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EXTREME HEAT AND AGRICULTURE

FAO–WMO joint report

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FOREWORD

Extreme heat is increasingly defining the conditions under which agrifood systems operate. Rising temperatures and heatwaves, occurring with greater frequency, duration and intensity, are often accompanied by prolonged drought and other climate extremes. Together, these hazards are exerting mounting pressure on crops, livestock, fisheries and forests, and on the communities and economies that depend upon them.

This joint report on extreme heat and agriculture brings together the scientific and operational expertise of the Food and Agriculture Organization of the United Nations (FAO) and the World Meteorological Organization (WMO) to assess how extreme heat is reshaping food production and food security. Drawing on the latest climate observations, agrifood systems analysis, and research, it provides a comprehensive assessment of risks that have too often been under-recognized in climate and development planning and identifies priority areas for policy attention and strategic investment.

Extreme heat magnifies existing weaknesses across agricultural systems. Higher temperatures parch soils, reduce harvests, strain livestock, disrupt fisheries and increase wildfire risk. When combined with water scarcity, the consequences intensify, cutting production, lowering incomes, and tightening food supplies.

These impacts extend far beyond the farm gate. They represent a systemic risk to global food security and to the livelihoods of more than 1.23 billion people who rely on agriculture. Agricultural workers are already experiencing effects on their health, productivity and income. As climate variability intensifies, hard-won progress in reducing hunger and poverty comes under strain, with shocks rippling through economies and households and disproportionately affecting the most vulnerable. The strongest line of defense is the resilience of agrifood systems and the farmers behind them.

The findings of this report make clear that building the resilience of agrifood systems requires coordinated and sustained action. Adaptation must be scaled across agrifood systems globally and be carried out at a pace that keeps ahead of the rate at which the damaging changes materialize. Climate-resilient practices, improved water and land management, the development of heat-tolerant crops and breeds and strengthened risk governance can reduce vulnerability and protect livelihoods.

Because extreme heat events are often predictable, forecast-based action offers a critical opportunity to reduce losses and protect agricultural workers. Timely and actionable weather and climate information, supported by effective early warning systems and agrometeorological advisories, can help farmers, fishers, herders and foresters anticipate risks and take preventive measures. As the frequency and severity of extreme heat increases, building the resilience of communities and ecosystems to cope will be critical.

The collaboration between FAO and WMO reflected in this report demonstrates how rigorous climate science can guide the transformation towards more efficient, more inclusive, more resilient and more sustainable agrifood systems.

We stand by our shared commitment to provide Members, partners and practitioners with the evidence needed to anticipate risk, guide policy and accelerate investments that enable agrifood systems to withstand a hotter and more volatile climate while continuing to sustain populations and economies.

Celeste Saulo
Secretary-General of the World
Meteorological Organization

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Director-General of the Food and Agriculture
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ABBREVIATIONS

AR	Assessment Report
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
ENSO	El Niño Southern Oscillation
FAO	Food and Agriculture Organization of the United Nations
FWI	Fire Weather Index
GHG	greenhouse gas
GPP	gross primary productivity
IPCC	Intergovernmental Panel on Climate Change
N_2O	nitrous oxide
NPP	net primary productivity
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
THI	Temperature–Humidity Index
USD	United States Dollars
WBGT	Wet Bulb Globe Temperature
WG	Working Group
WHO	World Health Organization
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Extreme heat has emerged as one of the most serious and acute hazards facing agriculture around the globe, threatening food security and the livelihoods of billions. Extreme heat is a powerful risk multiplier with direct and indirect impacts across all agricultural subsectors (crops, livestock, fisheries and aquaculture, and forestry). It amplifies existing hazards such as drought, heightens the risk of wildfires, and creates complex compound impacts that endanger not only production but also the health of agricultural workers, who are on the frontlines of the growing threat.

The fingerprints of extreme heat on agriculture are already visible worldwide. The analysis of scientific evidence and case studies presented in this report confirms that heat is driving significant productivity losses. For example, yields of staple crops like maize and wheat have declined by 7.5 and 6.0 percent per 1 °C of warming and are projected to decline by up to an additional 10 percent for every 1 °C of warming in the future. Under high-emission scenarios, nearly half the world's cattle could be exposed to dangerous heat by 2100, with annual losses nearing USD 40 billion (in 2005 dollars), although under a low-emission scenario (SSP1-2.6), impacts from livestock exposure to extreme heat are reduced by nearly two-thirds. In aquatic systems, marine heatwaves have already caused repeated mass mortality events and are forcing entire fish stocks to migrate in search of cooler water. Fruit and nut trees and natural forests are also subject to production losses and the growing risk of more frequent and intense wildfires. Together, these losses create a dangerous feedback loop, where shortfalls in production can lead to agricultural expansion to compensate, increasing GHG emissions that fuel further climate change.

Building resilience through adaptation to damaging changes that have already occurred and that are imminent is imperative. The need for adaptation action is particularly acute for the most vulnerable communities in the tropics and subtropics. Because extreme heat is predictable, strengthening climate services and early warning systems linked to anticipatory actions is a key opportunity. It is also clear that there are profound limits to what adaptation can achieve. With global mean temperatures on the cusp of exceeding the 1.5 °C warming limit outlined in the Paris Agreement, the urgency for adaptation and mitigation action only grows. The only durable solution to protect the future of global agrifood systems from the escalating threat of extreme heat lies in ambitious, multilateral climate change mitigation.

1. INTRODUCTION

1.1 Objectives

Ensuring food security for all is the most crucial of the Sustainable Development Goals. As of 2024, however, over 8 percent (8.2) of the world's population still faced hunger. In the same year, 2.3 billion people experienced moderate to severe food insecurity, and almost one-third of the world's population could not afford a healthy diet (FAO *et al.*, 2025). Achieving zero hunger will require greater efforts to transform agrifood systems so that they become more equitable and resilient. Efforts to achieve food security for all are increasingly challenged by the intensified impacts of climate change and extreme weather events such as extreme heat. Extreme heat has an impact on both terrestrial and aquatic food systems. It leads to lower crop yields and reduced product quality; increased mortality and decreased productivity from livestock, forests, fisheries and aquaculture; increased risks of wildfires; and greater health risks and lower productivity for agricultural workers. These impacts may have cascading effects on national economies. The potential is growing for synchronized production shocks among food-exporting nations due to climate change, heightening concerns about the future of global food availability (e.g. Tigchelaar *et al.*, 2018; Gaupp *et al.*, 2019).

In joining with the United Nations Secretary-General's Call to Action on Extreme Heat in 2024, this report provides an overview of the literature on extreme heat since the release of the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). Focus has been placed on food production and the impacts of extreme heat on crops, livestock, fisheries and aquaculture, forestry, and agricultural workers. The agricultural subsectors are vulnerable to the impacts of extreme heat through many different direct and direct pathways. The report provides an overview of the current scientific understanding of these pathways, presents observed and future projected impacts, and outlines options for risk reduction and adaptation. The ultimate goal of the report is to identify policy imperatives for responding to the growing threat from extreme heat and to lay the foundations for a more comprehensive assessment that will complement the on-going preparations of the 7th IPCC Assessment Cycle and Special Reports.

The rest of this report is organized into six sections:

- Section 2 describes the physical basis and meteorology of extreme heat.
- Section 3 looks at the relationships between extreme heat and agriculture, including vulnerabilities to extreme heat, and the observed and projected impacts on each subsector.
- Section 4 considers adaptation strategies and extreme heat risk governance.
- Section 5 presents a case study that illustrates the compound impacts of extreme heat.
- Section 6 provides a summary of findings and offers policy recommendations.

1.2 Key concepts

Extreme heat

Extreme heat is a broad meteorological concept of magnitude that has varying definitions. The term is commonly used in reference to exceptionally hot conditions compared to local climatological norms. The definition of extreme heat as an expression of a statistical percentile (e.g. 90th or 95th percentile) (Klein Tank *et al.*, 2009; Perkins and Alexander, 2013) or relative to the exceedance of some threshold value (e.g. greater than 40 °C) is less common outside of individual studies. In this report, and in the agricultural subsectors generally (crops, livestock, fisheries and aquaculture, and forestry), extreme heat refers to the exceedance of temperature thresholds that result in increasing levels of physiological stress (moderate and above) and/or, direct physical damage to reference organisms. Extreme heat can also contribute to what are referred to as indirect impact pathways such as those affecting associated species, biological communities and food chains, and critical resources. Extreme heat is thus a contextual and impact-based concept, noted for its negative outcomes.

Heatwaves

Reference to extreme heat is commonly made in the context of heatwaves. Whereas extreme heat is defined solely by temperature magnitude, heatwaves include a temporal dimension of unspecified duration ranging from days to months. A spatial dimension of extent is also occasionally included in defining heatwaves. Similar to extreme heat, heatwaves do not have a widely used, single definition (e.g. Bunting *et al.*, 2024). WMO defines heatwaves as prolonged periods of abnormally hot weather, lasting from several days to months when both daytime and night-time temperatures exceed typical regional averages (WMO, 2015). High night-time temperatures are particularly concerning because they prevent essential cooling and prolong heat accumulation into the next day (WMO, 2015; WMO and WHO, 2025). Local factors such as geography, urbanization and climate strongly influence heatwave characteristics (WMO, 2015). Marine heatwaves also occur, as do heatwaves in freshwater bodies, and are defined as a period of extreme temperatures at the water's surface or at greater depths that persist for days to months (IPCC, 2022b). Marine heatwaves can have an impact on areas covering several thousand square kilometers and can penetrate to a depth of hundreds of meters.

Heat stress

Heat stress denotes the impact(s) of high temperatures on an individual organism or species. It encompasses a variety of phenomena and timescales, covering the entire range of behavioral, biochemical, physiological, and morphological impacts that result from exposure to increasingly high temperatures. The effect of extreme heat on an organism can accumulate and range from mild levels of stress (typically mitigated through behavioral adjustments) to increasingly severe stress levels that cause metabolic disruption, cellular breakdown, systemic failures and death. Stress from extreme heat in the context of this report is concerned with the upper range of possible impacts. Extensive research into heat stress on crop and livestock species has led to the definition of widely used indices and threshold temperature values. Examples include the temperature–humidity index used for livestock species, wet bulb measures for agricultural workers, and the accumulation of extreme heat days for crop species.

BOX 1. Difficulties with definitions of extreme heat

The use of extreme heat (defined in this report as the level of heat causing moderate and above impacts) and heatwave events more generally (however they may be defined), as a metric in assessing heat damages is not widely reflected in the research and poses several methodological challenges, particularly for crops. Research to date has focused, and rightly so, on the identification of crop-specific temperature thresholds at which yield damages begin to appear (e.g. above 30 °C), or crop yield sensitivities per unit of warming (e.g. a reduction in yields per 1 °C). The impacts have been assessed over varying spatial scales and temporal periods using a variety of methods and data (Lobell *et al.*, 2013; Butler and Huybers, 2015).

The use of higher temperature thresholds, corresponding to a particular definition of extreme heat, as in this report, is not commonly applied. Percentile definitions of extreme heat have occasionally been used in examining the impacts on crop yields (e.g. Zampieri *et al.*, 2017). However, percentile values represent a statistical artifact and are not based on crop physiological responses to temperature. Alternatively, studies have superimposed documented heatwaves on annual yield data as the basis of analysis. In these studies, however, no attempt is made to attribute a portion of the observed damages to extreme heat separate from the damages that begin to occur at lower temperatures before and after an extreme heat threshold is reached, or damages resulting from other stressors (Lesk *et al.*, 2016; Heinicke *et al.*, 2022; Sidhu, 2023). The result, by default, is that all damages sustained within the season when the heatwave occurred are included. Most process-based crop models capture the effects of high temperatures on photosynthesis, the effect of accumulated heat in shortening the physiological phases in a crop's development cycle, and increased maintenance respiration demands.

Crop models have historically, however, not captured well the damages resulting from oxidative stress, enzyme, tissue and reproductive organ damages and functioning resulting in impacts on seed set and yield development (Schauberger *et al.*, 2017). In other words, those damages that might correlate with a definition of extreme heat have not been modelled, but this is changing with continued updates in crop models (e.g. the Agricultural Production Systems sIMulator - APSIM). Likewise, there is not a well-established body of evidence that would support the articulation of crop-specific response curves, with varying rates of yield loss determined by temperature as different plant systems are impacted and when crops reach different stages of development, that might be applied in statistical analysis, although this too is changing (e.g. Tran *et al.*, 2025). In sum, the ability to attribute losses to specific extreme heat events, other than those where observed yield impacts begin to occur, is limited.

Sources: See References.

Compound events and compound impacts

The impacts of extreme heat are increasingly being examined in agricultural contexts where they occur simultaneously with other extreme events, most notably drought, and result in what are referred to as compound events (AghaKouchak *et al.*, 2020; Lesk *et al.*, 2022). The impacts produced by compound events typically exceed those that would have resulted from the sum of the individual events had they occurred separately. Along with the concept of compound events, the report includes the concept of compound impacts. Compound impacts result when a single extreme heat event simultaneously affects several species and, or subsectors. The extent of compound impacts depends on the location, timing, and magnitude of the extreme heat event. Compound impacts can in turn lead to interactions among the affected components. These interactions can potentially trigger a cascade of impacts among the interdependent parts of the affected system or related systems.

In summary, extreme heat and heatwaves result in severe levels of heat stress that both directly and indirectly affect people, natural ecosystems and agricultural species. Periods of extreme heat can interact with other climatological variables (e.g. humidity, rainfall, solar radiation, and wind). These interactions can greatly exacerbate the direct and indirect effects of heat. The most damaging situation occurs when extreme heat combines with other extreme events, such as more frequent and intense droughts. More often, extreme heat events lead to compound impacts, where a single event simultaneously impacts crops, livestock, and forest systems due to the magnitude of the event, the proximity of species and the extent of the area impacted.

1.3 Scope of the analysis

This report analyses the direct and indirect impacts of extreme heat on primary agricultural production (crops, livestock, fisheries and aquaculture, and forestry). The goal is to describe the mechanisms through which extreme heat affects productivity and the stability of agricultural subsectors. The effects of extreme heat ripple throughout the entire agrifood system. However, a comprehensive examination of all related aspects of food security is beyond the scope of this report. To ensure clarity and depth, this document has deliberately set boundaries.

The report's analytical focus stops at the 'farm gate'; the point in the agrifood value chain where primary production ends. The analysis does not extend to the post-harvest stages (e.g. processing, packaging, transportation, markets, retail and use) of the agrifood value chain. Extreme heat can accelerate the degradation in quality and increase post-harvest losses, but these post-harvest challenges are not discussed. The report also does not cover the impacts of extreme heat on the transport of agricultural goods, nor does it assess the need for improved cold chain logistics to ensure foodstuffs arrive undamaged at their destination.

Although this report details production losses, it stops short of quantifying the downstream economic and social implications of these losses. It does not report on the economic impacts of production shortfalls, such as potential food price volatility, disruptions to global commodity markets, or the subsequent effects on the availability and affordability of food for consumers (e.g. Kotz *et al.*, 2025). The direct socioeconomic consequences for agricultural producers, such as income loss, reduced livelihoods and impacts on well-being as a result of production damage from extreme heat, are acknowledged as a grave concern, but are beyond the scope of this report. The socioeconomic impacts of climate stressors have been assessed in other FAO reports (Box 2).

BOX 2. Socioeconomic aspects of heat stress in agriculture

In a 2024 report, *The unjust climate*, FAO has assessed the socioeconomic aspects related to extreme weather events in agriculture (FAO, 2024a). The report found that in an average year, poor households lose 5 percent of their total income due to heat stress relative to better-off households. The impacts are even greater for female-headed households who experience annual average income losses of 8 percent due to heat stress relative to male-headed households. Globally, the average annual exposure to heat stress reduces the total incomes of rural female-headed households in low- and middle-income countries by a combined USD 53 billion relative to male-headed households. Over the long-term, a 1 °C rise in temperature results in a 54 percent increase in the reliance of poor households on agriculture for income relative to non-poor households. This greater reliance on agriculture increases their exposure to future climate change shocks.

Source: **FAO.** 2024a. *The unjust climate*. Rome. https://www.fao.org/socioeconomic-research-analysis/resources/unjust-climate/the-unjust-climate/en

2. METEOROLOGY OF EXTREME HEAT

Extreme heat is influenced by multiple interlinked drivers. These drivers include the trends and inertia of human-induced (anthropogenic) climate change, natural climate variability, and meteorological phenomena. All of these drivers operate across different spatial and temporal scales (see Figure 1).

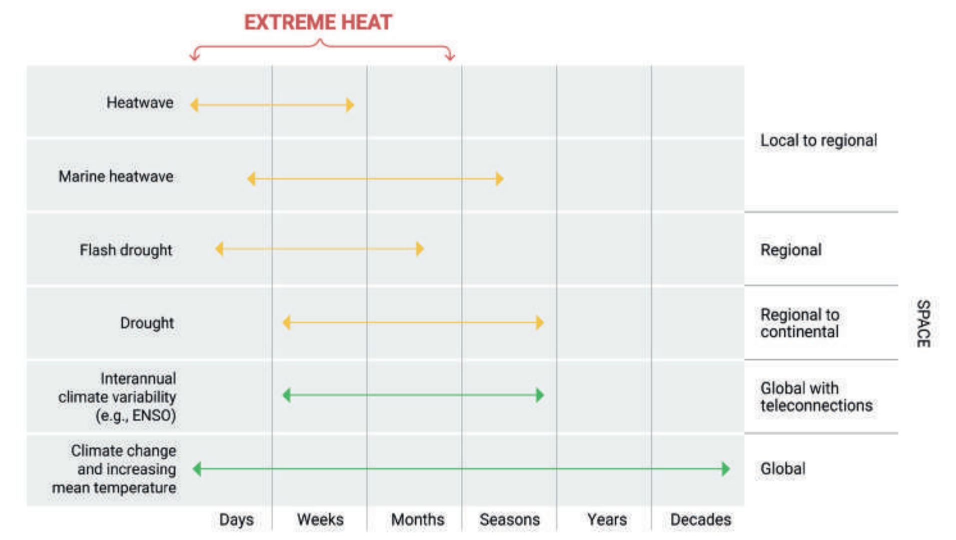
Heatwaves, both atmospheric and marine, typically occur at a regional scale over periods of days to weeks for terrestrial heatwaves, and days to months for marine heatwaves. When heatwaves persist over land areas, they can trigger flash (rapid-onset) droughts, which develop rapidly at local to regional scales. In contrast, seasonal to multiyear droughts, which evolve more gradually, tend to affect broader areas, from regional to continental scales.

At larger temporal and spatial scales, interannual climate variability such as the El Niño–Southern Oscillation (ENSO), modulates regional climate conditions and can influence the frequency and intensity of heatwaves and droughts. Over decades, human-induced climate change has contributed to the long-term rise in global mean temperature and intensified the risk and severity of extreme heat events across all scales. Figure 1 illustrates these phenomena over time (from days to decades) and space (from local to global) and highlights their interconnected nature and cumulative impact on climate extremes.

2.1 Human-induced climate change and natural climate variability

The increasing frequency and intensity of extreme heat events are driven by two distinct but interacting factors. The primary driver of changes in the occurrence of extreme heat is human-induced climate change, which is raising the global average temperature and altering atmospheric circulation patterns. These changes make it statistically easier for any weather pattern to produce record-breaking heat. The second driver is the short-term natural variability that operates on top of this warming baseline. Large-scale climate phenomena in one region, such as the ENSO in the tropical Pacific, can influence temperature variations and other weather patterns across the globe through a process

FIGURE 1. Drivers of extreme heat



Extreme heat, underlying climate change and variability, and meteorological phenomena. Yellow – meteorological phenomena; green – underlying mechanisms of extreme heat.

