10	Not Dryl Not Dryl	Not Dryl Not Dryl	Not Dryl Drylands	Not Dryl Drylands	Drylands Not Dryl	Drylands Not Dryl	Drylands Drl (drier)	Drylands Drl (drier)	Drylands Drl (wetter)	Drylands Drl (wetter)	Drylands Drl (same)	Drylands Drl (same)
Area (%)	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	72.0	72.1	0.7	0.5	0.6	0.8	1.4	0.3	0.2	1.2	25.0	25.0
LAC	75.5	77.3	2.6	0.7	0.4	0.7	1.7	0.6	0.3	0.5	19.5	20.2
EUR	84.5	85.6	1.7	0.8	0.5	0.5	1.4	0.4	0.1	0.2	11.8	12.6
AFR	25.8	26.7	1.3	0.6	0.5	0.6	3.3	1.7	1.2	0.8	68.0	69.6
ASIA	53.1	53.9	1.0	0.7	0.5	0.3	2.0	1.1	0.6	0.9	42.8	43.0
OCE	35.6	36.4	0.8	0.6	0.1	0.2	4.9	3.0	0.1	1.2	58.5	58.6
<b>GLOB</b>	<b>58.9</b>	<b>59.7</b>	<b>1.1</b>	<b>0.6</b>	<b>0.4</b>	<b>0.5</b>	<b>2.1</b>	<b>1.0</b>	<b>0.5</b>	<b>0.8</b>	<b>36.9</b>	<b>37.5</b>

From 1951–80 to 1981–10	Not Dryl Not Dryl	Not Dryl Not Dryl	Not Dryl Drylands	Not Dryl Drylands	Drylands Not Dryl	Drylands Not Dryl	Drylands Drl (drier)	Drylands Drl (drier)	Drylands Drl (wetter)	Drylands Drl (wetter)	Drylands Drl (same)	Drylands Drl (same)
Area (%)	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	72.1	72.2	0.6	0.4	0.5	0.8	0.9	0.4	0.4	0.8	25.5	25.4
LAC	75.5	77.0	1.3	0.4	0.4	1.0	1.1	0.5	0.4	0.6	21.3	20.4
EUR	84.8	84.8	1.1	0.4	0.2	1.3	0.9	0.1	0.0	0.2	12.9	13.1
AFR	25.5	26.8	0.6	0.6	0.8	0.5	1.0	1.6	1.5	1.0	70.7	69.5
ASIA	53.3	53.9	0.9	0.8	0.3	0.4	1.7	1.1	0.5	0.8	43.4	43.1
OCE	35.6	36.4	0.6	0.5	0.1	0.2	2.8	1.1	0.2	1.5	60.7	60.2
<b>GLOB</b>	<b>58.9</b>	<b>59.6</b>	<b>0.7</b>	<b>0.5</b>	<b>0.4</b>	<b>0.6</b>	<b>1.2</b>	<b>0.8</b>	<b>0.6</b>	<b>0.8</b>	<b>38.1</b>	<b>37.7</b>



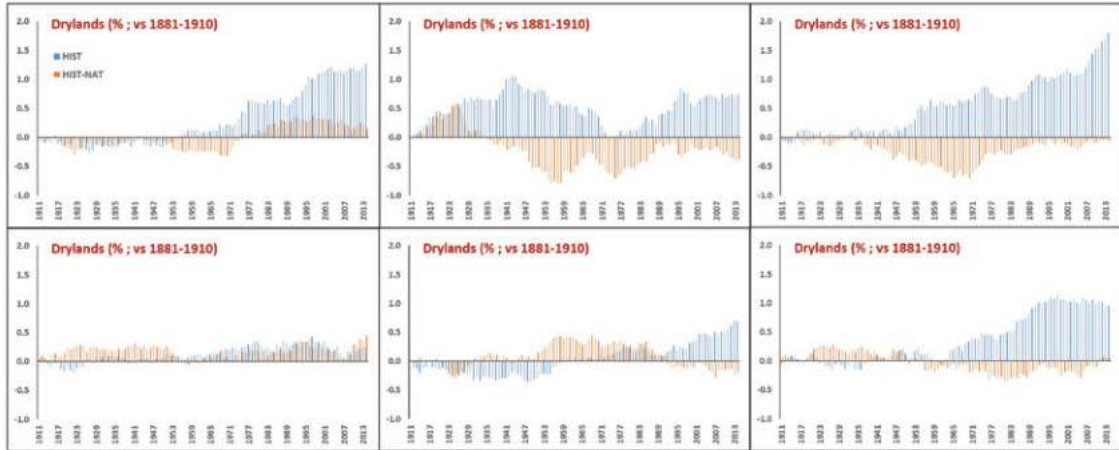
TABLE S5

Percentage of lands showing shifts between AI classes but with less than four models showing agreement on these changes.

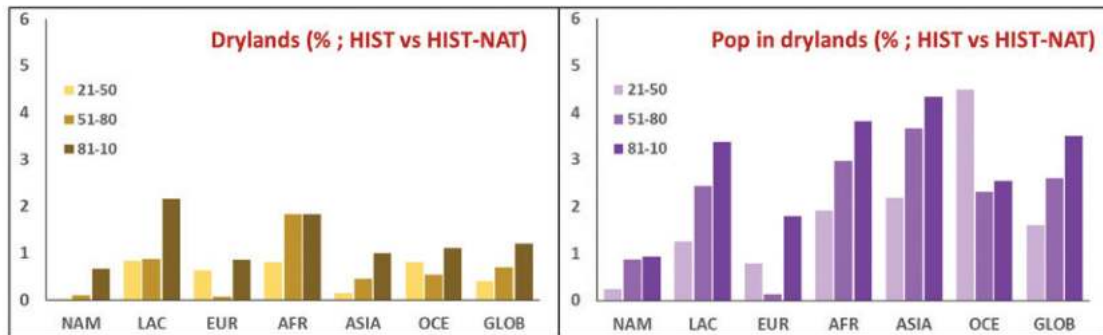
From 1881–10 To 1981–10	Not Dryl Not Dryl	Not Dryl Not Dryl	Not Dryl Drylands	Not Dryl Drylands	Drylands Not Dryl	Drylands Not Dryl	Drylands Drl (drier)	Drylands Drl (drier)	Drylands Drl (wetter)	Drylands Drl (wetter)	Drylands Drl (same)	Drylands Drl (same)
Unc (%)	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	3.1	4.4	0.3	0.3	0.3	0.6	0.5	0.2	0.2	0.6	0.8	1.4
LAC	2.5	4.4	0.6	0.4	0.2	0.8	0.4	0.4	0.2	0.5	0.6	1.1
EUR	2.5	5.4	0.8	0.4	0.0	1.1	0.5	0.1	0.0	0.1	0.4	1.1
AFR	1.5	3.4	0.3	0.5	0.4	0.5	0.6	1.2	0.6	0.7	1.1	4.0
ASIA	2.1	3.1	0.4	0.5	0.2	0.4	0.8	0.6	0.3	0.7	1.4	2.4
OCE	1.9	3.0	0.2	0.5	0.0	0.2	1.2	0.8	0.1	1.3	2.3	3.2
<b>GLOB</b>	<b>2.0</b>	<b>3.3</b>	<b>0.4</b>	<b>0.4</b>	<b>0.2</b>	<b>0.5</b>	<b>0.6</b>	<b>0.6</b>	<b>0.3</b>	<b>0.6</b>	<b>1.0</b>	<b>2.1</b>

From 1951–80 To 1981–10	Not Dryl Not Dryl	Not Dryl Not Dryl	Not Dryl Drylands	Not Dryl Drylands	Drylands Not Dryl	Drylands Not Dryl	Drylands Drl (drier)	Drylands Drl (drier)	Drylands Drl (wetter)	Drylands Drl (wetter)	Drylands Drl (same)	Drylands Drl (same)
Unc (%)	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat	Hist	Hist-nat
NAM	1.7	3.1	0.3	0.4	0.5	0.5	0.1	0.0	0.1	0.5	0.5	0.9
LAC	1.2	2.8	0.5	0.5	0.3	0.7	0.1	0.2	0.1	0.3	0.5	0.7
EUR	1.7	3.0	1.0	0.6	0.0	0.4	0.1	0.0	0.1	0.1	0.3	0.4
AFR	0.6	2.4	0.4	0.5	0.4	0.5	0.1	0.5	0.1	0.2	1.0	2.8
ASIA	0.9	2.1	0.3	0.5	0.3	0.3	0.3	0.4	0.1	0.5	0.7	1.6
OCE	1.1	2.3	0.3	0.3	0.0	0.1	0.3	0.1	0.0	0.9	1.1	2.7
<b>GLOB</b>	<b>1.0</b>	<b>2.2</b>	<b>0.4</b>	<b>0.4</b>	<b>0.3</b>	<b>0.4</b>	<b>0.2</b>	<b>0.2</b>	<b>0.1</b>	<b>0.4</b>	<b>0.6</b>	<b>1.5</b>