Source: Author's own elaboration.

known as teleconnection. These phenomena trigger changes in the normal circulation of the atmosphere and oceans, altering the path of storms and shifting pressure systems. In turn, the influences of these phenomena can lead to persistent shifts in temperature and rainfall in distant places. Natural interannual and decadal cycles in large-scale ocean-atmosphere circulations, such as the ENSO, can alter regional weather patterns, drive oscillations in average temperature at the global scale, and intensify the severity and duration of extreme heat in a given season or location.

The ENSO, in which sea surface temperatures in the tropical Pacific oscillate between warmer and cooler conditions every two to seven years, is one of the most significant natural cycles globally. During an El Niño phase of the ENSO cycle, a pool of warm water forms in the central and eastern Pacific Ocean and alters weather patterns worldwide. El Niño cycles often lead to warmer conditions and precipitation effects in specific regions (e.g. South Asia, Southeast Asia, Southern Africa in December-February; the Caribbean and Latin America in June-August). The opposite La Niña phase can also lead to warmer conditions and altered precipitation patterns but in different locations (e.g. Australia and the South Pacific in June-August). Other ocean-atmosphere oscillations, with variable periodicity, that are important for the formation of local heatwaves through teleconnections include the Madden-Julian Oscillation in the tropics, with an intraseasonal variability of 30 to 90 days; the North Atlantic Oscillation (intraseasonal to interannual); Indian Ocean Dipole (interannual); and Pacific Decadal Oscillation (interdecadal).

Both the amplitude of the ENSO and the frequency of high-magnitude events since 1950 are higher than during the 1850–1950 period. These changes in amplitude and frequency are not considered as exceeding the range of natural variability on decadal or longer timescales. The ENSO will continue to be the dominant mode of interannual climate variability, but there is no consensus yet on future changes in amplitude of ENSO sea surface temperature variability (IPCC, 2021). In response to global warming, it is possible that more regular ENSO intensification could synchronize with other atmospheric and air-sea coupled large-scale climate modes (e.g. the North Atlantic Oscillation and the Indian Ocean Dipole), which could greatly amplify impacts across the globe (Stuecker *et al.*, 2025).

According to the IPCC AR6 Working Group I, Physical Science Basis of Climate Change (AR6 WGI) the likely range of human-induced global warming was between 0.8 °C and 1.3 °C in 2010–2019 compared to the 1850–1900 pre-industrial period (IPCC, 2021). The observed warming is the net result of opposing forces, specifically forcing from greenhouse gas (GHG) emissions that are countered in part by aerosols, which lessen the impact of GHG emissions by reflecting a portion of the incoming solar radiation. More recently, estimates over the 2015–2024 period indicate a net warming relative to 1850–1900 of 1.24 °C, of which 1.22 °C was human-induced (Forster *et al.*, 2025). Human-induced warming has been increasing at a rate that is unprecedented in the instrumental record, reaching 0.27 °C per decade between 2015 and 2024. The past 11 years (2015–2025) are the 11 warmest years in the 176-year observational record (WMO, 2025a). The average across the eight datasets used by WMO in establishing its annual benchmark temperature show that for the three-year period (2023–2025), global temperatures averaged 1.48 °C above the pre-industrial period. The WMO estimates a 70-percent chance that the five-year period, 2025–2029, will average above 1.5 °C (WMO, 2024). Reinforcing this point, the Global Carbon Budget 2025 annual report notes that the remaining carbon budget to limit global warming to 1.5 °C is 'virtually exhausted' (Friedlingstein *et al.*, 2025), with annual emissions continuing to rise. Between 2023-2024 atmospheric concentrations of CO_2 experienced the largest increase yet recorded.

Assessments from five illustrative scenarios for warming in the IPCC AR6 WGI showed very likely (in IPCC terms) increases in temperature by 2100 with respect to the 1850-1900 base line in the range of 1.0 to 5.7 °C. Recent studies on the energy imbalance between incoming sunlight and outgoing radiation that drives global warming have observed an unanticipated doubling in retained energy over the past two decades (Loeb *et al.*, 2024; Mauritsen *et al.*, 2025; Minière *et al.*, 2023; Myhre *et al.* 2025). To achieve lower levels of future warming within the IPCC's range of projected temperatures the implementation of increasingly stringent mitigation efforts will be required (IPCC, 2022).

2.2 Heatwaves

As part of the changes driven by global warming, heatwaves have become more frequent and intense over recent decades, and this trend is projected to continue in a warming climate (IPCC, 2021).

A primary mechanism in heatwave formation involves a strong stationary high-pressure system in the upper atmosphere, known as a heat dome, that traps heat over a large region. Heat domes cause the underlying air to sink (subsidence). This downward movement compresses and warms the air below. High-pressure systems also suppress cloud formation, allowing more solar radiation to reach and heat the earth's surface. The stable air mass prevents the warmer surface air from rising and dissipating, causing the surface heating to intensify. When a heat dome is held in place for a prolonged period by atmospheric blocking, a major heatwave can form. Another key driver can be the large-scale horizontal movement (advection) of very hot air masses, such as subtropical air moving into the mid-latitudes.

Heatwave events can be quantitatively analysed using either an absolute temperature threshold value or a percentile of historical temperature variability, combined with a measure of duration (e.g. number of days). Interannual variability in large-scale atmospheric circulation also modulates heatwave frequency and intensity at the regional scale. For instance, the ENSO has been linked to warmer and/or drier than normal conditions in certain regions and seasons (Yeh *et al.*, 2018). Due to the variety of underlying causes, and the definitions employed by individual studies, a single definition of heatwave has not been adopted in this report.

Historical simulations designed to distinguish between natural and human-induced changes in global warming have shown that anthropogenic GHG emissions are the main driver of the observed changes in hot extremes on the global scale (IPCC, 2021).

Multiple studies point to an observed increase in the frequency of heatwaves at the regional scale. These findings raise the issue of simultaneous events potentially affecting multiple regions. A recent study (Rogers *et al.*, 2022) quantified the trend in concurrent heatwaves during the May-September warm season across the mid-latitude regions (30° to 60° North) in the Northern Hemisphere between 1979–2019. The authors found a significant 46 percent increase in the mean spatial extent of concurrent heatwaves; a 17 percent increase in their maximum intensity; and an approximately 500 percent (or six-fold) increase in their frequency. The quantification of relative contributions made by anthropogenic and natural causes to these trends, and the attribution of recent heatwave events is an active area of research. Quantifying the relative human and natural contributions to individual heatwave events is scientifically challenging in many regions due to the lack of reliable observations and/or the persistent systematic errors of climate models (van Oldenborgh *et al.*, 2022). Using operational weather prediction systems, Leach *et al.* (2024) estimate that human-induced warming made a temperature extreme at least as high as the peak of the observed 2021 North American (Pacific Northwest) heatwave 700 percent (8 times) more likely. In Canada, the heatwave set a new all-time temperature record, 4.6 °C above the previous record. There are attempts to routinely conduct rapid attribution studies immediately after extreme weather events (e.g. World Weather Attribution in the United Kingdom and the Weather Attribution Center in Japan).

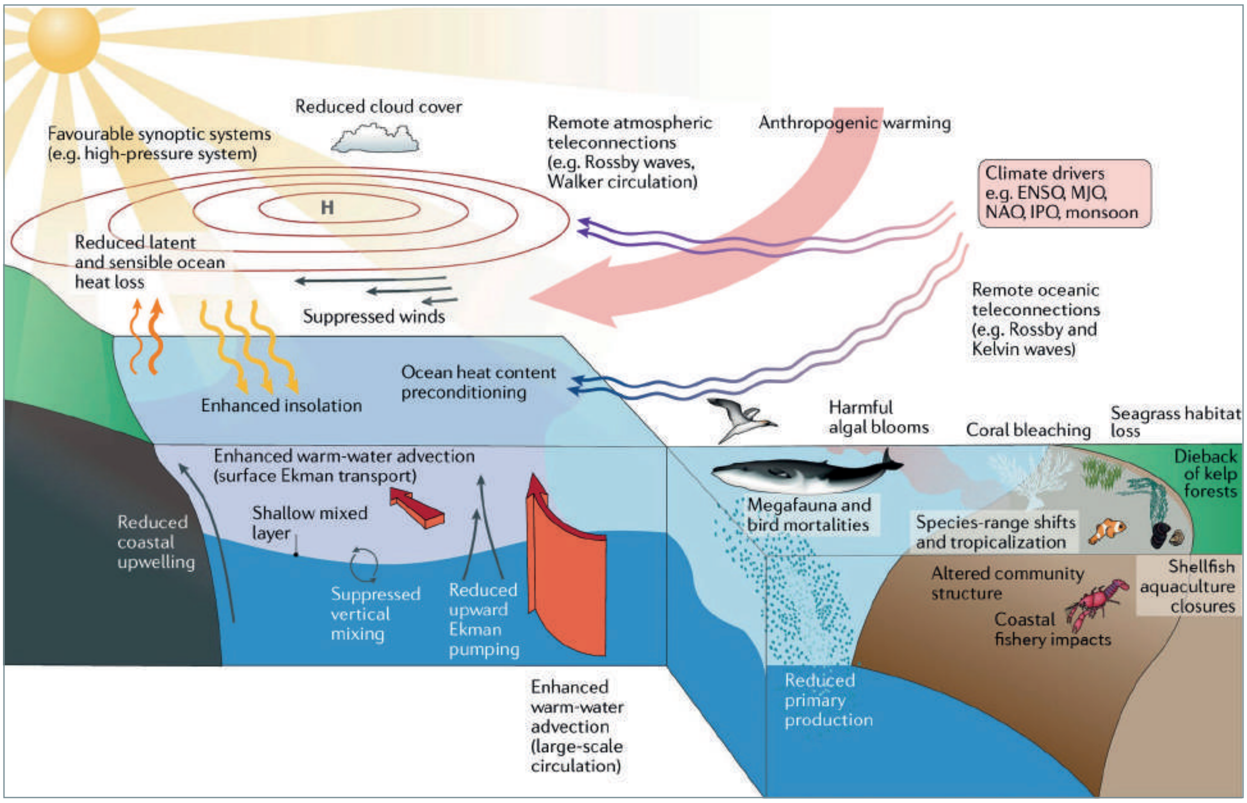
According to the AR6 WGI, the frequency and intensity of high temperature extremes will continue to increase at global and continental scales as global warming continues (IPCC, 2021). Relative to present-day conditions, changes in the intensity of extremes would be at least double at 2 °C of global warming, and quadruple at 3 °C, compared to changes at 1.5 °C of global warming (IPCC, 2021). The number of hot days and hot nights and the length, frequency, and/or intensity of heatwaves will increase over most land areas. Future changes in the intensity of temperature extremes are expected to be proportional to changes in global mean surface temperature, but up to 100 to 200 percent (two to three times) larger. In other words, the frequency of high temperature extremes is expected to increase nonlinearly with increasing levels of global warming, with larger percentage increases for rarer events. The highest increase of temperature on the hottest days is projected in some mid-latitude and semi-arid regions and in the South American monsoon region. A recent review of heatwave studies confirms that observed increases in their frequency, intensity and duration are projected to continue with global warming (Barriopedro *et al.*, 2023). Another recent study (Thompson *et al.*, 2023), highlights that to date only one-third of the world's regions have experienced exceptional daily maximum temperatures relative to their current baseline climate, which suggests that a large fraction of the world population may not be prepared for such extreme events.

2.3 Marine heatwaves

Marine heatwaves and heatwaves in freshwater bodies are defined in a similar way as heatwaves on land, using measures of heat intensity and duration, for example, a period of five days or more, with temperatures exceeding the 90th percentile (Hobday *et al.*, 2016). The warming of the global ocean is unequivocal and is associated with an observed increase in frequency and intensity of marine heatwaves (e.g. Storto and Yang, 2024; Xu *et al.*, 2022). Ocean surface temperatures have increased by 0.88 °C since the pre-industrial baseline (1850–1900) (IPCC, 2021). The rate of annual increase in global ocean heat content (averaged across all depth intervals) has risen 200–400 percent since the 1980s (Cheng *et al.*, 2025; Merchant *et al.*, 2025). Average ocean sea surface temperatures, and ocean heat content in the upper 2000 metres below the surface, where over 90 percent of excess heat in the climate system has been stored since 1960 (von Schuckmann *et al.*, 2023), reached their highest recorded level in 2024 (Pan *et al.*, 2025; Cheng *et al.*, 2025). Since 2023, 74 percent on the additional heat stored in the ocean has accumulated in the uppermost 300 metres compared to a historical average of 45 percent (Pan *et al.*, 2025). This pattern of heat storage has significant implications for the formation of future heatwaves, as the build-up in near-surface ocean heat content is a potent driver of marine heatwaves (Cheng *et al.*, 2022; 2024).

Marine heatwaves emerge from a combination of atmospheric and ocean conditions (Figure 2). Contributing atmospheric conditions include the presence of atmospheric high-pressure systems, reduced cloud cover, increased incoming solar radiation (insolation), suppressed winds and reduced latent and sensible heat loss. Marine heatwaves are also influenced by remote atmospheric teleconnections related to the ENSO and other large-scale climate phenomena. Ocean conditions that allow heat content to build include reduced vertical mixing, a shallow mixed layer, reduced coastal upwelling and enhanced horizontal warm-water mixing (advection) from large currents in the oceanic environment (Holbrook *et al.*, 2019; 2020; Capotondi *et al.*, 2024).

FIGURE 2. **Drivers of marine heatwaves**



Source: **Holbrook, N.J. *et al.*** 2020. Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, 1(9): 482–493. https://doi.org/10.1038/s43017-020-0068-4

Globally, the frequency of marine heatwaves has approximately doubled since the 1980s, and they have also become increasingly intense, had longer durations and covered larger areas (IPCC, 2021). Over the past four decades, satellite observations have detected a slowdown in the rate of subsidence in sea surface temperatures following marine heatwaves, which coincides with an increase in marine heatwave duration (Lee *et al.*, 2025). For every 1 °C increase in sea surface temperature, the globally averaged frequency in marine heatwave increases by 3.7 events per year, with an increase in duration of 7.5 days, and an increase in maximum intensity to 2.2 °C (Cheng *et al.*, 2023). Under the representative concentration pathway 8.5 (RCP8.5), a high-emission scenario used in climate modelling to represent a future with rapidly increasing GHG emissions, by 2100, the frequency of marine heatwaves is projected to increase by 4 900 percent (or 50 times) relative to 1850–1900, or 1 900 percent (20 times) under a low-emissions scenario (RCP2.6) (IPCC, 2019). The largest changes are projected to occur in the Northeast Pacific, the North Atlantic, the central and western South Indian oceans, and parts of the Southern Ocean (Cheng *et al.*, 2023; Qiu *et al.*, 2021). The intensity of marine heatwaves is projected to increase by 900 percent (or 10 times) as assessed under the most severe RCP8.5 by 2081–2100, relative to 1850–1900 (IPCC, 2022b), reaching projected maximum intensities of up to 4 °C above average in the tropics, North Pacific, and North Atlantic by the end of the twenty-first century under the shared socioeconomic pathway (SSP) 5-8.5. In contrast there are no obvious changes projected for the low-emissions pathway SSP1-2.6 (Qiu *et al.*, 2021). Studies comparing the SSPs in the models of the Coupled Model Intercomparison Project (CMIP6), find that the most extreme marine heatwaves are expected under the high-emissions scenario (SSP5-8.5), with a near-permanent heatwave state emerging in 14.8 percent (± 5.7) of the global ocean by 2100 (Cheng *et al.*, 2023) to a majority of the global ocean by 2070s (Qiu *et al.*, 2021). Again, no discernable increase in marine heatwaves is projected under the SSP1-2.6 pathway, further emphasizing the importance of emission reduction efforts.

Global warming will also lead to an increased frequency of heatwaves in freshwater lakes, with lake heatwaves projected to become hotter and longer (Woolway *et al.*, 2021). By the end of the twenty-first century, under the RCP8.5 high-emission scenario, the average intensity of lake heatwaves, defined relative to the 1970–1999 period, could increase from 3.7 °C (± 0.1) to 5.4 °C (± 0.8), and their average duration could increase dramatically, from 7.7 days (± 0.4) to 95.5 days (± 35.3). In the RCP2.6 low-emission scenario, freshwater heatwave intensity would increase to 4.0 °C (± 0.2), and the duration would increase to 27.0 days (± 7.6) days.

The increase of water temperatures through global warming and heatwaves results in changes in water chemistry (e.g. dissolved oxygen, salinity and pH) that are important to aquatic organisms. From the perspective of fisheries and aquaculture, one of the most significant of these changes is the impact of higher temperatures on dissolved oxygen content. As water warms, it holds less oxygen due to changes in gas solubility. Higher surface water temperatures also increase the thermal stratification within the water column, resulting in less mixing between the upper and lower layers (IPCC, 2022b). Less mixing can lead to a further reduction of oxygen levels. The extreme water temperatures and reduced mixing during marine heatwaves can trigger extreme low-oxygen events (hypoxia) that amplify the global trend of deoxygenation (Li *et al.*, 2024). Similar processes can lead to a decline in dissolved oxygen levels in freshwater lakes and rivers (Zhang *et al.*, 2025a). An increasing trend in coastal hypoxia events, caused by the over-enrichment of water bodies with nutrients (eutrophication), ocean warming, and changes in circulation have been observed globally (IPCC, 2022a). In hotspot regions, such as the Baltic Sea, the increasing number of marine heatwaves has significantly increased the risk of hypoxia events in coastal zones (Safonova *et al.*, 2024). Because the spatial distribution of coastal hypoxic areas is uneven, assessing future trends in oxygen depletion and marine heatwaves in a changing climate requires local data and modelling (IPCC, 2022a).

2.4 Droughts

Drought is generally considered as a slow-onset phenomenon marked by a prolonged absence or notable deficiency of precipitation, or a period of abnormally dry weather sufficiently long for the lack of precipitation to cause a serious hydrological imbalance (WMO, 1992). Drought typically develops slowly over months and years, with the precise start and end difficult to identify. Drought events are characterized in terms of frequency, magnitude, extent, duration, and timing.

The impacts of droughts are commonly distinguished according to the sectors affected. Drought can have impacts on a broad range of sectors, including health, agriculture, energy (hydropower), transport (through lower water levels) and industry. The impacts of droughts in specific sectors are a function not only of the severity of the event but also of the degree to which communities, their social and economic assets, and the surrounding environment are exposed and vulnerable to these events (IDMP, 2022). There is usually a progression in the severity of impacts with the duration of drought. Monitoring the parameters of both the hazard (e.g. precipitation, river discharge, and soil moisture) and associated impacts (e.g. water shortages and associated sector-specific impacts) in a broad and flexible way (Wilhite and Glantz, 1985; Crausbay *et al.*, 2017) is preferred to strict definitions of drought according to their impacts (WMO and GWP, 2016).

Drought has often been described using categories such as meteorological, agricultural, hydrological, or socioeconomic drought. A more integrated perspective, however, recognizes that these categories are not distinct types of drought but rather distinctly different impacts and manifestations of a single, complex phenomenon that spreads through the hydrological cycle and into human systems. A drought usually starts as meteorological drought that is defined by a deficit of precipitation relative to normal conditions over a specific period and region. Meteorological drought represents the departure of precipitation from long-term average values and is typically the first manifestation of drought conditions, as precipitation deficits propagate through the hydrological system.

Agricultural drought occurs when a lack of soil moisture during and/or prior to the growing season prevents plants from meeting their transpiration demands. More broadly, ecological drought is a deficit in water availability that drives ecosystems beyond their thresholds of vulnerability, causing negative impacts on ecosystem services. Hydrological drought describes the depletion of water resources (e.g. streamflow, reservoirs, and groundwater). Socioeconomic drought occurs when water supply and water demand from human systems and economic activities are not balanced.