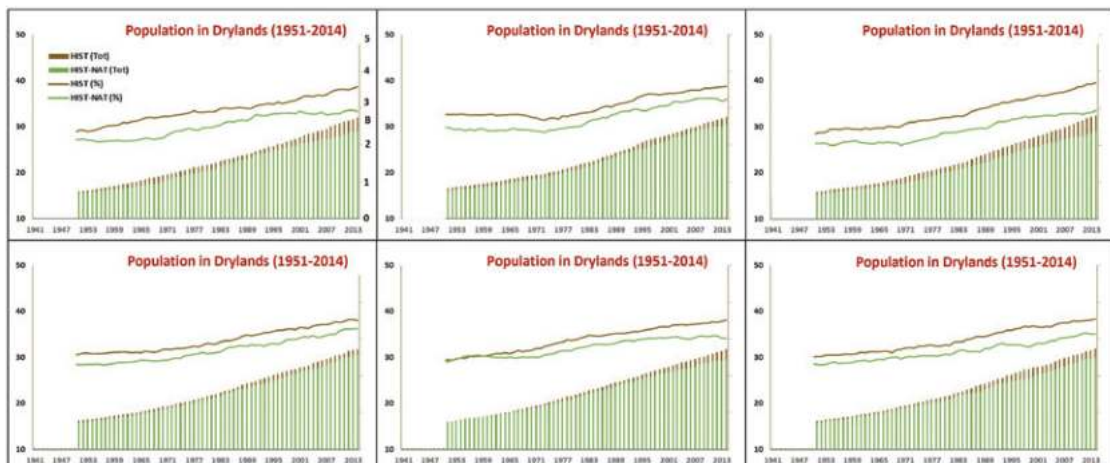
**FIGURE S4** Global annual time series of drylands (AI classes 1-4) for the six models with both historical and historical-natural outputs in the ISIMIP3b dataset. The values are presented as anomalies from 1911 to 2014 compared to the reference period 1881–1910.



**FIGURE S5** Differences between historical and historical-natural simulations regarding dryland extent and the population in drylands at macroregional and global scales. The three periods investigated include 1921–1950, 1951–1980 and 1981–2010.



**FIGURE S6** Global annual time series, 1951–2014, of populations in drylands (in percentage and total values) for the six models with both historical and historical-natural outputs in the ISIMIP3b dataset.



**FIGURE S7** Changes in the aridity index values relative to the reference period of 1981–2010 for projected Global Warming Levels. Similar to Figure 14.

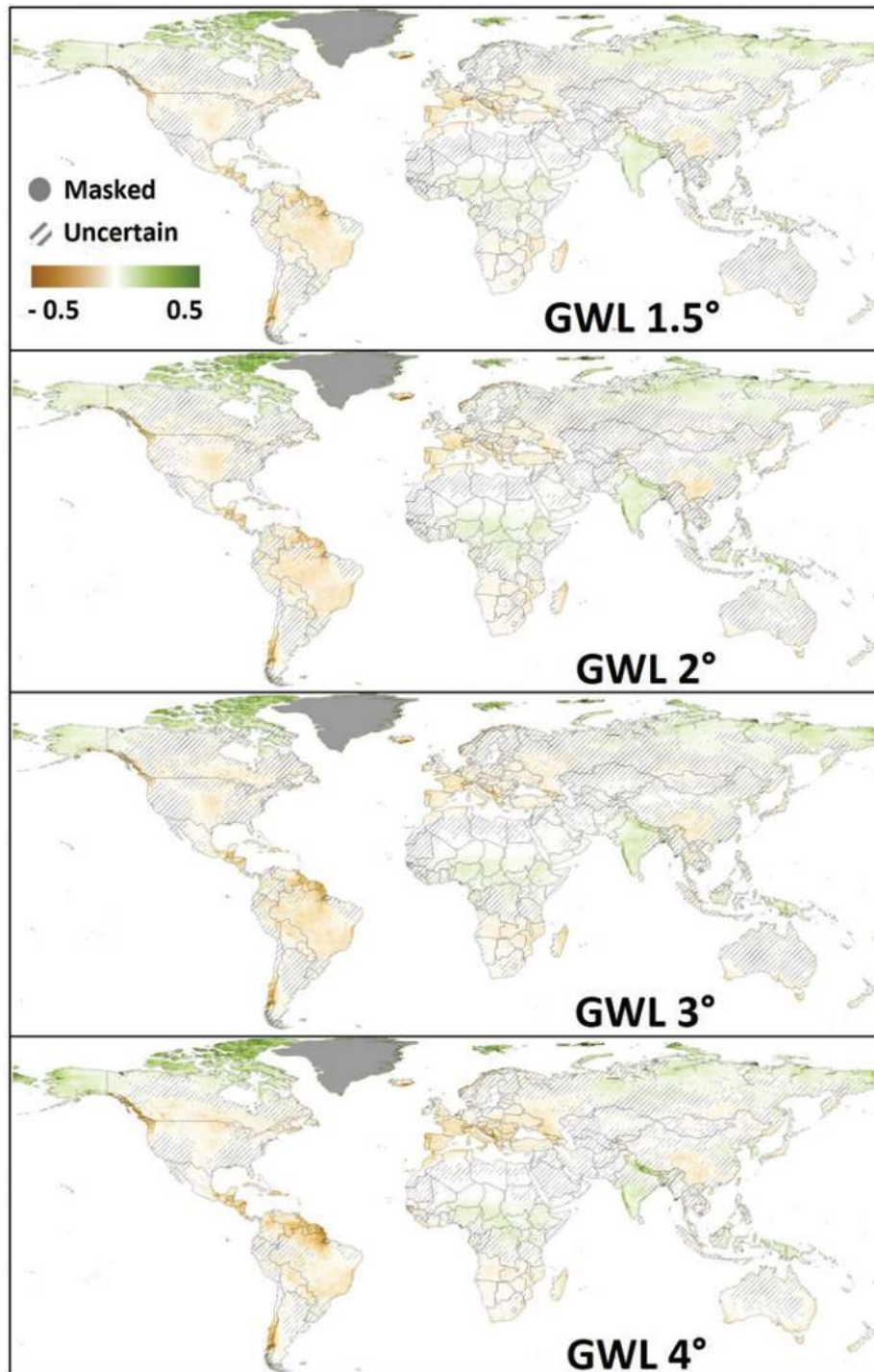