Extreme heat can intensify drought, but it may not be the main cause of drought. In contrast, a flash drought (e.g. Otkin *et al.*, 2018; Christian *et al.*, 2024), defined by its unusually rapid onset and accelerated intensification over days and weeks, is often directly triggered by extreme heat and associated meteorological conditions (e.g. high wind, low humidity and high solar radiation). Heatwaves are the main engine of a flash drought and an amplifier of a normal drought. Flash droughts primarily deplete moisture from the topsoil and root zone, whereas persistent drought conditions may impact the entire water system (e.g. streamflow, reservoirs, deep soil moisture, and groundwater aquifers). Notable flash drought events in recent years include those in the United States of America in 2012 and 2017, the Russian Federation in 2010, southern Africa in 2015, eastern Australia in 2018 and 2019 and southern China in 2022 (Nguyen *et al.*, 2019, 2021; Gu *et al.*, 2025). Over recent decades (2001–2020), flash droughts have exhibited an acceleration in onset times and lasted longer compared to the 1981–2000 period. Changes in frequency vary by region. As a result of these changes, 20 percent more agricultural land, 17 percent more forested areas and 30 percent more people have been exposed to the impacts of flash droughts (Zeng *et al.*, 2023; Qing *et al.*, 2022; Gu *et al.*, 2025).

BOX 3. The heat–drought connection

Extreme heat and drought have a critical two-way relationship. A heatwave can worsen drought conditions by increasing evaporative demands and removing the remaining moisture from the soil surface. The resulting dry soil surface can no longer dissipate the energy of incoming solar radiation through evaporation, and instead radiates the energy as sensible heat, which further warms the surrounding land and air, allowing the heatwave to intensify and last longer. Because of this feedback loop, a compound extreme heat and drought event often leads to more destructive impacts for agriculture.

According to the IPCC AR6 Working Group II, Impacts, Adaptation and Vulnerability (AR6 WGII), human-induced climate change has contributed to increases in agricultural and ecological droughts in many regions due to increases in evapotranspiration. Regions observing an increase in agricultural and ecological droughts include: Western North America; Northeastern South America; Western, Central, West and East Southern Africa; West-Central Europe, Mediterranean, West-Central Asia, East-Central Asia, Eastern Asia and Southern Australia. Northern Australia is the only region that has seen a decrease in drought since the 1950s. For the rest of the world, there was low agreement on the types of changes in agricultural and ecological droughts.

2.5 Compound events

The formation of compound events is driven by the simultaneous occurrence of two or more hydrometeorological conditions (AghaKouchak *et al.*, 2020). Compound events in this report denote the combination of multiple drivers and/or hazards that contribute to elevated societal or environmental risk (Zscheischler *et al.*, 2018; 2020; IPCC, 2021). As has been noted for flash droughts, one of the most important of these combinations occurs when extreme heat coincides with drought conditions. Heatwaves are often driven by atmospheric blocking patterns that disrupt the normal jet stream flow and favour the formation of high-pressure systems, clear skies (no rain) and high solar radiation, which can trigger the potential onset of both extreme heat and flash drought conditions. Periods of extreme heat can also lead to extreme rainfall, a compound hot-wet event, where the warming air, holding more water vapour, can fuel short, intense periods of rainfall, often accompanied by convective thunderstorms (Lesk *et al.*, 2022; Biess *et al.*, 2024). If prolonged, heatwaves can harden soils and reduce their ability to absorb water quickly. As a result, heavy rainfall following a heatwave can cause severe surface runoff, soil erosion and flash floods, with impacts that can exceed those of an extreme heat event alone. Additional compound events can occur when extreme heat combines with high humidity. Hot-humid compound events can have a significant effect on agricultural workers and livestock as they reduce the potential of evaporative cooling. When extreme heat combines with high winds, there is increased vegetative drying and greater risk of wildfires. In marine environments, there is an increased risk of marine heatwaves forming when high temperatures coincide with periods of low air movement or calm.

Compound heatwaves and droughts have become more frequent over the last century, and this trend is projected to continue with higher global warming. (IPCC, 2021). Recent studies confirm that there has been an overall increase in compound drought and extreme heat events since the 1950s at regional and global scales, with an increase of more than 200 percent recorded in some regions (Hao *et al.*, 2022). The increased frequency is mainly the result of a rise in high temperature extremes. Since 1950, there has been a notable increase in the frequency of compound extreme heat–flash drought events. Compound extreme heat–droughts have become 6.7 to 90.8 percent more severe and exhibited 8.3 to 114.3 percent longer recovery times than droughts not associated with extreme heat (Gu *et al.*, 2025). Projections for 2081–2100 indicate a 200- to 300-percent increase in compound drought and extreme heat events over most land areas compared to 1986–2005, including most of Europe, the Middle East, Western and Central Asia; Australia, South America, West and Southern Africa, and large areas of North America (Hao *et al.*, 2022).

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3. EXTREME HEAT AND AGRICULTURE

3.1 An overview of extreme heat impact pathways for agriculture

Temperature is the dominant abiotic factor determining the distribution of biological diversity on the planet. Extreme temperatures have a profound impact on the performance of all species, including homo sapiens, and ultimately determine where species can continue to thrive (Arnold *et al.*, 2025). The direct impacts of extreme heat are felt within the agricultural sector through the exposure and sensitivities of individual species, from the intracellular to community level. Due to shared physiology, broad collections of species show similar responses to benchmark threshold temperatures (e.g. Parent and Tardieu, 2012). Most major crops species, for example, exhibit negative yield responses at temperatures exceeding 30 °C, while most livestock species show negative responses above 25 °C. Genetic differences in varieties and breeds and the profile of individual exposure events lead to more nuanced reactions to extreme temperatures.

Many factors contribute to the nature and extent of damage caused by individual extreme heat events. Differences in rate of onset, magnitude, duration and frequency of exposure to extreme temperatures, combined with differences in the sensitivity of species, the physiological stage of development of the individual organism when exposed, and its history of previous exposure, result in a wide range of outcomes. Potential outcomes include temporary adjustments to acute short-term shocks, longer-term changes in systemic functioning, and permanent impacts on genetic expression that can alter the characteristics of offspring. When temperature extremes stay within the limits of a species upper tolerance, and events do not occur during critical stages of physiological development, extreme heat events that build slowly over days or weeks allow individuals to acclimatize and less damage results. Below critical thresholds, extreme heat events of shorter duration generally cause less damage than events of equal magnitude that apply sustained or successive pressure over weeks and months (González-Trujillo *et al.*, 2023; Mahecha *et al.*, 2024). Prior exposure to moderate levels of heat stress can confer some resilience to subsequent extreme events (Zhang *et al.*, 2025b). In cases of exposure to damaging extreme temperatures, however, repeated exposure can result in greater impacts on individuals and biological communities, especially when exposure periods are longer and the interval between exposure events is short (Ma *et al.*, 2024; Martínez-De León and Thakur, 2024).

As noted, a species' sensitivity with regard to upper threshold limits where physical damage occurs and the timing of exposure to extreme heat in terms of the stage of physiological development are critical in determining the overall impact. Species have differing thresholds for damage from extreme heat during their progressive stages of development. As a general rule, individuals are most vulnerable when they are young, undergoing reproduction and during embryonic development or yield formation (for crops). For domesticated agricultural species, human influence on the genome through selective breeding for enhanced performance in increasingly homogenous production environments has resulted in a loss of natural genetic variability that have accentuated many species vulnerability to temperature extremes.

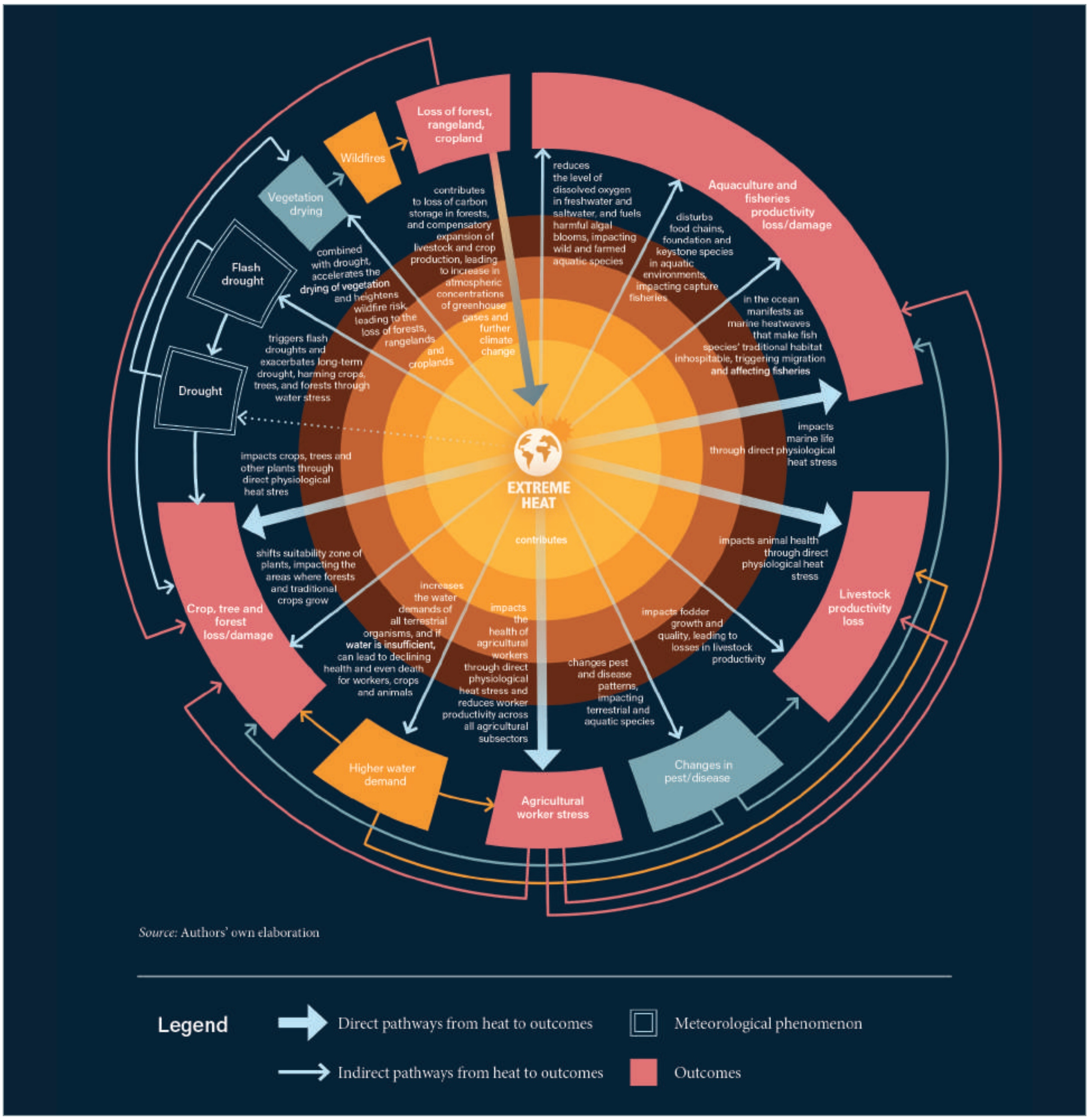
In addition to the direct impacts of extreme temperatures on agricultural species, extreme heat can also contribute to an equally wide range of potential indirect impacts on the health and performance of agricultural species and agricultural systems more generally. Principal among these indirect risks is the potential for changes in:

- populations of insect pests and pest predators;
- pollinators;
- disease vectors and pathogens;
- livestock feed availability and quality;
- water availability and quality;
- aquatic food-chain resources;
- soil and vegetation moisture loss;
- the incidence and severity of wildfires; and
- health risks to agricultural workers.

By definition, the indirect impacts of extreme heat are mediated through relationships that involve critical resources and the life cycles of intermediary organisms.

These associated organisms and resources can in turn be affected by the co-occurrence and legacy effects of other stressors, leading to sometimes complex interactions. As a result, the establishment of causal relationships between individual extreme heat events and specific indirect outcomes can be challenging. Climatic conditions can provide a conducive environment for indirect impacts to occur (e.g. the potential for insect pest populations to increase or widespread disease outbreaks) but do not unilaterally cause these outcomes because other conditions must also be satisfied. More often, extreme heat events result in compound impacts with all species (e.g. hosts, pests, pest-predators, disease vectors and disease organisms) in the area directly affected. The ways in which these species interact may also be impacted, with indirect knock-on effects on agricultural species (Figure 3). As a result, reference to the potential indirect impacts of extreme heat events is best made as cautionary indications of what may happen, rather than definitive projections of occurrence.

FIGURE 3. Direct, indirect and compound impact pathways of extreme heat in agriculture



Source: Authors' own elaboration.

Extreme heat events can trigger abrupt, long-lasting, potentially permanent changes in the structure of local food chains (trophic composition) and other ecosystem features (Piatt *et al.*, 2020; Renner *et al.*, 2024). The potential for these changes to occur is particularly high when foundation and keystone species are involved (Wernberg *et al.*, 2024; Wernberg *et al.*, 2025). Agricultural activities that depend on natural populations, such as capture fisheries (Szuwalski *et al.*, 2023), are most vulnerable, with observed impacts on ecosystem services and biodiversity becoming increasingly frequent (Wernberg *et al.*, 2025). In most cases, the impacts of observed changes in magnitude, frequency and duration of extreme heat events are best seen as the leading edge of a broader shift in planetary thermal regimes associated with global warming, where current acute events forewarn of the trend towards these conditions becoming future norms (Litzow *et al.*, 2024; Battisti and Naylor, 2009). Extreme events are thought to have greater influence in delimiting a species' habitable range than the slow-onset shifting in average climatology. However, these two forces work in tandem in a changing climate (Germain and Lutz, 2020; Xi *et al.*, 2024). In this regard, the concept of thermal safety margin (i.e. the gap between the prevailing high temperatures that a species encounters and their threshold for damage) is critical for anticipating and monitoring the onset of damages and pace of change in a species' range (e.g. Sunday *et al.*, 2012). In relational terms, all things kept equal, as mean temperatures rise, the gap between high temperatures and the species-specific thresholds for damage decline. Thus, it becomes increasingly easy for extreme heat events (of decreasing magnitude) to breach the damage threshold. Compared with 1.5 °C of warming, the intensity of extreme heat is anticipated to increase by at least 100 percent under 2 °C of warming and by 300 percent under 3 °C of warming (IPCC, 2021). As a result of rising mean temperatures, and the more rapidly rising intensity of extreme heat, the transformation of species range will occur with increased speed and affect more species as global warming continues.

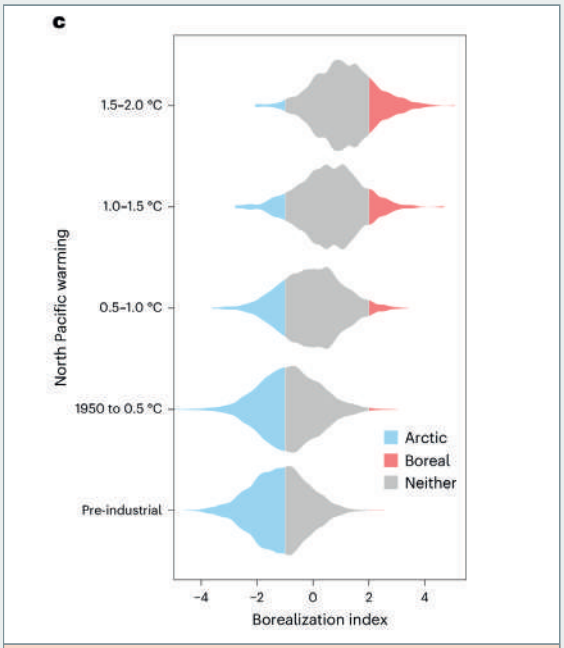
The change in global temperature regimes and the robust selective pressure applied through extreme events signal a level of engagement with evolutionary dynamics for which our species has no prior experience. Species migration, 'bottleneck' evolutionary events, niche elimination and extinctions, are not only possible but are being observed (Urban, 2024; Román-Palacios and Wiens, 2020). The displacement of species from their current range and niche locations, such as the migration of marine stocks in search of cooler water (Pinsky *et al.*, 2020; Hastings *et al.*, 2020); changes in rangeland and forest species composition (Xi *et al.*, 2024; Liu *et al.*, 2018); and changes in the geographic range of agricultural weeds, pests and diseases (Peters *et al.*, 2014; Osunkoya *et al.*, 2025; Ma *et al.*, 2025; Skendžić *et al.*, 2021; Hossain *et al.*, 2024a; Lahlali *et al.*, 2024), are increasingly well documented in the literature. These changes are evidence of the forces of natural selection acting on the biosphere, set in motion through slow-onset climate changes and extreme events. The outcome of these forces acting on agricultural activities is uncertain, with the sector's ability to continue to feed the global population hanging in the balance. It is only through innovation and the implementation of adaptative measures (e.g. selective breeding, making changes in the physical environment and altering management practices) that the global community can shelter agricultural activities from the larger forces of planetary human-induced climate change.

In the wider context of global climate change, incidences of extreme heat increasingly occur in combination with other extreme events (Zscheischler *et al.*, 2020; Ridder *et al.*, 2020). These compound events, such as heatwaves occurring at the same or nearly the same time as drought conditions and heavy rainfall events (Zhang *et al.*, 2024; Wang *et al.*, 2024, Tang *et al.*, 2025), can lead to widespread damage in the agricultural sector that exceed the impacts of the same events occurring separately. The impacts resulting from compound events can vary by the magnitude, order of onset, and duration of each of the components (Zscheischler *et al.*, 2020). In the case of compound events involving extreme heat and drought or heavy rainfall, the events can originate from the same climatological conditions.

Apart from high-impact compound events, agricultural species are subject to many other stresses that can be experienced in different combinations, simultaneously and in various sequences. The cumulative impacts of different stressors can be fatal even when individual stressors are present at sublethal levels. Extreme heat events, by themselves, are commonly the source of compound impacts where single events affect entire ecologies and adjoining ecosystems. Compound

BOX 4. Snow crab population collapse and extreme heat

FIGURE 4. Transition from arctic to boreal conditions in the north Pacific



Estimated or projected probability density functions for borealization index at different levels of North Pacific warming. 'Arctic' conditions are defined by borealization index values <–1, the threshold for more Arctic conditions observed in 2007–2013. 'Boreal' conditions are defined by index values >2, the threshold for highly boreal conditions in 2018–2019 associated with the snow crab collapse. 'Neither' refers to values of the borealization index between the two thresholds.

Source: **Litzow, M.A.** ***et al.*** 2024. Human-induced borealization leads to the collapse of Bering Sea snow crab. *Nature Climate Change*, 14(9): 932–935. https://doi.org/10.1038/s41558-024-02093-0

A marine heatwave in the eastern Bearing Sea in 2018–2019 triggered a collapse in the snow crab population. More than 90 percent of the population perished, leading to the closure of one of the Arctic's most valuable fisheries (Litzow *et al.*, 2024). Using available data, researchers have pieced together the chain of events and the contributing factors that led to the collapse (Litzow *et al.*, 2024; Szuwalski *et al.*, 2023, Stabeno and Bell, 2019). Beginning with the marine heatwave, and persistent southernly winds, the Bearing Sea witnessed the lowest formation of sea ice ever recorded. The reduced sea ice coverage prevented build-up in the winter ice-dependent phytoplankton populations. It also markedly reduced the volume of surface freshwater released from summer sea ice melting that is required to maintain the saline mediated thermocline barrier. Without this barrier surface heating penetrated to the ocean floor. The summer of 2018 saw the smallest seafloor cool-water pool on record (Fedewa *et al.*, 2020). The mass snow crab die-off is believed to be the result of several compounding direct and indirect factors:

- increased seafloor water temperatures, which, although below the snow crab's thermal maximum, led to an increase in metabolic energy demands that required greater food intake;
- a concentration of the snow crab population into the remaining seafloor cold water refugia, resulting in elevated food resource competition;
- shifting in critical food chain populations, resulting in reduced prey availability; and
- increased predation (cod) and disease (bitter crab disease) by species favoured by the warmer waters.