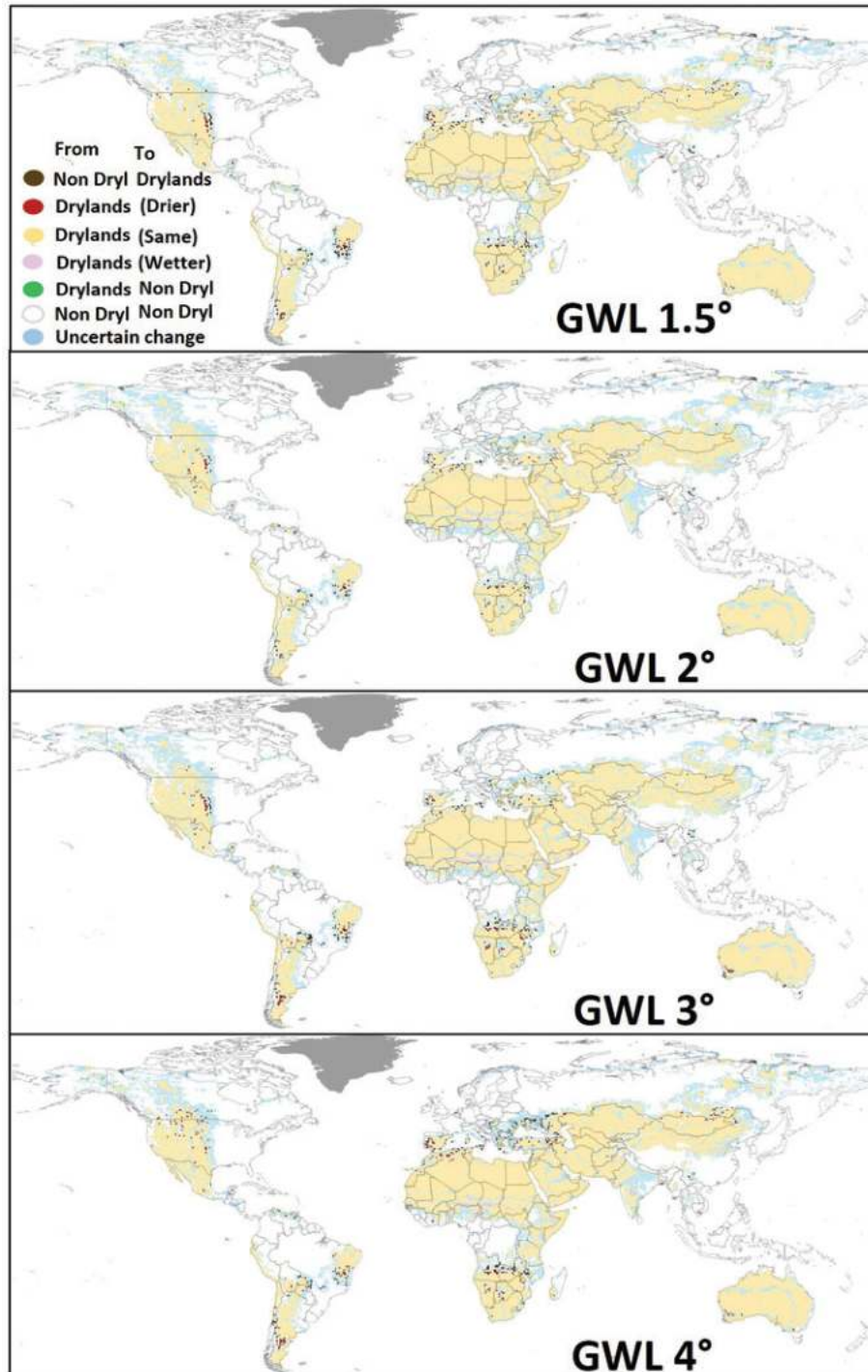