Ultimately, it is believed that an estimated 10 to 47 billion individual snow crabs died, primarily through starvation.

The collapse of the Bearing Sea snow crab population is part of a larger ecological regime shift occurring in the arctic gateway: the borealization of an arctic environment brought on by human-induced climate change (Figure 4). The transformation of this arctic environment, manifested in the snow crab population collapse, is thought to be 19 900 percent (200 times) more likely due to climate change (Litzow *et al.*, 2024). There is a 94-percent likelihood of the low sea ice extent observed in 2018 becoming the norm by 2040 (Thoman *et al.*, 2020). One result of this transformation is that assemblages of cold-water adapted species, including the snow crab, historically found in this location, will no longer dominate, and will be replaced with subarctic warm water assemblages as conditions continue to change.

Sources: See References.

impacts can affect multiple species and critical resources in adjacent and overlapping agricultural subsectors (crops, livestock, fisheries and aquaculture, and forestry). The impacts may be accompanied by secondary interactions between the affected elements and have the potential to trigger cascading impact chains (Niggli *et al.*, 2022).

3.2 Crops

3.2.1 Vulnerabilities to extreme heat

Crop growth and productivity face direct and potential indirect impacts from extreme heat. As plants come under increasingly high levels of heat stress, they respond in various ways, beginning with effects seen in the functioning of the whole plant and progressing to damages to critical plant processes, organs and individual cells. For all crops, growth and development begins above some minimum temperature, with rates of development increasing up to an optimal temperature threshold. At temperatures above the optimal temperature threshold, a non-linear decline in development is observed until development stops. If temperatures continue to rise, at some point plant death occurs. Minimum, optimal and maximum temperatures (known as cardinal temperatures) are species-specific and vary over the course of plant development. Generally, the stages of vegetative growth benefit more from warmer temperatures than the reproductive stage (Roberts and Summerfield, 1987; Garcia-Huidobro *et al.*, 1982). An upper optimum during reproduction and yield formation of around 30 °C is common for many important agricultural crops (e.g. maize, soy, cotton). Other major crops show damaging sensitivities at lower temperatures during their reproductive period (e.g. barley, beans, wheat and potatoes) (Schlenker and Roberts, 2009; Lobell *et al.*, 2011; Luo, 2011; Hatfield and Prueger, 2015).

When exposed to increasingly high temperatures during the growing season, the rate of plant maturation accelerates. As a result, there is a decrease in the time spent in each stage of development, including reproduction and grain-filling. A shortening of these critical periods decreases the opportunity for reproductive success and reduces the time for yields to accumulate and fully develop, resulting in an overall reduction of yields. Under higher temperatures, crop metabolism speeds up, with an accompanying increase in maintenance respiration. The energy invested in maintenance respiration is unavailable for growth and yield formation. High temperatures at night, when photosynthesis is not occurring to offset higher maintenance energy losses, is particularly damaging, resulting in a lowering of yields (Sadok and Jagadish, 2020). Increasing temperatures also result in an increase in the atmospheric water vapour pressure deficit, which leads to higher rates of plant moisture loss as plants attempt to cool themselves through transpiration. Should soil moisture become limited, and plants come under moisture stress, leaf stomal openings in most plants close to reduce transpiration moisture loss, which reduces photosynthesis and slows growth. Rising temperatures also increase the rate of soil moisture evaporation and indirectly contribute to the possibility of crop moisture stress. Reduced crop transpiration and dry soil conditions during heatwaves can create a feedback loop, where more of the sun's energy is radiated as sensible heat, rather than dissipated as latent heat through moisture evaporation, further increasing localized air temperatures (Tian *et al.*, 2024). Crops under moisture stress that are exposed at the same time to temperatures above their optimal temperature threshold can have nearly double the yield loss (Lobell *et al.*, 2011). The closure of the plant's stomatal cells and the reduction in transpiration under high temperatures increases leaf temperature, with crop canopy temperatures potentially exceeding ambient air temperatures by as much as 10 °C (Luan and Vico, 2021). Higher canopy temperatures increase the likelihood of tissue damage should temperatures continue to rise. It is possible for the decrease in evapotranspiration, due to high air temperatures and moisture stress, to result in an increase in surface temperatures, serving as feedback to the intensification of localized extreme heat (Proctor *et al.*, 2025; Lesk *et al.*, 2021).

At increasingly high temperatures that reach or exceed the point where plants experience a failure in photosynthesis and reproductive functioning (temperature failure point), the timing and duration of extreme heat events and the plant's history of prior heat exposure play an important role in determining outcomes. For most major agricultural crops, the temperature failure point is reached when air temperatures exceed 35 °C, with potential for equally serious impacts of high night-time exposure (Luo, 2011). Extreme heat exposure during vegetative growth prior to flowering (anthesis) has important effects on photosynthesis and respiratory processes that lead among other things to the denaturing of proteins and critical enzymes, the weakening of cell walls, the production of toxic oxidative compounds, which can cause passive cell necrosis and trigger programmed cell death (Zahra *et al.*, 2023; Wahid *et al.*, 2007; Goraya *et al.*, 2017; Kacprzyk *et al.*, 2025). At sublethal levels, crops can recover much of their productive functioning from these impacts after removal of the heat stress. In the period immediately prior to flowering (anthesis), extreme heat exposure can impact the development of reproductive organs (inflorescent, anther and pistil) (Wang *et al.*, 2021) and interfere with ovule and pollen genesis and pollen tube growth. At fertilization, extreme heat can render pollen sterile, cause fertilized embryos to be aborted, and have other negative impacts (Resentini *et al.*, 2023; Ul Hassan *et al.*, 2022; Rosenberger *et al.*, 2024). Damage to reproductive organs and reproductive processes is permanent, although research has shown that prior exposure to high temperatures below temperature failure point thresholds can lead to fewer losses, indicating the possibility of some degree of plant acclimation to high temperatures, some of the benefits of which are inheritable (Staacke *et al.*, 2025; Pissolato *et al.*, 2024; Suriyasak *et al.*, 2025). The exact temperatures and exposure times leading to permanent damages to reproductive functioning are crop-, even variety-specific, but generally range from one-time exposures over several hours to temperature below 45 °C, with most results evident at temperatures below 40 °C (Resentini *et al.*, 2023; Nuttall *et al.*, 2018), which is well within the range of temperatures and duration of recorded extreme heat events.

Extreme heat events occurring after fertilization have an impact on the survival, size and quality characteristics of the yield. By limiting resource translocation from photosynthesis to the developing grains, extreme temperatures reduce grain size and quality. Depending on the crop and the timing and severity of the stress, qualitative impacts can include the level of sugars, presence of organoleptic compounds, protein and minerals, the quality of starch and other impacts resulting in produce with lower nutritional and market value (e.g. Hafeez *et al.*, 2023).

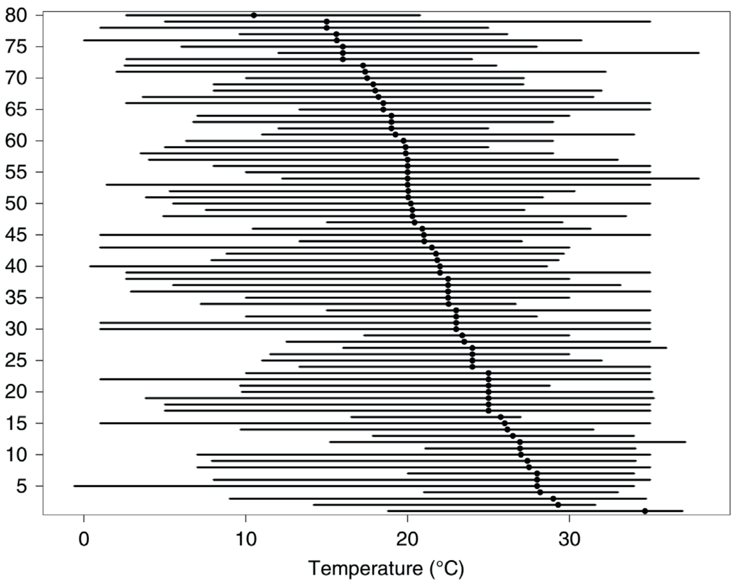
Beyond the immediate direct impacts of extreme heat on crops, episodes of exposure to extreme heat can lead to other significant indirect impacts. One of the most important impacts are the effects of extreme heat events on the development, behaviour and success of pollinators for crops that rely on other species for pollination. For example, extreme heat can directly alter bee foraging behaviour and the nutritional value that bees obtain from flowers, which can contribute to lower bee survival, development and reproduction with implications for seasonal pollination rates (Walters *et al.*, 2022). Female bees visiting heat-stressed plants lay fewer eggs, and their offspring have significantly lower survival rates and reduced adult longevity compared with bees provided access to non-stressed plants (i.e. temperatures less than 25 °C) (Walters *et al.*, 2024). The impact of rising temperatures on insect pests is generally understood, with strong seasonal increases noted (Ma *et al.*, 2025; Skendži *et al.*, 2021). The specific impacts of extreme heat on insect feeding behaviour depend on the responses of the host plant, pests and pest predators, as well as the timing and magnitude of extreme heat occurrence (Kharouba and Yang, 2021). As with plants, insects also have upper thermal thresholds, which when exceeded can limit their reproductive success, development and feeding behaviour. Both increases and decreases in individual pest and disease vector species is to be expected depending on sensitivities involved (Murtaza *et al.*, 2025; del Rio and Simpson, 2014). High temperatures can also affect rates of crop infection by creating the environmental conditions conducive to rising infection rates from fungal and bacterial pathogens. At the same time, high temperatures lower the health status of crops, rendering plants more susceptible to infection (Hossain *et al.*, 2024a; Lahlali *et al.*, 2024; Cohen and Leach, 2020). Depending on the organism, pathogens also exhibit sensitivities to extreme heat, with each organism having their own optimum, and maximum and minimum temperatures that govern their growth and survival (see Figure 5). Given these sensitivities, the prevalence and range of pathogens will likely change with the evolving climate regime (e.g. Chaloner *et al.*, 2021).

3.2.2 Observed impacts of extreme heat

There is robust empirical evidence, from subnational to regional scales, on the negative impacts associated with high temperature on the productivity of the major grains that supply 60 percent of global caloric food intake (maize, rice, soy, wheat) (e.g. Lesk *et al.* 2016). Through statistical analyses of large historical crop yield and weather datasets (with 20 000 and

FIGURE 5. Minimum, optimal and maximum temperatures of 80 crop pathogens infecting 12 major crop species

The (midway) points mark the optimal temperature threshold, and the bars refer to the temperature range (defined by the minimum and maximum temperature thresholds for each pathogen.



Source: **Chaloner, T.M., Gurr, S.J. & Bebber, D.P.** 2021. Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, 11(8): 710–715. https://doi.org/10.1038/s41558-021-01104-8

100 000 observations), studies have identified the optimal temperature thresholds beyond which yields begin to decline with exposure to additional heat (Schlenker and Roberts, 2009; Lobell *et al.*, 2011; Tack *et al.*, 2015). Assessments have quantified the negative impacts of heat stress on crop yields at various spatial and temporal scales of interest (e.g. Tack *et al.*, 2015; Gammans *et al.*, 2017; Malikov *et al.*, 2020). Averaged globally, a meta-analysis of research based on observational data of the temperature impacts to annual crop yields are reported as -7.5 percent (±5.3) for maize, -1.2 percent (±5.2) for rice, -6.8 percent (±5.9) for soybean and -6.0 percent (±3.3) for wheat per 1 °C of warming, with other estimates within the confidence bounds of these figures (Hu *et al.*, 2024; Lobell and Di Tommaso. 2025). Globally, temperature extremes have been found to hold greater explanatory power over national crop yield anomalies than drought (Ortiz-Bobea *et al.*, 2019; Lesk *et al.*, 2016; Vogel *et al.*, 2019; Zampieri *et al.*, 2017). Due to methodological challenges, however, empirical studies capture not only the direct impacts of extreme heat but also yield reductions occurring at lower temperatures (i.e. high but not extreme temperatures) and reductions due to faster development and temperature-induced moisture stress.

The importance of interaction effects between temperature, evapotranspiration and soil moisture is well established. Compound hot-dry events lead to observed yield losses exceeding 30 percent in affected areas, and temperature extremes have the greatest impacts in locations with lower precipitation and higher evapotranspiration (Lesk *et al.*, 2021; 2022). In comparison to the effects from high temperatures alone (extreme degree days), with observed yield losses of 9 percent in affected regions, losses from combined heatwaves and low precipitation were observed to be nearly triple at 24.89 percent (Xiao *et al.*, 2025). Over the past 64 years, there has been an observed transition from traditional drought to incidence of flash drought across 74 percent of the global regions at risk (e.g. regions covered in the 2021 IPCC Special Report, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*) (Field *et al.*, eds., 2012), with an 6.7 to 90.8 percent increase in severity stemming from flash droughts (where extreme heat plays a critical role) (Yuan *et al.*, 2023; Gu *et al.*, 2025).

Crop yield losses and the overall global reduction in total agricultural factor productivity due to heat and related stresses have led to an estimated 88 million more hectares being brought into production across 110 countries worldwide between 1992–2020 than would have otherwise been expected (Ortiz-Bobea *et al.*, 2021; Potapov *et al.*, 2022; You *et al.*, 2025). The GHG emissions from bringing this additional land base into production (21.8 billion tonnes of CO_2 equivalent) is equivalent to nearly one-fifth (18.9 percent) of the total land-use emissions for the countries involved (You *et al.*, 2025). Additional emissions fuel further global warming and increase the potential for extreme heat impacts. The overall loss in total factor productivity in agriculture (the relative contributions from land, labour and capital) to heat stress since 1961 is estimated at 21 percent, equivalent to the elimination of seven years of global productivity gains (You *et al.*, 2025). An assessment of the extent to which grain production has adapted to extreme heat (set at 30 °C for maize, soy and wheat based on observed optimal temperature thresholds) found no statistically significant evidence of net adaptation over the past 50 years, albeit with regional differences (Burke *et al.*, 2024). In other words, when examined globally, net crop yields are nearly as sensitive now to extreme heat impacts as in the past, with some countries (e.g. Brazil) showing increased sensitivity. The feedback loop of the need to compensate for heat damages by expanding the area under production leading to an increase in GHG emissions, and the accompanying loss of productivity gains and lack of evidence of net adaptation, is worrying to say the least.

3.2.3 Projected impacts of extreme heat

As with efforts to quantify the observed impacts of climate change on crop yields, a range of approaches are used in projecting crop yield responses to future climate scenarios generally, and with regards to temperature change in particular. The approaches employed can be placed into four basic categories; process-based crop modelling, both gridded and point-based; statistical regression of crop yield-temperature relationships based on historical data; a rapidly growing body of studies using various forms of machine learning; and warming field experiments. Each approach has their relative strengths and weaknesses. The use of mixed methods and model ensembles is common, if not the norm. Results are generally reported as the percent of yield impact, either per degree Celsius of warming, or until the middle or the end of the century under varying emissions scenarios. Principal sources of error are internal to the methods, models, and climate datasets used; all of which are under constant state of refinement (e.g. Müller *et al.*, 2021; Yin *et al.*, 2025; Proctor *et al.*, 2025).

Averaged globally, the overriding trend from the various projection efforts is one of declining crop yields in response to rising temperature. The range of projected yield impacts from recent global studies resulting from 1 °C of warming estimate losses of 4 to 10 percent for maize; 1.1 to 5.6 percent for rice; 2.9 to 5.4 for soy; and 3.8 to 10 percent for wheat (Wang *et al.*, 2020; Makowski *et al.*, 2020; Abramoff *et al.*, 2023; Lobell and Di Tommaso, 2025). As highlighted in Figure 6, crops grown in northern latitudes, where seasonal temperatures are often suboptimal, generally show signs of potential increase, whereas temperature impacts at lower latitudes show distinct declines (Jägermeyr *et al.* 2021; Abramoff *et al.*, 2023; Tran *et al.*, 2025). These regional differences highlight the narrow thermal safety margin in the tropics, where current seasonal high temperatures are close to the thermal damage threshold of key crops.

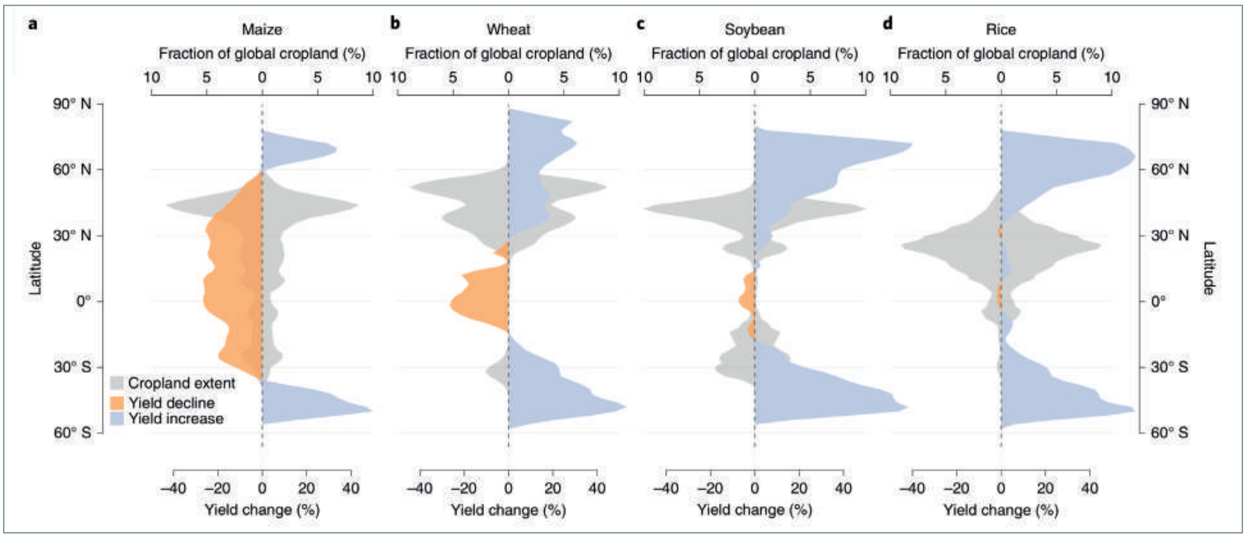
BOX 5. Crop pests and disease and extreme heat in Kyrgyzstan

Kyrgyzstan and other countries in Central Asia experienced an exceptionally strong heatwave in spring of 2025. The Jalal-Abad Region in Kyrgyzstan recorded temperatures up to 30.8 °C, which is 10 °C above the average for that period. The abnormally early heat, occurring during the flowering of fruit crops and the start of spring wheat vegetative growth, affected fruit yields, and impacted the germination and early development of spring wheat (Clarke *et al.*, 2025). Extreme heat also contributes to the proliferation of pests and plant diseases. In 2025, the first appearance of locusts was recorded on 3 April in Nooken district of Jalal-Abad Region, and in Chuy oblast on 3 May in Panfilov district according to the report by the Ministry of Agriculture. According to its data, the early onset of spring, drought, and abnormally high temperatures in May contributed to the mass reproduction of locusts in historical focal areas. In 2025, mass aggregations were observed in locations where they had not been seen for 12 to 20 years (Kutueva, 2025).

Sources: See References.

A narrow thermal safety margin makes it increasingly likely that thresholds will be exceeded, with a lower variance in temperature amplitude required to do so. None of the recent studies identified single out potential damages resulting from extreme heat events as defined in this report. Damages from extreme heat are assumed within those reported from rising global temperatures generally.

FIGURE 6. Projected changes in crop yields by latitude under SSP5-8.5 for the period 2069–2099



Source: **Jägermeyr, J. *et al.*** 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, 2(11): 873–885. https://doi.org/10.1038/s43016-021-00400-y

BOX 6. Rice farming and extreme heat in India

Rice is an extremely important staple food crop in many areas of the world. Its cultivation is closely linked with global food security, economic growth, employment, and social stability. Rice is the main source of calories for half the global population and supplies 20 percent of the global dietary energy.

In India, 70 percent of the caloric intake comes from rice. Summer monsoon rainfall provides up to 80 percent of the annual precipitation in India. Compound hot and dry extremes are a major threat to Indian agriculture. The most severe events during the major summer monsoon were observed in 1972, 1987, 2002, 2009, 2014, and 2015. The 20-percent deficit of monsoon rainfall in 2002 resulted in billions of dollars in economic damages (Gadgil *et al.*, 2004) and affected more than a billion people.

High temperature extremes are anticipated to be more frequent and more intense throughout the Indian subcontinent, making rice farming increasingly vulnerable to heat stress (Hossain *et al.*, 2024b). To sustain production, several strategies have been already explored: using cultivars that flower early in the morning; adjusting sowing and planting times; and breeding genetically resistant cultivars. Another possible strategy to mitigate heat stress is irrigation, which may have a surface cooling effect from local to subnational levels.

In India, rice farming is not highly mechanized and employs millions of agricultural workers. Based on an ensemble of high-resolution climate change simulations, Im *et al.* (2017) have shown that extremes of wet bulb temperature in South Asia are likely to approach and, in some locations, exceed critical thresholds for worker safety by the late twenty-first century under high-emission scenarios. The most intense risk from future heat waves is concentrated around densely populated agricultural regions of the Ganges and Indus River basins. Without further mitigation, heatwaves will become a major threat to Indian agricultural workers and rice production.

Sources: See References.

3.3 Livestock

3.3.1 Vulnerabilities to extreme heat

As with crops, livestock growth and productivity face both direct and potential indirect impacts from extreme heat events. Individual animals of the major livestock species have a defined range of air temperatures (the thermoneutral range) within which they can control their core body temperatures without energy loss or coming under stress. The lower bound of the range varies by species. Unacclimated cattle, goats and sheep share a common upper threshold of 25 °C. Chicken and swine, which cannot sweat as a means of cooling themselves, have a slightly lower threshold (24 °C) in their thermoneutral range. At temperatures above these thresholds, individuals come under increasing levels of heat stress. Depending on the magnitude and duration of the exposure and characteristics of the individual, heat stress triggers behavioral adjustments and changes in respiratory, circulatory and metabolic functioning that can lead to organ failure, cardiovascular shock and death. Under rising levels of heat stress, individuals exhibit commiserate levels of decreasing productivity and reproductive success. In addition to ambient air temperature, wind speed, solar radiation and especially humidity all influence the point of onset and level of heat stress. Humidity is of particular importance in the overall consideration of heat stress for ruminants due to its impact on evaporation and the ability of animals to sweat as a means of controlling their temperature. Other factors that influence heat stress include the breed and age of the individual animal, diet, history of previous heat exposure, housing, stall and field conditions, extent of body fat accumulation, thickness and colour of their coat (Tao *et al.*, 2020).

At the onset of heat stress, livestock can maintain their body temperatures with minimal productive losses through behavioral adjustments (e.g. seeking shade, decreasing their movements and increasing water intake) and through autonomic responses of increased respiration, heart rate and sweating. As temperatures rise further, animals expend increasing amounts of energy attempting to cool themselves, which impacts their productivity and health. Heat stressed animals show increased panting, reduce their food intake to lower metabolic heat production, have reduced feed conversion efficiency, redistribute nutrients within the body and redirect blood flow to extremities (Collier *et al.*, 2017; Wheelock *et al.*, 2010). For each additional degree above 30 °C, cattle, sheep, goats, pigs and chickens reduce their feed intake by three to 5 percent (Thornton *et al.*, 2015). The decrease in feed intake and greater metabolic energy output create a negative energy balance leading to reduced productivity (e.g. less milk, fewer eggs) and weight loss. Sustained high levels of heat stress leads to a disruption of rumen functioning in ruminant animals, and a breakdown in the impermeability of the digestive track in monogastric species, with acute health impacts. Overall, repeated exposure to extreme heat weakens animals' immune response, making individuals more susceptible to infections and disease, and leading to higher mortality rates (Chauhan *et al.*, 2021; Pearce *et al.*, 2013; Cross *et al.*, 2020; Renaudeau and Dourmad, 2022).

Beyond their generally shared physiological responses, species and breeds show differences in their vulnerability and response to extreme temperatures. The impact of extreme temperature on dairy cattle is one of the most studied relations, with the milk yield of cattle under heat stress found to decline by approximately 2 percent for each additional unit of increased heat stress (Ravagnolo *et al.*, 2000; Bouraoui *et al.*, 2002). Due to the inability of swine to cool themselves through sweating and with smaller lungs to help with control body temperature through panting, pigs are more sensitive to heat stress than other livestock. Breeding sows in particular require cooler environments. In addition to being more productive, higher yielding dairy and swine breeds are more sensitive to high temperatures and experience greater yield losses when under heat stress (Ouellet *et al.*, 2019). Heavier individuals and those with modern genetics produce more metabolic heat (up to 20 percent more). These animals experience heat stress at lower temperature and are impacted more significantly by hot temperatures (Renaudeau *et al.*, 2011; Brown-Brandl *et al.*, 2004; Cross *et al.*, 2018). For unshorn sheep, their thick coat reduces their ability to cool themselves through sweating. As a result, sheep achieve most of their cooling through panting and radiative heat transfer through the redirection of blood flow to extremities (ears and legs). Sheep and goats are generally more tolerant to heat stress than cattle and swine. However, depending on age, breed, hair length, diet and health of the individual, these species also experience significant negative impacts when they come under heat stress (Marai *et al.*, 2007; Al-Dawood, 2017; Al-Ramamneh, 2023). During hot weather sheep can increase their water intake by up to 1 100 percent (12 times) to compensate for moisture lost through panting and sweating. Chickens, due to their inability to sweat and feather coat, achieve most of their heat dissipation through panting and wing spreading. Ensuring sufficient water is available to the birds is critical. If sufficient water in not available during periods of high demand, the impacts on all animals are severe, and can result in death if allowed to continue.

The quality of produce from individual animals under heat stress is also affected. Milk from heat-stressed dairy animals (cattle, goats and sheep) has lower fat and protein content and higher somatic cell counts (Skibiel *et al.*, 2022; Nasr and El-Tarabany, 2017; Joy *et al.*, 2020; Sevi and Caroprese, 2012; Salama *et al.*, 2021), an indication of bacterial infection. The carcass quality of heat-stressed sheep, swine, cattle and chicken are notably affected (Gonzalez-Rivas *et al.*, 2020; Liu *et al.*, 2022), with meat containing increased fat accumulation and less muscle development. Wool production in sheep is also sensitive to heat. Higher temperatures lead to decreased fleece quality and quantity (Gowane *et al.*, 2017). In chickens, heat stress results in markedly lower egg production, eggs with thinner shells and altered yolk quality (Kim *et al.*, 2024).

Exposure to extreme heat and heat stress has major direct impacts on reproduction for all livestock species. In mammals, high levels of heat stress delay the onset of puberty and greatly reduces conception rates. Following periods of heat stress, rams require six to seven weeks before they are again able to produce viable sperm. Following conception, heat-stressed mothers have shorter gestation periods, higher rates of embryo mortality and aborted foetuses, and slower rates of embryo development. Overall, litter sizes of heat-stressed mothers are smaller, and there are lower lambing rates and longer gaps between pregnancies (wean-to-estrus interval) (Chebel *et al.*, 2004; Bilby *et al.*, 2008; Arero and Ozmen, 2025; Romo-Barron *et al.*, 2019; Ross *et al.*, 2017). Heat stress during gestation also leads to intergenerational effects. Offspring from heat stressed mothers have lower birth weights, lower weaning weights and shorter life expectancies. Affected offspring are less productive as adults. Dairy cows and sheep from heat-stressed mothers have lower milk yields (Ouellet *et al.*, 2020); sheep and swine have reduced feed efficiency and higher body temperatures that result in greater energy loss; and swine have greater sensitivity to heat stress (Ross *et al.*, 2017; Pearce *et al.*, 2013; Johnson and Baumgard, 2018). In dairy cows, mothers who come under heat stress during their dry period have reduced performance in their lactation cycles following birth and are less productive in subsequent lactation cycles (Skibiel *et al.*, 2022; Nasr and El-Tarabany, 2017).

Extreme heat events, either separately or combined with other climate events, are responsible for additional indirect threats related to the availability and quality of livestock feed, and changes in pest and disease pressure. For ruminants, forage produced under heat stressed conditions is generally of lower quality, with less protein and mineral content and more lignin and fibre, resulting in feed that is less palatable and requires more energy to digest. Poor-quality feed leads to lower milk yields, less weight gain, and the production of more methane (Lee *et al.*, 2017; NRC, 1981). In sheep and goats, which have higher conversion rates of fibrous feed, the consumption of poor-quality feed leads to more body heat being generated during digestion, as it does with cattle, which contributes to individuals being more vulnerability to heat stress. Higher levels of atmospheric CO_2 have been found to decrease the protein content of forage and C_3 grains[1] (e.g. barley and wheat) commonly used in feed for monogastric animals (pigs and chickens) and produce less nutritious feed. Leguminous species, however, are less affected (Taub *et al.*, 2008). Climate change has also been found to increase rates of mycotoxins and deoxynivalenol contaminations in grain, which, among other effects, can increase livestock's susceptibility to infections and disease and their severity (Renaudeau and Dourmad, 2022). The potential impacts of extreme heat on livestock pests (e.g. ticks, flies and helminths) and the prevalence and severity of vector and non-vector spread of diseases is less certain (Thornton *et al.*, 2009). For the factors involved in the spread of disease (e.g. host, vector, disease organism and environment), extreme heat has a distinct negative impact on livestock health status, rendering individual

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[1] C_3 grains are plants that produce a three-carbon compound during photosynthesis.

animals more vulnerable. The direct and indirect impacts of extreme heat on specific disease and vectors species, however, are complex and species-specific (Ali *et al.*, 2020). The same is true for pest species. Increased heat generally accelerates the rate of physiological development of insects and helminths, thus allowing more generations to be produced per season and pest populations to increase. However, extreme temperatures can also exceed individual species thermal limits, which can suppress populations and limit the potential for outbreaks and the spread of vector-borne diseases.

3.3.2 Observed impacts of extreme heat

Studies on the impacts of temperature and associated meteorological variables on livestock health, productivity and welfare precede the current concern over the effects of climate change and extreme heat (e.g. NRC, 1971). Using various combinations of air temperature, humidity, wind, solar radiation and in situ temperature measurements, clinical trials and field observation have led to the establishment of indices, such as the temperature–humidity index (THI) and the heat load index. Associated with these indices, threshold values of increasing levels of heat stress (mild, moderate, extreme) among the major livestock species (beef and dairy cattle, chickens, goats, sheep, swine) have been established that link atmospheric conditions with observable responses to heat. These indices, and other measures (e.g. wet bulb temperature) have been used to assess the occurrence of heat stress among livestock populations over varying temporal ranges at subnational and national scales (Key *et al.*, 2014; Hutchins *et al.*, 2025; Palandri *et al.*, 2025). One benefit of the graduated stress-scale of the THI is that it offers researchers the ability to segregate the amount of time individual animals are subjected to conditions of extreme stress (e.g. Thornton *et al.*, 2021; Gisbert-Queral *et al.*, 2021; Van Wettere *et al.*, 2024). Unlike observations on heat stress in crop agriculture, where a single threshold is used to assess productive damages, livestock studies can give specific attention to assessing the occurrence of accumulated days of extreme stress, as defined by the indices, in addition to heatwaves using definitions applied by researchers (e.g. Morignat *et al.*, 2014; Vitali *et al.*, 2015; Bionda *et al.*, 2024).

Studies focusing on the occurrence of the impacts of heat stress on livestock highlight the acute damages that these events can cause. Taking the example of dairy cattle, the most data-rich and studied livestock species, a study involving review of 56 million monthly milking records over a five-year period (2012–2016) found a loss of 1 percent in average annual milk yields due to heat stress, with losses in qualitative characteristics (protein and fat content) having greater financial impacts to farms than quantity (Hutchins *et al.*, 2025). In another national study (Israel), involving 320 million daily milk records spanning a 12-year period, average daily milk yields were observed to drop 0.5 percent for each hour dairy cows were exposure to wet bulb temperatures exceeding 26 °C (Palandri *et al.*, 2025). Cows in the most productive period of their lactation cycle were impacted most heavily. The negative impacts on yields were found to persist for 10 days following the last day of exposure, with higher temperatures and longer duration hot spells resulting in greater residual yield losses, a finding that underscores the important latent effect of extreme heat exposure in livestock. Another study that analysed milking records from 1981–2018 found a significant decrease in sensitivity to yield losses due to heat stress over time, indicating adaptation (Gisbert-Queral *et al.*, 2021). The decreased sensitivity is explained at least in part by the considerable consolidation that had occurred within the sector during the study period, during which the number of dairy farms had declined by more than half and the median herd size increased from an average of 80 to 1 300 cows. The majority of large farms are confinement facilities, with cows kept indoors. On smaller farms, the cattle typically graze outdoors, and thus farmers have less control over heat exposure of their animals. While the overall losses due to temperature–humidity exposure were reduced, the reductions were achieved in the low and moderate THI stress categories. Losses due to the extreme THI stress category were unchanged.

Beyond productivity impacts, extreme heat can lead to significant livestock mortalities. Individual heatwaves, defined either as the exceedance of a percentile of daily norms (e.g. 90th) or fixed temperature threshold (e.g. more than 35 °C), have led to mortality rates in dairy and beef cattle of up to 10 and 24 percent (Hahn, 1999; Morignat *et al.*, 2014). A study examining the death of 46 000 dairy cows in relation to eight major heatwaves over a six-year period found that on average dairy cows had a 20 percent greater chance of dying during a heatwave (Vitali *et al.*, 2015), with rates of up to 30 percent occurring early in the summer before cattle had become acclimated to heat exposure. Heatwaves in this study were defined as a minimum three-day period with daytime highs exceeding the 90th percentile for that date (averaging 31.7 °C). Individual animals most at risk were cows who had begun lactating (older than 28 months), which is associated with greater metabolic heat production, and animals that had been exposed to heatwaves of longer duration. Mortalities remained statistically significant in the three days following a heatwave, indicating again the negative latent effect of extreme heat exposure in livestock.

Across the range of production systems, livestock vulnerabilities to extreme heat stress are significantly elevated during times when high temperatures and other meteorological factors coincide. The combination of high temperatures with high levels of humidity, reduced windspeed and increased direct sun exposure are particularly dangerous. Dangerous conditions can occur both naturally under ambient conditions, or as the result of the design of transportation or production facilities. The role of confinement in accentuating the effects of heat stress among ruminant animals (cattle, sheep, goats), such as in feedlots, during transport and at slaughter facilities, is a consistent factor noted in high mortality events (e.g. Vale *et al.*, 2010; Cowan *et al.*, 2024). The intensive rearing of monogastric species (swine and poultry), typically carried out in indoor facilities, generally includes ventilation. However, cooling systems are uncommon outside of modern production facilities, and their absence contributes to conditions that can lead to high mortality events during periods of extreme heat. Mass mortality events from extreme heat involving livestock (pigs, dairy and beef cattle) can range into the thousands of animals, and in poultry production, heatwave induced deaths can soar into the millions (e.g. Government of Canada, 2022; Jadhav, 2015). The impacts of extreme heat on animals managed under extensive free-range conditions are less well documented due to observational data constraints (e.g. Feng *et al.*, 2021).

3.3.3 Projected impacts of extreme heat

Studies conducted on the anticipated impacts of rising global temperatures on livestock production commonly use species-specific THI thresholds, combined with projected climate data, to estimate future changes in risk exposure. Using various emission scenarios, projection studies capture several aspects of future impacts, including the increase in surface area exposed to damaging heat, the increase in number of animals subjected to heat stress, and the number of additional days animals are under heat stress (e.g. Wankar *et al.*, 2021; Thornton *et al.*, 2021; 2022). Results are generally reported in terms 1 °C of warming, or under one of the IPCC emissions scenarios (e.g. RCP 2.6 or 8.5) until the middle or the end of the century (e.g. North *et al.*, 2023; Emediegwu and Ubabukoh, 2023). Studies estimating productivity impacts typically sum the number of individual days above an established threshold and multiply it by a productivity reduction factor. Some studies go further and express productivity losses in financial terms (e.g. Thornton *et al.*, 2022). Although less common, studies have also looked specifically at changes in exposure to THI extreme stress conditions (e.g. Thornton *et al.*, 2021; 2022). No studies were found that attempted to assess the differential impacts occurring when livestock are subjected to sustained periods of high temperatures, as in a heatwave, as opposed to damages occurring from the aggregate of unrelated, non-sequential hot days.

Overall, the studies conducted to date show a distinct declining trend in future productivity under rising temperatures. The impacts vary by species, the scope and the methods of the assessment, the assumptions regarding the rate of future warming, and whether or not adaptive actions are considered. The resulting estimates of the current rate of heat exposure indicate that nearly 80 percent of the global cattle herd are being exposed for 30 days or more per year to stress-inducing heat (North *et al.*, 2023) and that 8 to 20 percent of the global population of cattle, goats, sheep pigs and poultry are exposed to at least one day per year of THI extreme stress (Thornton *et al.*, 2021; Carvajal *et al.*, 2021). By 2100, estimates indicate that cattle located in temperate areas may be exposed to 180 or more days of heat stress under SSP5-8.5, while the expansion of areas with over 180 days of heat stress is limited to sub-tropical regions under SSP1-2.6 (North *et al.*, 2023). In the tropics cattle would be under perpetual heat stress conditions under a high-emission scenario. Between 61 to 75 percent and 17 to 31 percent of the global cattle, goats, sheep, pigs and poultry populations could be exposed to extreme THI days under SSP5-8.5 and SSP1-2.6, respectively, by 2090 (Thornton *et al.*, 2021). Regionally, a low-emissions scenario (SSP1-2.6) would reduce the projected heat risk for cattle by at least 50 percent in Asia, 63 percent in South America, and 84 percent in Africa in comparison with SSP3-7.0 (North *et al.*, 2023). Depending on the emission scenario, tropical regions are expected to face an increase of 100 to 300 percent (two to four times) in the number of days livestock are exposed to extreme heat by 2050 (Thornton *et al.*, 2021; 2022). One of the few studies focusing on sheep, indicates a potential loss of 0.4 million lambs in Australia due to 1 °C of additional warming (a 20-percent increase), with losses rising to 1.2 million lambs with 3 °C of warming (a 57-percent increase) (Van Wettere *et al.*, 2024). Pig production in China, the largest global producer of pigs, is projected to decline by 5.6 percent, with hotter areas experiencing losses of 10 percent (Niu *et al.*, 2024a). It is thought that technical advances might reduce the magnitude of losses on average by 52 percent by 2050, but the remaining losses are not covered. For all species, the projected impacts on livestock pests and diseases are less studied. There is the potential for regional increases in some major pest and diseases, whereas other regions and species may see declines driven by future climate trends (warm-wet; warm-dry) (Younan and Simpson. 2014). As with other climate change variables, heat exposure is negatively correlated with socioeconomic variables and generally shows that low-income countries and livestock-dependent tropical countries will be the most affected (Emediegwu and Ubabukoh, 2023).