FIGURE S8

Change in the aridity index classes for Global Warming Levels (GWLs). Similar to Figure 15. The overall changes are frequently uncertain because all SSPs are used to reach the GWLs and different models show the same GWL at more than 15 years of difference. Consequently, the approach, which divides between the SSPs and focuses on fixed periods, better fits the scope of this study and reflects population projections that are discrete in time.



**TABLE S6** The percentage of new drylands (“Dry”) and areas shifting to a drier AI class (“Drier”) from 1981–2010 to 2021–2050 and 2071–2100, according to four SSPs. The final “S” refers to areas subjected to significant changes (“DryS” and “DrierS”). The other columns include areas with less than two-thirds simulations agreeing on the sign of these changes.

	vs HIST (%)	2050 DryS	2050 Dry	2050 DrierS	2050 Drier	2100 DryS	2100 Dry	2100 DrierS	2100 Drier
<b>SSP1</b>	<b>NAM</b>	0.2	0.9	0.8	2.9	0.2	0.6	0.7	2.6
<b>SSP1</b>	<b>LAC</b>	1.0	1.9	1.3	3.3	0.6	2.3	1.1	4.0
<b>SSP1</b>	<b>EUR</b>	1.1	3.0	1.8	4.4	1.4	3.7	2.7	5.8
<b>SSP1</b>	<b>AFR</b>	0.4	0.6	1.4	3.6	0.8	1.2	2.6	5.2
<b>SSP1</b>	<b>ASIA</b>	-0.1	-1.0	0.1	0.6	-0.3	-1.6	0.1	0.6
<b>SSP1</b>	<b>OCE</b>	0.2	0.8	0.5	2.3	0.5	1.0	1.2	4.1
<b>SSP1</b>	<b>GLOB</b>	0.3	0.4	0.7	2.2	0.3	0.4	1.0	2.7
<b>SSP2</b>	<b>NAM</b>	0.1	0.7	0.6	2.6	1.3	2.7	2.0	5.6
<b>SSP2</b>	<b>LAC</b>	1.1	2.3	2.1	4.5	1.2	4.3	2.5	7.3
<b>SSP2</b>	<b>EUR</b>	1.9	4.2	3.1	6.5	4.6	7.1	8.6	12.1
<b>SSP2</b>	<b>AFR</b>	-0.1	-0.2	0.7	2.5	1.1	2.4	3.7	8.0
<b>SSP2</b>	<b>ASIA</b>	0.1	0.1	0.5	1.7	0.1	-0.6	0.6	1.9
<b>SSP2</b>	<b>OCE</b>	0.2	0.9	0.8	3.8	0.6	1.4	2.2	5.0
<b>SSP2</b>	<b>GLOB</b>	0.3	0.7	0.9	2.6	0.9	1.8	2.2	4.9
<b>SSP3</b>	<b>NAM</b>	0.2	0.6	0.7	2.8	1.4	4.0	3.7	8.7
<b>SSP3</b>	<b>LAC</b>	1.4	2.8	2.3	4.7	1.1	6.3	4.0	11.4
<b>SSP3</b>	<b>EUR</b>	1.2	3.0	2.5	5.1	6.3	9.6	12.4	16.9
<b>SSP3</b>	<b>AFR</b>	0.2	0.0	1.5	3.7	2.1	2.3	6.7	11.1
<b>SSP3</b>	<b>ASIA</b>	-0.1	-0.5	0.4	1.4	0.1	-1.4	1.2	2.5
<b>SSP3</b>	<b>OCE</b>	0.3	0.5	0.9	2.4	1.0	2.0	3.9	8.9
<b>SSP3</b>	<b>GLOB</b>	0.3	0.5	1.0	2.6	1.3	2.1	3.8	7.2
<b>SSP5</b>	<b>NAM</b>	0.3	1.0	1.0	3.3	1.3	4.7	4.1	10.3
<b>SSP5</b>	<b>LAC</b>	1.3	3.3	2.3	5.6	1.8	9.7	5.2	15.7
<b>SSP5</b>	<b>EUR</b>	1.4	3.1	2.7	5.1	6.6	11.9	14.4	20.7
<b>SSP5</b>	<b>AFR</b>	0.2	-0.7	1.5	3.5	1.9	2.2	7.1	13.1
<b>SSP5</b>	<b>ASIA</b>	-0.1	-0.8	0.3	1.1	0.0	-0.8	1.5	4.0
<b>SSP5</b>	<b>OCE</b>	0.3	0.4	0.5	1.3	1.0	2.1	5.3	10.1
<b>SSP5</b>	<b>GLOB</b>	0.3	0.4	1.0	2.6	1.3	2.9	4.4	9.2



TABLE S7

The percentage of net change in population in drylands from 1981–2010 to 1021–2050 and to 2071–2100, according to four SSPs. The final “S” refers to areas subjected to significant changes (e.g., “PDryIS”).

vs HIST (%)	SSP1	SSP1	SSP2	SSP2	SSP3	SSP3	SSP5	SSP5
	2050	2100	2050	2100	2050	2100	2050	2100
	PDryIS	PDryIS	PDryIS	PDryIS	PDryIS	PDryIS	PDryIS	PDryIS
NAM	1.6	-0.3	2.5	4.4	5.8	17.4	0.6	0.0
LAC	-0.3	1.6	-0.2	3.5	2.4	6.2	1.5	7.0
EUR	0.8	-0.5	1.9	4.5	2.1	16.0	1.0	7.3
AFR	-1.1	-5.9	-3.6	-6.0	-4.1	-7.9	-5.0	-9.2
ASIA	-3.0	-1.4	-0.4	1.1	-2.5	-1.5	-3.8	-6.7
OCE	-6.6	-0.2	-6.7	-4.6	-7.9	-0.3	-5.4	10.3
GLOB	-0.9	-0.7	0.3	1.8	-0.1	2.0	-2.2	-3.4





**Rising aridity—the growing, long-term loss of available, life-sustaining moisture by terrestrial climates—is threatening people and environments in almost every global region.**

Increasingly—as climate change causes drying across more than three-quarters of the world’s land—aridity-related land degradation and water scarcity are contributing to food and water insecurity, poor soil fertility, losses in crop and plant productivity, biodiversity declines, ecosystem degradation, intense sand and dust storms, wildfires, poor health and large-scale human migration.

Assessing and understanding aridity trends and future projections is critical to developing resilient adaptation and mitigation strategies. This report addresses the challenges in assessing aridity, aridity’s current and future trends and the multifaceted impacts resulting from aridity, aiming to catalyse global, regional and local efforts towards sustainable adaptation to drying lands around the world.

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