Climate projections for the middle and end of the century have been also used to estimate changes in the value of cattle milk and meat production at the global level (Thornton *et al.*, 2022). For a high emissions scenario (SSP5-8.5), global production losses from heat stress are estimated to amount to around USD 40 billion per year by the end of the century, or 9.8 percent of the value of production of meat and milk from cattle (in 2005 dollars) (Thornton *et al.*, 2022). Under a low-emission scenario (SSP1-2.6), impacts from livestock exposure to extreme heat are reduced by nearly two-thirds, with production losses estimated at around USD 15 billion per year, or 3.7 percent of 2005 value. The significant difference between outcomes under the high- and low-emission scenarios highlights again the importance of emission reductions in limiting future losses. Losses in tropical regions are projected to be far greater than in temperate regions.

These trends stand in stark contrast to the anticipated rise in consumption demands based on projected population growth and changing dietary patterns. Under a business-as-usual pathway, consumption of animal protein per capita is anticipated to increase by 17 percent by 2050 from a 2012 baseline. Under a 'sustainability' pathway, the per capita increase is only expected to be 3 percent (Henchion *et al.*, 2021). Factoring in anticipated population growth by 2050, with a global human population reaching 9.8 billion (UN DESA, 2025), animal protein production will need to increase by 50 to 70 percent (FAO, 2011; Searchinger *et al.*, 2018). The magnitude of this increase in demand means that even small reductions in productivity due to temperature stress will place greater pressure on the global land-base, resulting in further emissions as land use changes and production increases within the sector attempt to compensate for the losses.

3.4 Fisheries and aquaculture

3.4.1 Vulnerabilities to extreme heat

Compared to terrestrial systems, the vulnerabilities and responses to climate change and extreme heat events in aquatic systems are vastly more complex (e.g. Antão *et al.*, 2020; Hobday and Pecl, 2014; Nagelkerken *et al.*, 2023). All impacts on aquatic species are mediated through the water environment (saline, brackish or fresh). Species are found across a multitude of ecological niches that include isolated inland freshwater ponds and lakes; connected riverine systems, some of which may reach the sea, passing through fresh-saline water transitional zones and estuaries; coastline environments and reef systems; continental shelves and the open ocean, which stretches from the tropics to ice-covered high latitudes. Within these environments, species occupy various positions within the water column, from surface to mid-depths, to the bottom. Some species are residents and spend their entire life in the same location. Other species are migratory and spend periods of each year in various locations. Some species are nomadic during a portion of their lives or entirely, living independently or in immense schools. Species commonly occupy different niches as they undergo morphological changes in their development. Species may even move from fresh to saline environments, and back. Many species are highly mobile (e.g. finned fishes and cephalopods), whereas others have limited mobility (e.g. crustaceous, gastropods and echinoderms). Other species are largely sedentary or immobile (e.g. bivalves, cnidarian and sponges). Directly or indirectly, all aquatic species rely on food chains comprised of organisms that occupy different trophic levels with equally diverse life cycles linked to the great ocean gyres, currents and upwelling systems, as well as unique habitats, such as kelp forests, seagrass meadows, coral reefs and mangroves. Aquaculture systems aim to recreate or isolate portions of these niches to enable the production of individual or multi-species systems, which vary in the extent to which they rely on natural processes, from nearly entirely (e.g. ocean ranching) to not at all (e.g. land-based, recirculating systems).

Across the span of ecological niches, the impacts of extreme heat on organisms can be categorized in three general pathways. The first pathway relates to the direct impact of rising temperatures on water quality, and the indirect impact this has on organism health, productivity and survival. Higher water temperatures result in lower levels of dissolved oxygen and can increase salinity levels in marine environments resulting in species coming under increasing degrees of physical stress. Changes to water quality impact feeding behaviour, reproductive success, immune system response, and at the extreme can result in death. The inverse relationship between water temperature and oxygen solubility (dissolved oxygen), results in water at 25 °C having only 56 percent as much dissolved oxygen as water at 0 °C. Salinity levels also influence the solubility of oxygen. At 25 °C, saltwater contains 23 percent less dissolved oxygen as freshwater. As salinity levels increase through evaporative losses during extreme heat events, oxygen levels decrease, potentially placing marine species in affected areas at greater risk to oxygen stress. The absence of wind and surface mixing, conditions that often accompanies marine heatwaves, can further intensify the effects of extreme heat on dissolved oxygen and salinity levels. In coastal environments, the variable biological activity of phytoplankton and microbial communities strongly shapes oxygen dynamics in the water and can create a mosaic of oxygen levels that strongly influence the physiology, behaviour and stress responses of different organisms, which influence the suitability of local habitats (Fusi *et al.*, 2024).

The second impact pathway relates to the impacts of extreme heat on species' supportive habitats. Examples include coral bleaching events, mangrove dieback, the thinning of seagrass beds and the reduction in kelp forests. Extreme heat impacts on habitats can lead to the unravelling of the intricate web of relationships necessary for species to occupy specific locations (Wernberg *et al.*, 2025; Smith *et al.*, 2024). The third impact pathway relates to the broader impacts of extreme heat events on species' food chains. For example, the increase in thermocline stratification, the weakening of ocean currents and upwelling events associated with high temperatures, can reduce the cycling of nutrients that drive the oceanic food webs (IPCC, 2022a) causing a precipitous collapse of primary and secondary producer populations, species of phytoplankton, zooplankton and krill.

As with terrestrial species, all aquatic organisms have a species-specific thermal range within which they thrive, temperatures that they can tolerate and those that are fatal. Similar to livestock species, the lower temperature threshold for aquatic species ranges widely. Aside from tropical freshwater species, however, few fish species thrive in water temperatures above 28 °C, and many begin to show negative impacts well below this temperature (20 to 24 °C) (Islam *et al.*, 2022). The thermal safety margin (Buckley *et al.*, 2022), the range between the upper temperature threshold of what a species can tolerate and the highs that they currently face, declines as average water temperatures rise. The narrowing of a species' thermal safety margin increases its vulnerability to episodic impacts of marine and freshwater heatwaves. Aquatic species generally show a high level of plasticity in response to shifting temperature regimes, as can be seen in the fluctuation of diurnal and seasonal temperatures. However marine species in many locations, especially the equatorial regions, already inhabit environments that are close to their thermal maximum, making them particularly vulnerable to extreme heat events (Van Wert *et al.*, 2024; Molina *et al.*, 2025).

For organisms whose body temperature mirrors the surrounding environment (ectotherms), temperature controls all their major physiological processes, making them highly sensitive to temperature change. The impact of extreme heat exposure on individual organisms depends on the profile of the heat event, its timing, the rate of increase, magnitude and duration, as well as the species, the age of the individual, its developmental stage and history of prior exposure (Islam *et al.*, 2022; Bruning *et al.*, 2024; Rodrigues-Dominguez *et al.*, 2019). Species grown in most aquaculture systems are particularly vulnerable to heat stress due to their inability to relocate or seek thermal refugia when temperatures rise. Regardless of the environment, as individuals come under heat stress, their metabolic, cardiac and respiratory rates increase, while food intake decreases. Heat stress compromises digestion, leads to poor assimilation of nutrients, resulting in reduced growth and lowered reproduction. In shrimp, crabs and lobsters, moulting can be disrupted. Sustained and increasing stress levels amplify these responses. Individual organisms can experience hormonal and osmoregulatory disruption (an imbalance of fluids and electrolytes inside and outside of their bodies), altered brain and nervous system functioning, decreased blood flow to organs and compromised immune function, leading to increased risk of infection and disease. Fish deaths during extreme heat events typically result from cardiac failure as individuals struggle to maintain elevated metabolic demands through increased respiration in an environment with reduced levels of dissolved oxygen (Alfonso *et al.*, 2021; Little *et al.*, 2020; Islam *et al.*, 2022; Van Wert *et al.*, 2024).

In marine, brackish and freshwater bodies, increased water temperatures and high nutrient loads fuel algae growth, and can lead to the emergence of harmful algal blooms, comprised of various microalgae and bacterial species. When blooms of high-biomass producing microalgae species die, their decomposition can rapidly deplete the available dissolved oxygen, creating hypoxic (low oxygen) and anoxic (no oxygen) 'dead zones' leading to widespread deaths of fish and other aquatic organisms (Pitcher and Jacinto, 2019). Warm nutrient-rich water can also lead to the proliferation of toxin-producing algae and bacterial species, resulting in the contamination of aquatic products and the death of a wide-range of freshwater and marine life, including fish, mammals, seabirds, turtles and invertebrate species. Deaths, including human deaths, are caused either by the direct effects of the toxins produced or through the consumption and bioaccumulation of toxins in contaminated organisms (Brenckman *et al.*, 2025; Griffith and Gobler, 2020). The principal species responsible for harmful algal blooms are all regular components of the phytoplankton communities found in coastal waters, upwelling zones and freshwater bodies. Of the 4 000 species of plankton identified, only 1 to 2 percent are known to be harmful (Shumway *et al.*, 2018). Depending on the emergence of favourable conditions, populations of toxin-producing species can dominate, leading to potential poisoning events.

Similarly, the major disease organisms are generally present in most waters and represent a potential indirect threat to aquatic organisms from extreme heat. Elevated stress levels caused by exposure to extreme heat can compromise the immune functioning of host organisms making them vulnerable to pathogens (Genin *et al.*, 2020). The high-density levels found in aquaculture systems makes the spread of disease a major management concern, and the danger is amplified by extreme heat (e.g. Vega-Heredia *et al.*, 2024). Some of the greatest impacts of extreme heat events on aquatic species are felt through the indirect effects on their food chains. The indirect impacts on food chains involve several trophic levels of biological diversity, with organisms in each level having their own requirements, tolerances and dependencies (Arteaga and Rousseaux, 2023; Chauhan *et al.*, 2023).

3.4.2 Observed impacts of extreme heat

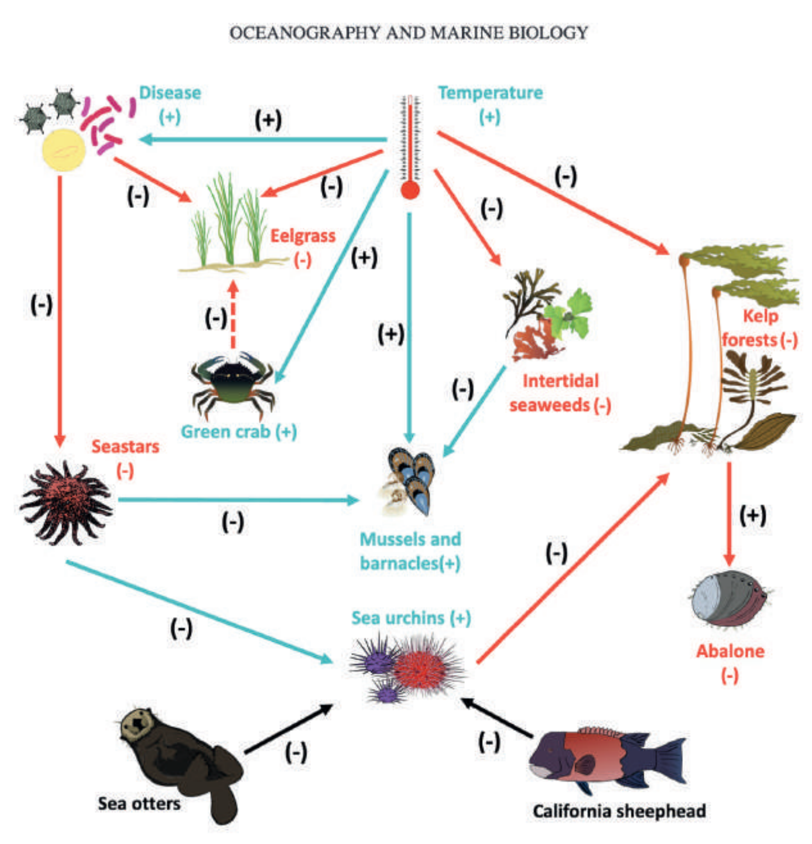
Direct and indirect impacts of extreme heat on capture fisheries and aquaculture have been observed worldwide. In 2022, the total volume of production from fresh and saltwater aquaculture surpassed that of capture fisheries for the first time. Nevertheless, marine capture fisheries remain the largest global source of aquatic protein (FAO, 2024b). The vastness of the oceanic environment, the high level of diversity and mobility of fish stocks, and the difficulty of obtaining observational data at varying depths, make direct measurements of the impacts of extreme heat on specific species challenging. Using catch records and survey data, researchers have been able to piece together the impact of ocean warming on fish stocks. One of the most important findings has been on the rate of fish stock migration poleward and offshore to greater depths, as they seek cooler waters within their thermal range. Stocks have disappeared from the warm tail of their traditional range and expanded into new areas beyond their historic range on the cool tail (e.g. Hastings *et al.*, 2020). Species living in the upper 200 m of the ocean are believed to be moving poleward at an annual rate of 52 km (+/- 33 km), while species living near the seafloor are moving at an annual rate of 29 km (+/- 16 km) (IPCC, 2022b). Due to the ubiquitous warming of waters in the low latitudes, species in those waters must travel further to reach cooler waters than species at higher latitudes. Species movements are driven by rapidly warming baseline temperatures and the effects of marine heatwaves. Since the 1940s, the average number of heatwave days has increased by 200 percent, from 15 to 50 days, and the average maximum heatwave temperatures has increased by 1 °C (Marcos *et al.*, 2025). In 2023, 22 percent of the global ocean experienced at least one severe to extreme heatwave (von Schuckmann *et al.*, 2024). In 2024, 91 percent of the global ocean experienced at least one heatwave, 46 percent of which were strong, and 8 percent severe. The global average length of heatwave conditions was 100 days (the previous record set in 2016 was 58 days) (Johnson and Lumpkin, 2025).

The acute rise in ocean temperatures during marine heatwaves has led to some of the most dramatic incidence of extreme heat stress yet observed. The marine heatwave that impacted the northeast Pacific in 2013–2016 (referred to as the 'blob') illustrates the range of far-reaching impacts that these events have on oceanic environments. A recent comprehensive review of research has summarized the impacts of this heatwave in terms of the shift in species' range, changes in food chain dynamics in various locations and depths, and die-offs due to various direct and indirect causes (Starko *et al.*, 2025). The 2014–2016 heatwave led to water temperatures increasing 4 to 6 °C above the norm. Water in sheltered coastal areas was observed to rise as much as 7 °C in a single hour. The heatwave evolved into the largest and longest-lived heatwave yet recorded. Over 100 species of invertebrates, fish, birds and mammals were observed to have shifted beyond their known habitable range, and another 139 species were found far outside their usual locations. The observed range shift for over 80 percent of species was up to 500 km, with an average displacement of 343 km. Some species moved over 1 000 km.

The heatwave triggered a complex cascade of impacts among species in coastal areas (see Figure 7). Warm waters triggered outbreaks of eelgrass wasting disease and sea star wasting disease. Eelgrass and sea stars are critical foundation and keystone species of coastal ecosystems. Diseases outbreak led to the decimation of eelgrass meadows in some locations. In other areas, populations of sea urchins, normally held in check by sea stars, exploded, resulting in increased sea urchin herbivory in kelp forests. Giant kelp, another critical foundation species, already directly impacted by rising water temperatures, was vulnerable to increased sea urchin pressure. The loss of eelgrass meadows, kelp forests and intertidal seaweed set in motion a cascade of secondary, tertiary impacts on other dependent species due to the loss of habitat and critical food sources.

FIGURE 7. **Impacts of the 2014–2016 marine heatwave**

Network diagram describing the impacts of the 2014–2016 marine heatwave on coastal benthic ecosystems. Each entity (taxon or driver) is labelled with coloured text and a (+) or (-) sign indicating whether it increased (blue, +) or decreased (red, -) during the marine heatwave. The black text reflects entities on which the marine heatwave is thought to have had little to no direct effect. Each arrow is labelled with a positive (+) or negative (-) sign that indicates the directionality of the interaction under normal conditions, while the arrow colour indicates whether the entity at the head of each arrow was impacted positively (blue), negatively (red) or neutrally (black) by the interaction during the marine heatwave. The dashed arrow indicates an interaction that is likely but was not directly demonstrated by observational studies during the heatwave. Note that sea otters and green crabs have patchy distributions across the study region and California sheephead are only found in southern portions of the study region.



Source: **Starko, S. *et al.*** 2025. Ecological Responses to Extreme Climatic Events: A Systematic Review of the 2014–2016 Northeast Pacific Marine Heatwave. In: *Oceanography and Marine Biology*. First edition, pp. 42–96. Boca Raton, CRC Press. https://doi.org/10.1201/9781003589600-2

Further offshore, the extreme heat triggered some of its most devastating impacts (Starko *et al.*, 2025). The heatwave saw the largest recorded outbreak of diatom toxic algal bloom. Toxin levels exceeded safety limits in human-consumed species by up to 14 000 percent (150 times). As a result, important bivalve and crustation fisheries (e.g. Dungeness crab) were closed, causing over USD 25 million in losses. Sea surface warming strengthened the thermocline barrier, which reduced the delivery of nutrients from subsurface waters by 50 percent. This reduction set in motion another cascade of impacts beginning with a restructuring of the phytoplankton and zooplankton food chain. Populations of some short-lived and opportunistic species (e.g. squid, shrimp and northern anchovy) rose in response to the altered food chain, but other important fisheries (Pacific cod and walleye pollack) collapsed. The cod population in the Gulf of Alaska fell by over 70 percent due to the combined impacts of increased metabolic demands from warmer water and reduced food availability, and as a result the fishery was closed. The impacts of the heatwave on other major fisheries (e.g. salmon) and their local food chain resources were observed to depend on the species, and the location and timing of heatwave. Overall, the heatwave had a negative impact on these fisheries as well. Fluctuations in these and important forage fish populations resulted in impacts on dependent species higher in the food chain. Deaths of seals and sea lions were recorded during and immediately following the heatwave. Around 7 000 humpback whales died and over 4 million common murres perished.

Global coastal areas, seamounts and ocean regions where cold, deep, nutrient-rich waters rise to the surface (upwelling zones) are among the most productive aquatic areas on the planet. Due to the shallower depths, these areas are highly vulnerable to extreme heat events. At the time of writing this report (2025), the world was in the midst of a 4th global coral bleaching event that began January 2023. This event, the largest to date, has affected 84.4 percent of the world's coral areas. Documented coral bleaching has been observed in 83 countries and territories (NOAA, 2025). The previous largest bleaching event, which occurred in 2014–2017, impacted 68 percent of the global coral areas. Bleaching events also occurred in 2010 and 1998. Coral is another critical foundation species, and its formations provide home to thousands of species that support reef-based fisheries around the globe. Following past bleaching events, coral in many areas quickly recovered, which gave a sense of optimism. However, in other instances they have not recovered. The trend towards increasingly frequent, longer and more intense bleaching events does not bode well for the future. In the context of current warming and the ongoing global coral bleaching event, it is believed (with greater than 99-percent probability) that the world has passed its first major ecological tipping point of which we are aware. Warm-water coral systems are in the process of exceeding their upper thermal maximum associated with 1.5 °C of global warming and will disappear (Lenton *et al.*, 2025).

When combined with changes in inland rainfall and reduced flow of ocean-going rivers, the evaporative power of extreme heat can contribute to the onset of devastating hypersaline events in saltwater and brackish estuaries. In Senegal's Casamance river, for example, the abrupt changes in freshwater discharge during the 1970–1980 drought led to the formation of hypersaline conditions in the river. Salinity rose to 90 parts per thousand (ppt), nearly three-times the normal concentration found in seawater. The hypersaline

BOX 7. Harmful algal blooms, salmon farming and marine heatwave in Chile

In Southern Chile, sea surface temperatures rose by 2 to 4 °C above average in 2016, triggering massive algal blooms that caused hypoxia and toxicity conditions in an area of concentrated aquaculture. As a result, an estimated 100 000 tonnes of farmed salmon and trout were lost, the largest aquaculture mortality event ever recorded (Mardones *et al.*, 2021). Economic damages exceeded USD 800 million. This event highlights the vulnerability of aquaculture systems to marine heatwaves, especially in high-density farming areas. It underscores the need for marine heat early warning systems, adaptive site selection, and ecosystem-based aquaculture management to strengthen climate-smart and disaster-smart fisheries.

Sources: **Mardones, J.I., Paredes, J., Godoy, M., Suarez, R., Norambuena, L., Vargas, V., Fuenzalida, G. *et al.*** 2021. Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016. *Science of The Total Environment*, 766: 144383. https://doi.org/10.1016/j.scitotenv.2020.144383 conditions resulted in the loss of all fish species in the areas most affected; a collapse in shrimp catch numbers, the retreat seaward (towards lower salinity) of oysters and cockles populations; blocked movement of migrant species travelling from the sea upstream by the warm and hypersaline water; and the death of large vertebrates (e.g. hippopotamus, crocodile and manatee) due to food shortages. Riverian flora was also greatly affected. Freshwater reed swamps (*Phragmites communis*) retreated 100 km upstream; *Rhizophora* mangrove totally disappeared; and only remnant communities of *Avicennia* mangrove (the most salt-tolerant species) survived far from the riverbanks, which remained bare years after the event, with further knock-on effects to species dependant on mangrove habitat (Savenije and Pagès, 1992; Claude, 1985).

Whether living in wild populations, or raised in aquaculture facilities, aquatic species are the most vulnerable of all to variations in temperature and the impacts of extreme heat due to their metabolic dependence on water temperature. The maximum sustainable yields of several wild fish populations are estimated to have decreased by 4.1 percent between 1930 and 2010 due to ocean warming, with some regions experiencing losses of 15 to 35 percent (IPCC, 2022a). Species in aquaculture installations have limited ability to seek refuge from warming water and are particularly vulnerable to the impacts of extreme heat. Higher temperatures and heatwaves can also lead to incidences of toxic algal blooms, disease and parasite outbreaks. These indirect impacts can result in catastrophic losses in aquaculture species (e.g. mussels, oysters, salmon) grown in confined, high-density systems (Lattos *et al.*, 2022; Gonzalez *et al.*, 2025). Species in smaller freshwater bodies (lakes and rivers) suffer in the same way, as waters become more eutrophic and hypoxic. Nutrient-poor lakes have become more nutrient-limited over recent decades, which has reduced their productivity (Jeppesen *et al.*, 2021), increased the stress on fish populations and elevated the potential for disease outbreaks.

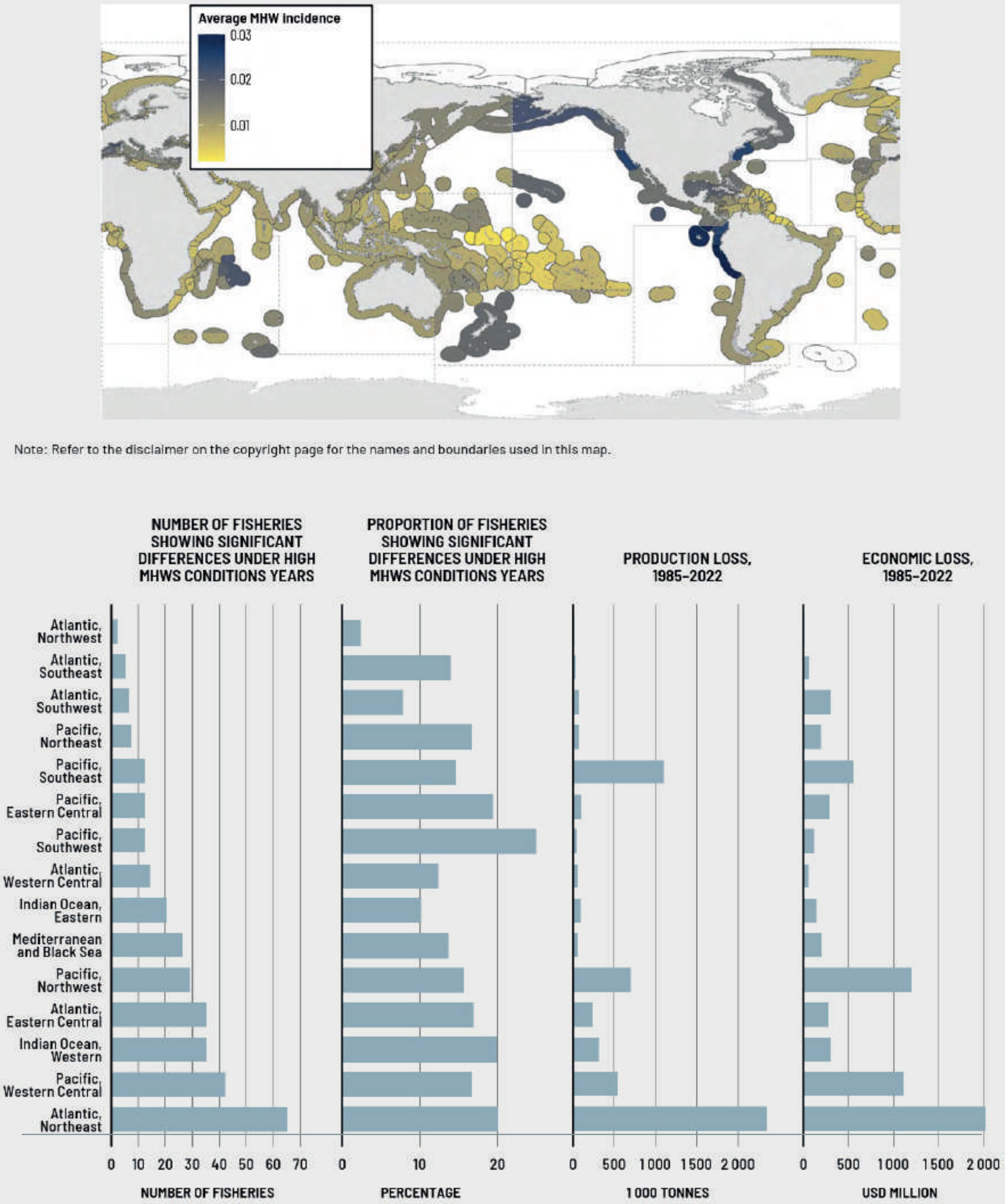
The global ocean dominates the planet's surface area (71 percent) and plays a pivotal role in the biological, geological, and chemical cycles that support all life. Historically, oceans have served as an important carbon sink, absorbing 25 to 30 percent of anthropogenic CO_2 emissions. Yet the strength of this important sink is changing. Ocean warming and marine heatwaves have a negative effect on CO_2 solubility and ocean currents, and a positive influence on thermocline stratification. The effects on ocean currents and stratification reduce the upwelling of nutrient rich subsurface waters (Venegas, *et al.*, 2023; Rallu de Malibran *et al.*, 2024). Cut off from sources of nutrients, ocean plankton populations have been in decline at a global scale (Silsbe *et al.*, 2025; Ryan-Keogh *et al.*, 2025). The decline in plankton populations can potentially alter oceanic foodwebs, and the biological carbon and oxygen cycles. Plankton produce at least half of all atmospheric oxygen, twice the amount coming from forests. Between 2003 and 2021, over half of the increase in global net primary productivity (NPP) in terrestrial systems, stimulated by warming and atmospheric CO_2 enrichment, was erased by the decline in ocean NPP (Zhang *et al.*,

BOX 8. Fisheries and marine heatwaves

An empirical analysis of the links between marine heatwaves and marine fisheries was undertaken at a spatial scale that combined Exclusive Economic Zones (EEZ) and the FAO definition of major fishing areas (FAO, 2025a). The analysis, which covered a period of 37 years (1985 to 2022), involved 2 088 fisheries throughout 128 regions and 108 countries. Production from countries fishing outside their EEZ was excluded. The study provided empirical evidence that marine heatwaves had an impact on 15 percent of fisheries and caused production losses of over 5.6 million tonnes. These losses were concentrated in the last decade of the study period (2013 to 2022). The economic losses due to the production shortfalls are USD 6.6 billion, of which USD 3.9 billion were from 2013 to 2022. The analysis showed that there was no clear link between areas with more marine heatwaves and the number or size of fisheries affected. Instead, the proportion of affected fisheries is relatively constant among regions. However, fisheries with the largest catches felt the impact more severely (see Figure 8).

Source: **FAO.** 2025a. *The Impact of Disasters on Agriculture and Food Security 2025 – Digital solutions for reducing risks and impacts*. Rome. https://openknowledge.fao.org/items/74d08f97-306a-4653-8ffe-140a2fc4d783

FIGURE 8. Marine heatwaves and fisheries



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Upper panel: Average marine heatwaves incidence per exclusive economic zone/marine fishing area. Lower panel: Impacts on fisheries per marine fishing area: Number (a) and proportion (b) of fisheries show significant differences under high marine heatwave conditions years, and production (c) and economic (d) loss for the 1983 to 2022 period.

At the national level, China, Denmark, Japan, and Norway account for over half of the global impact. Peru, one of the world's top fish producers, is also significantly affected. There is no clear pattern among the species most affected. Production and economic losses are more linked to the number of fisheries analysed than to species traits. However, herrings, sardines, and anchovies stand out in showing the greatest production decline, even though they rank fourth in the number of cases examined.

Source: **FAO.** 2025a. *The Impact of Disasters on Agriculture and Food Security 2025 – Digital solutions for reducing risks and impacts*. Rome. https://doi.org/10.4060/cd7185en

2025c). This decline in NPP, and the reduction in CO_2 solubility due to surface warming, affects the global carbon cycle and potential of future warming. Marine heatwaves also exacerbate fluxes of oceanic nitrous oxide (N_2O). Global oxygen minimum zones in the ocean are a major source of N_2O (Garçon *et al.*, 2019), with oceans responsible for approximately 22 percent of the annual global N_2O emissions. As an important feedback mechanism, it is predicted that an expansion of oxygen-depleted zones, exacerbated by marine heatwaves, will intensify global N_2O fluxes (Capone and Hutchins, 2013), further contributing to global warming and its related impacts on terrestrial and marine environments.

3.4.3 Projected impacts of extreme heat

The number of factors influencing how extreme heat affects individual aquatic organisms makes it particularly challenging to model three-dimensional marine ecosystem dynamics. Early projections of the impacts of climate change on the biosphere suggested long-term declines in the global animal biomass and that the impacts on fisheries will be unevenly distributed. More recently, an enhanced suite of global marine ecosystem models from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) was paired with new-generation earth system model outputs from CMIP6 to provide insights into how projected climate change may affect future ocean ecosystems (Tittensor *et al.*, 2021; Blanchard and Novaglio, eds., 2024). Compared with output from the previous generation of models, the new simulations show a greater decline (up to 30 percent) in mean global ocean animal biomass under both strong-mitigation and high-emissions scenarios. This is thought to be due primarily to the stronger ocean warming projected by some CMIP6 models. However, there are also large uncertainties in marine ecosystems models, with greater biomass declines projected by global versus regional marine ecosystems models for many regions (Eddy *et al.*, 2025). Moreover, the specific impacts resulting from temperature extremes on fish stocks, fisheries, and dependent people were generally not considered in the assessment, or at least not separately quantified.

Through the use of an integrated climate-biodiversity-fisheries-economic impact model, it has been projected that for any occurrence of an annual high temperature extreme in an exclusive economic zone, there will be an average decline in biomass of 77 percent in exploited fishes and invertebrates, with the maximum catch potential dropping by 6 percent (Cheung *et al.*, 2021). The decrease in biomass and shifts in the distribution of fish stocks due to marine heatwaves is projected to be at least 300 percent (four times) faster and larger in magnitude than the effects of mean temperature changes through the twenty-first century, with a 100 percent increase in impacts projected by 2050 amongst the most important fisheries (Cheung and Frölicher, 2020). Heatwaves and increased temperatures are predicted to also impact fish disease pressures, potentially affecting all trophic levels of the marine environment, although the trends are more complex. While temperature stress negatively affects fish immune functioning, and may increase pathogen virulence, changes to the ranges of pathogens and hosts may also result in the uncoupling of host-pathogen pairs (Cohen *et al.*, 2018).

Fish in freshwater systems have been largely ignored in climate change assessments. However, assessments have been carried out on the threats of future flow and water temperature extremes on approximately 1 500 riverine fish species (Barbarossa *et al.*, 2021). At 3.2 °C of global warming above a preindustrial baseline, 36 percent of freshwater species will have over half of their present-day geographic range exposed to climatic extremes beyond current levels. The largest threats are found in tropical and subarid regions. Increases in maximum water temperature were found to be more important drivers than changes in flow extremes. In comparison, only 9 percent of the species are projected to have more than half of their current geographic range threatened in a 2 °C warmer world. The difference between impacts resulting from high- and low-emission projections reinforces the importance of making progress in climate change mitigation to reduce the future negative consequences from extreme heat.

3.5 Forests, plantations and orchards

3.5.1 Vulnerabilities to extreme heat

As immobile, long-lived species, trees and forest ecosystems are notably vulnerable to the effects of extreme heat. The composition of today's mature forests is a reflection of past climate regimes that have long since been altered by rising baseline temperatures and exposure to increasingly severe and long-lasting extreme heat events. Extreme heat has impacts on trees from the cellular to ecosystem level. Forests are approaching and at times exceeding critical physiological tolerances (Hartmann *et al.*, 2022; Hammond *et al.*, 2022; Duffy *et al.*, 2021). Unconstrained by soil-moisture availability, trees exposed to increasing temperatures, like other plants, increase their rate of transpiration. The evaporation of moisture through leaf stomata cells is the primary means by which plants dissipate heat. The rates of photosynthesis and respiration also increase with higher temperatures. As the duration and magnitude of heat exposure continue to rise, but still at sublethal levels, the rate of photosynthesis reaches a maximum and begins to decline in response to cellular biochemical changes and the build-up of toxic oxidative compounds (Zhao *et al.*, 2020; Mondal *et al.*, 2023). While a great deal of diversity exists between species and within populations, at the leaf-level the upper temperature threshold for photosynthesis for trees have been measured at greater than 40 °C for temperate species and greater than 45 °C in tropical species. However, biome-level measurements show a decline in peak photosynthesis at much lower temperatures, with a global average of 23.6 °C (18 °C for C_3 species and 28 °C for C_4 species)[2] (Teskey *et al.*, 2015; Slot *et al.*, 2021; Huang *et al.*, 2019; Duffy *et al.*, 2021).

In contrast, transpiration, and particularly respiration, continue to increase with temperature. Leaf-level respiration reaches its maximum at temperatures up to 40 °C to 60 °C depending on the species, whereas average biome measures peak at a notably lower level (26.6 °C) (Niu *et al.*, 2024b; Duffy *et al.*, 2021; Liu *et al.*, 2025). The growing energy imbalance created by the decline in photosynthesis at high temperatures and continued increase in respiratory energy loss, slows tree growth and weakens their overall health. Sustained exposure to extreme heat leads to a breakdown in cell membranes and cell death, resulting in scorched leaves, loss of foliage, branch and crown dieback and eventually the death of the whole tree (Teskey *et al.*, 2015). The increase in respiration and lowered photosynthesis also leads to decreased carbon assimilation, which reduces the ability of forests to sequester CO_2 from the atmosphere, with implications for the global carbon cycle.

The timing of when extreme heat events occur during a tree's life cycle, and the timeframe over which impacts are observed, can vary widely. As with other organisms, trees are highly sensitive to extreme heat when they are young. Due to their short stature, seedlings can suffer high mortality rates during extreme heat events as surface temperatures of exposed ground can greatly exceed ambient air temperature (Teskey *et al.*, 2015). Among temperate zone species, extreme heat events that occur early in the spring can affect trees throughout the growing season, perhaps linked to the lifetime of individual leaves, while the same magnitude events occurring later in the growing season are less damaging, suggesting some degree of potential acclimation, but this is not true of all species (Teskey *et al.*, 2015; Kullberg and Feeley, 2024; 2022). Leaves exposed to extreme heat, however, have been observed to have reduced photosynthetic capacity after exposure. Affected trees produce fewer leaves and show slower growth up to two years after an extreme heat event, which indicates a protracted recovery period (Teskey *et al.*, 2015). Leaf damages caused by temperatures below 40 °C to photosynthetic capacity are thought to be reversable, but those resulting from exposure to temperatures greater than 40 °C may be permanent.

The impacts of extreme heat events on the productivity and quality of tree and forest products are most studied for fruit and nut species and mirror many of the impacts noted for annual crop species. Depending on the species and the stage of development when extreme heat events occur, the impacts of extreme heat can vary. Fruit and nut species originating from temperate environments require a minimum chilling period, measured in chilling hours (e.g. below 7.2 °C), to break their winter dormancy and initiate reproductive development. The required chilling hours range from less than 100 to more than 1 000 depending on the species and variety. Failure to accumulate sufficient chilling time can delay vegetative development, compress the flowering and pollination window and reduce yields. During the critical reproductive period extreme heat stress can result in reduced and asynchronous flowering, flower drop, reduced pollination and fertilization, causing significant yield loss (Li *et al.*, 2023a; Yang and Chen, 2024; Wang *et al.*, 2025b). Heat events that occur after reproduction is completed can result

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[2] As noted, C_3 grains are plants that produce a three-carbon compound during photosynthesis, whereas C_4 plants produce a four-carbon compound, which enables them to thrive in hot, dry, and sunny conditions with higher water-use efficiency.

in reduced fruit and nut set, fruit that is deformed and undersize, shrivelled nuts, increased fruit drop, fruit with colour loss and that is sunburned and scorched, with altered sugar, acid and organoleptic qualities, reduced vitamin content and reduced storage potential (Li *et al.*, 2023a; Yang and Chen, 2024; Wang *et al.*, 2025b). A common optimal temperature of fruit and nut species productivity is between 30–32 °C. Temperatures above 35 °C cause damage and yield loss in a wide range of fruit (e.g. apple, cherry, peach), nut (e.g. hazelnut, macadamia, walnut) and plantation crops (e.g. cacao, coffee, oil palm).

As with field crops, the impact on trees and forests from extreme heat events are greatly magnified by reduced water availability. High temperatures raise atmospheric evaporative demands, leading to higher rates of moisture loss through transpiration and evaporation from soils. A reduction in the availability of soil moisture, coupled with a faster rate of moisture loss through transpiration, places trees under stress. In severe cases, they may experience xylem cavitation (where air bubbles enter tree sap under extreme moisture stress) (Cochard, 2006), which increase the potential for cellular and whole leaf damage. Widespread tree mortality events are often the result of the compound effects of extreme heat and drought stress. The nature of the damage is shaped by the health status of the forest and the sequence, magnitude and duration of stresses (Hartmann *et al.*, 2022; Hammond *et al.*, 2022).

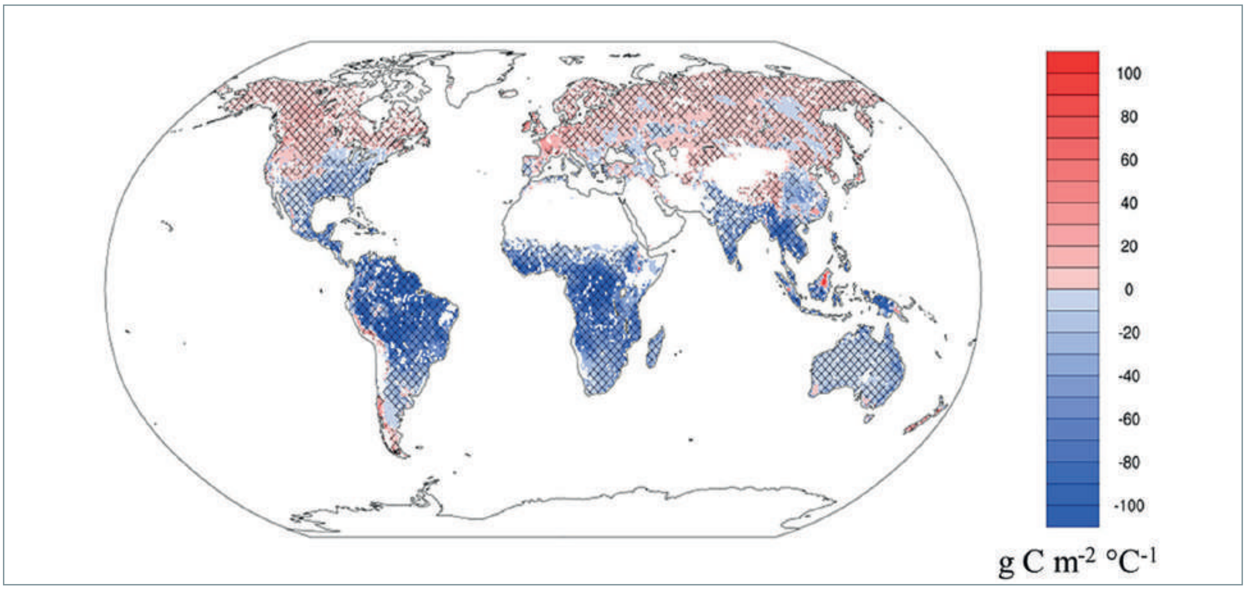
By weakening trees, extreme temperatures can make individual trees more susceptible to insect pest attacks and disease. As noted in the sections on crops and livestock, the ongoing rise in baseline temperatures leads to lower mortality rates of temperate zone insect pests during the winter period. In addition, a longer growing season and faster development of individual organisms in a warmer environment can result in more reproductive cycles per season. The combined outcome from these forces is the potential for greatly increased levels of pest damage and a higher likelihood of diseases spreading (Bhagarathi and Maharaj, 2023). In addition to weakening host species, extreme heat events can also negatively affect insect pest, pest-predators and disease vector species, which makes the projection of outcomes challenging. More certain is the increase in fire risk due to extreme heat events. Prolonged heatwaves dry potential fuel sources, elevating fire risk, especially when combined with drought conditions, low humidity and higher wind speeds. Set against a backdrop of an increasingly long fire season in temperate zones, high temperatures are associated with more ignitions, larger fires and deeper burns (Wasserman and Mueller, 2023; Jain *et al.*, 2022).

3.5.2 Observed impacts of extreme heat

Trees, whether in natural forests, plantations or orchards, have observed limits with regards to tolerance of the stresses applied by extreme heat. Currently, broad-based evaluations of observed impacts from extreme heat on vegetative communities are limited. However, the evaluations that have been conducted have detected the impacts of extreme heat on vegetation globally (see Figure 9) at annual and monthly time scales (Pan *et al.*, 2020; Yang *et al.*, 2023). Compared with other types of individual extreme event stressors (e.g. low temperature, an excess or deficit in precipitation and soil moisture, and high vapour pressure deficit), the independent impact of extreme heat on tree growth is less pronounced in these studies, exceeding only high vapour pressure deficit in severity. In contrast, when included in definitions of compound events (e.g. high temperature and low soil moisture, or high vapour pressure deficit), the visible impacts of high temperatures are among the most widespread and severe. The assessed low significance of extreme heat by itself is in some ways not surprising. The use of temporal and spatial accounting units longer (e.g. monthly average temperatures) and larger (e.g. 15 X 15.05 grid cells) than extreme heat events themselves negates the ability to capture the true intensity of events through temporal and spatial dilution. Risks also exist in losing sight of heatwaves altogether through the potential division of 'hot days' from a single event across successive accounting periods. In addition, likely mismatches between the use of statistical definitions of extreme heat (e.g. one standard deviation above mean) and the biological thresholds of individual species limits the ability to align temperature data records with remote sensing observations on biological responses.

Examining the impacts of individual heatwaves provides perhaps most the accessible view into the *in situ* responses of trees to extreme heat, and the critical interplay between extreme heat and moisture stresses (e.g. Fleishman *et al.*, 2025). One such event occurred

FIGURE 9. **Sensitivity of terrestrial carbon fluxes**



Note: map shows the averaged results of the 19 simulations. Stippling indicates locations where over 75 percent of the simulations have the same sign (positive or negative) of sensitivity.
Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: **Pan, S.** ***et al.*** 2020. Climate Extreme Versus Carbon Extreme: Responses of Terrestrial Carbon Fluxes to Temperature and Precipitation. *Journal of Geophysical Research: Biogeosciences*, 125(4): e2019JG005252. https://doi.org/10.1029/2019JG005252

in the northern hemisphere summer of 2021, when one of the strongest heatwaves ever recorded struck southwestern Canada and northwestern United States of America (Thompson *et al.*, 2022). Peak temperatures during the heatwave rose to four standard deviations above normal, setting consecutive daily records, with little night-time cooling (Thompson *et al.*, 2022). The heatwave established a new global temperature record above 45° latitude and impacted an area of over 3 million km^2 (Fleishman *et al.*, 2025; Sang and Hamann, 2023; White *et al.*, 2023). Deemed a 1-in-1 000-year event, the heatwave is thought to have been 14 900 percent (150 times) more likely due to climate change. The area impacted was 34 percent larger, the duration 59 percent longer and the maximum temperature 6 percent higher than would have been the case in the absence of climate change (Mckinnon and Simpson, 2022; Philip *et al.*, 2022; Jain *et al.*, 2024). Remote sensing analysis and ground survey revealed that 40 percent of the area impacted showed signs of leaf and needle scorch damage. The south- and west-facing sides of trees with the greatest sun exposure showed the most damage (Sang and Hamann, 2023; Still *et al.*, 2023).

The high temperatures lead to elevated atmospheric vapour pressure deficits, drying vegetation and soil. This situation created a feedback loop where dry soil conditions contributed to the record heat as more of the sun's energy radiated from soil surface as sensible heat, rather than being dissipated through moisture evaporation. In areas of the Amazon, this feedback loop with exposed soils has been found to increase the local effects of background warming by over 300 percent (factor of four) due to varying levels of forest cover loss, with the effects observed to extend up to 100 km from areas of deforestation (Butt *et al.*, 2023). In the case of the 2021 heatwave, however, not all areas affected by extreme heat were especially dry, nor were trees in the hottest areas most severely impacted (Fleishman *et al.*, 2025). Trees showing the greatest damage were predominantly species from the Pinaceae family located within old growth coastal forests historically protected from extreme heat by the cooling maritime influence (Still *et al.*, 2023; Sang and Hamann, 2023). The observed dominance of these characteristics underscores the importance of species-specific vulnerabilities and histories of prior short- and long-term heat exposure.

In addition to the impacts of the 2021 heatwave on natural forests, perennial orchard and plantation crops also suffered severe damages. The area impacted by the heatwave is the leading fruit producer in Canada, and the leading producer of apples, sweet cherries and processed raspberries in the United States of America. In Canada, fruit yields for sweet cherries, plums, grapes and raspberries declined by two standard deviations from yield projections prior to the heatwave, and the yields of apples, nectarines, peaches and pears declined more the one standard deviation (White *et al.*, 2023). In the United States of America, raspberry and blackberry yield losses ranged from 60 to 100 percent across locations, and there was an average 2.4 percent reduction in apple yields (Preston *et al.*, 2024). Blueberry yield losses ranged from none to nearly 100 percent, depending on the location. Christmas tree plantations of newly planted noble fir suffered yield losses of 70 percent, with other species less impacted. Overall, Christmas tress production was reduced by 5 to 10 percent (Kowalski, 2021). Losses across all locations depended on orchard and plantation position, especially elevation, the species or varieties planted, the fruit or tree developmental stage at the time of the heatwave, and what adaptation measures might have been undertaken by growers.

The impacts of the 2021 heatwave are characteristic of those found in other heatwave events worldwide. Heatwaves have been linked to a 30- to 50-percent reduction in forest gross primary productivity (a proxy for the removal of atmospheric carbon) (Ciais *et al.*, 2005; Bastos *et al.*, 2014; Yuan *et al.*, 2016). One of the most documented aspects is the relationship between extreme heat, vegetative drying and the incidence of wildfires. For example, the 2021 heatwave in North America contributed to a 21- to 24-percent increase in the area burned that year (Jain *et al.*, 2024). More generally, over the past two decades (2001–2019), 26 to 29 percent of global forest-cover loss has been attributed to wildfires (Tyukavina *et al.*, 2022), while the frequency of extreme fire events (≥ 99.99th percentile) increased by 120 percent from 2003 to 2023 (Cunningham *et al.*, 2024). Six of the most extreme fire years have occurred within the last seven years of this period. The two hottest years yet recorded, 2023 and 2024, saw the rate of forest cover lost due to wildfire increase by 130 percent. In North America the rate of forest cover loss increased by 270 percent; in Latin America, 240 percent; and in Africa, 140 percent (Potapov *et al.*, 2025).

Studies have examined global changes in fire weather, using various fire weather index driven by meteorological inputs of precipitation, relative humidity, temperature and wind speed. These studies have found that climate change generally, and rising trends in high temperatures and reduced relative humidity specifically, to be the dominant meteorological factors associated with the observed increased frequency and intensity of severe fire weather days (Abatzoglou *et al.*, 2025; 2018; Fan *et al.*, 2023). The findings from these studies are consistent with observations on the trends in rising global temperatures, decline in wind speeds, decline in relative humidity over land, and variable trends in precipitation (e.g. Kim and Johnson, 2025; Tahroudi, 2025; Deng *et al.*, 2022). Analysing data on the incidence of fire and meteorological variables for 1979–2013, researchers detected a nearly 20 percent (18.7) increase in the global mean fire weather season length. This increase contributed to a doubling of the burnable area exposed to long fire weather seasons, with a 50 percent increase in the frequency of longer fire weather seasons observed in the second half of the data record. Temperature was found to be a leading factor in these changes (Jolly *et al.*, 2015). The increase in fire weather season length, number of extreme fire weather days and annual fire weather maximum have been confirmed in other studies. Overall, there has been a 100-percent increase in extreme fire weather seasons (one year in 15) for 46 to 65 percent of the world's forested areas compared to the pre-industrial period (Quilcaille *et al.*, 2023; Abatzoglou *et al.*, 2025).

Few studies have attempted to single out the specific role of extreme heat events on increased fire occurrence (e.g. Still *et al.*, 2023; Hegedüs *et al.*, 2024). However, climatic conditions (e.g. high-pressure atmospheric blocking patterns) are one of the leading causes in heatwave formation and atmospheric drought and have been found to be closely associated with intense wildfire outbreaks (Sharma *et al.*, 2022; Jain *et al.*, 2024; Hegedüs *et al.*, 2024). In northern latitudes, large fires (greater than 500 ha) have been found to be up to 600 percent more likely to start in the presence of atmospheric blocking patterns (Sharma *et al.*, 2022; Little *et al.*, 2025). Heatwaves forming under such patterns not only dry vegetation, but the increased atmospheric convective activity associated with high temperatures also leads to increased lightning strikes (Hegedüs *et al.*, 2024; Jain *et al.*, 2024). Lightning strikes are the leading cause of fire ignition in higher latitudes (Janssen *et al.*, 2023). Once ignited, the convection column from large wildfires can lead to the formation of pyro-cumulonimbus events, which greatly increases lightning activity. One of these events emerged from a fire started during the 2021 North American heatwave, which generated 50 000 cloud-to-ground lightning strikes over an eight-hour period, leading to the ignition of several additional fires (Jain *et al.*, 2024). Thus, the atmospheric conditions most conducive to the formation of heatwaves, also leads to increased fuel-load flammability and elevated fire ignition risks, and creates the possibility that fires, once ignited, evolve into self-propagating extreme fire events.

In some regions, indirect impacts of rising temperatures may be contributing to further elevating wildfire risk. According to AR6 WGII, global warming has caused increased insect pest outbreaks in northern temperate and boreal forests (IPCC, 2022a). Continued warming has allowed some insects, such as species of bark beetle, to greatly expand their geographic range to more northernly latitudes and higher elevations (Jaime *et al.*, 2024). Warmer winters have led to fewer cold-season mortalities, while earlier springs and later autumn have lengthened the beetle's growing season. These factors, combined with the accelerate development due to higher growing season temperatures, have enabled beetles to produce additional generations in a single season resulting in greater predation pressure on forests. Trees, weakened by extreme heat and moisture stress (see Figure 10) have lower defences and are more easily overwhelmed by insect attacks. As infested trees weaken, then die, they contribute to forest fuel loads, which elevates the risk of more intense surface fires and the potential for rapid spreading crown fires (Gaylord, 2014). As noted in the case of other host-pest relationships, host species, pests and their predators, all have upper thermal limits at their various stages of development, which can be surpassed during heatwaves.Determining the outcome of extreme heat exposure is ultimately one of identifying the thermal thresholds of the principal organisms involved.

Overall, the increase in forest cover loss due to wildfire has led to an equally significant increase in carbon emissions from fires. Global carbon emissions from wildfires increased by 60 percent between 2001

BOX 9. Wildfires and extreme heat in Portugal

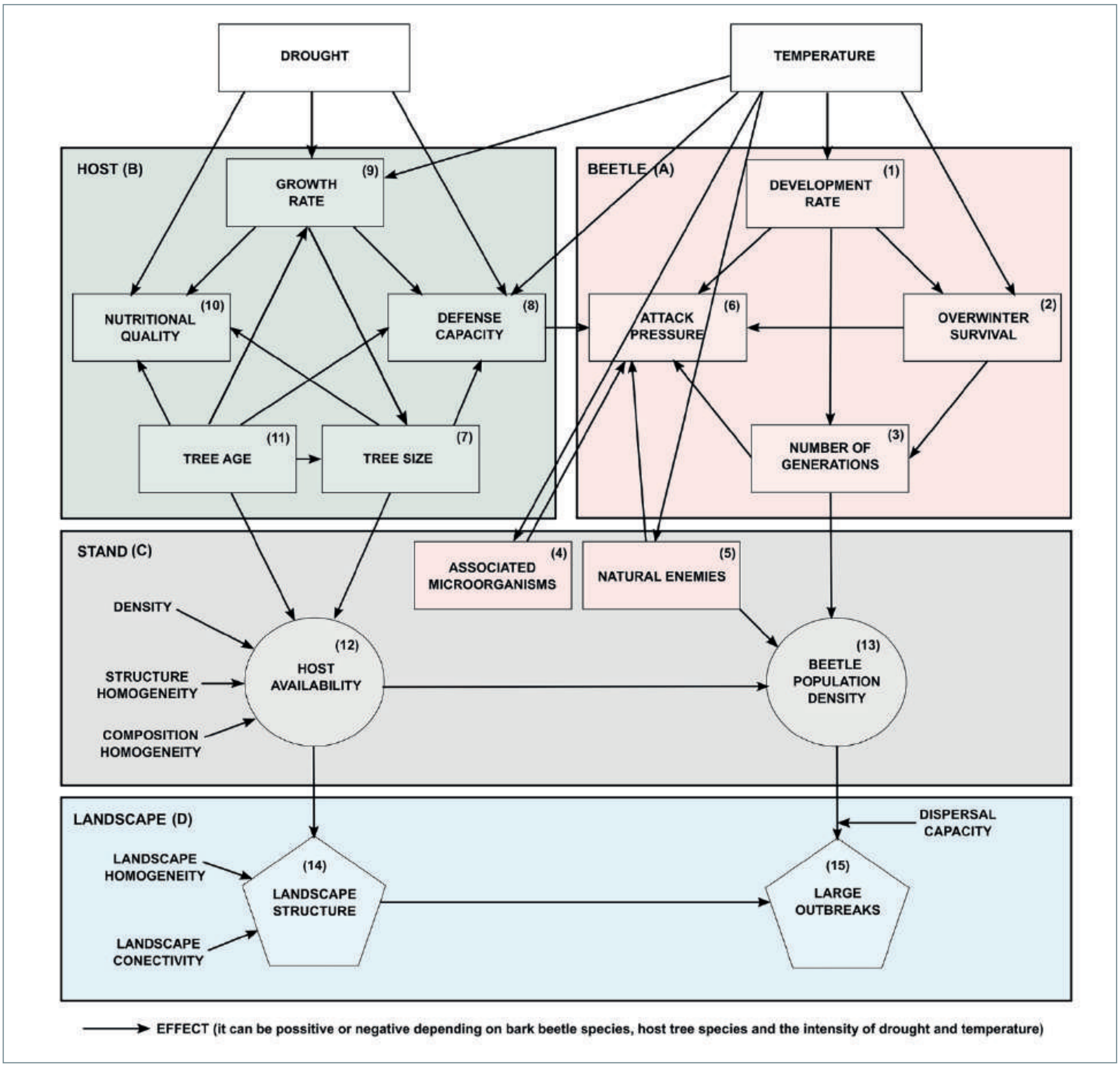
Portugal experienced a catastrophic fire season in 2017. A record 540 000 hectares burned, 60 percent of the total area burned in Europe that year (Ramos *et al.*, 2023). Tragically, there were 116 fatalities. The economic losses totaled nearly USD 1.2 billion, making it the costliest natural disaster in the country's history, with USD 295 million in insurance industry payouts.

There were two serious fire events in the 2017 fire season (17–20 June and 15–17 October; Pinto *et al.*, 2018). These events were characterized by anomalous high temperatures compounded by low humidity and strong winds. It is noteworthy that both events occurred outside of the official fire season, typifying the global trend towards longer fire seasons under climate change. The 2017 wildfires led to efforts undertaken by the entire government that resulted in an innovative national policy for integrated fire management; a set of guiding principles, goals, and governance proposals, for adjusting strategies, policies; and the adoption of a landscape fire governance framework.

Extreme heat is not solely responsible for extreme wildfire behavior, but it can serve as a warning signal along with other meteorological conditions associated with wildfire risk. Adaptation and mitigation strategies include the use of fire danger rating models with meteorological forecasts to provide early warning, enhanced fire prevention programmes, and fuel management in high-value and high-risk areas.

Sources: See References.

FIGURE 10. **Bark beetle-host climate relationship**



Source: **Jaime, L., Batllori, E. & Lloret, F.** 2024. Bark beetle outbreaks in coniferous forests: a review of climate change effects. *European Journal of Forest Research*, 143(1): 1–17. https://doi.org/10.1007/s10342-023-01623-3

and 2023 (Jones *et al.*, 2024). This period also witnessed important changes in the type, intensity and location of wildfires. Globally, there has been a 26-percent decline in the annual extent of areas burned by wildfires (2002-2021). This decline has been driven primarily by the decrease in savanna fires related to agricultural expansion (Seydi *et al.*, 2025). In contrast, the percentage of annual forest cover loss due to fire has increased, rising to 44 percent in 2024, nearly double what it had been two decades prior (MacCarthy *et al.*, 2025). Most of this increase has occurred in the great boreal forests of North America and Eurasia, where wildfires have increased by 200 percent (Jones *et al.*, 2024). The amount of carbon release per area burned has risen by 50 percent, indicating an increase in fire severity (Jones *et al.*, 2024). The number of extreme fires in northern Eurasia, for example, account for only 10 percent of all fires, but are responsible for 30 percent of the carbon released (He *et al.*, 2025a). Globally fires in intact forests, representing 1.2 percent of the global area burned, contribute 8.5 percent of the total carbon emissions from fire (Van Wees *et al.*, 2022). The rise in emissions from forest fires since

2000 (Zheng *et al.*, 2021) can be seen as part of a terrestrial feedback loop involving GHG emissions, rising temperatures and extreme heat events, forest fires, further GHG emissions and global climate change. As a possible glimpse of future conditions, the first example of a forest transitioning from a net carbon sink to emissions source has been recently documented in Australia (Carle *et al.*, 2025). The rise in extreme temperatures was identified as a leading driver in this transition.

3.5.3 Projected impacts of extreme heat

The projected impact of rising global temperatures on the rate of forest growth shows a range of potential outcomes through the end of the twenty-first century. Measured as changes in gross primary productivity (GPP) or net primary productivity (NPP), studies broadly agree on increasing tree growth through mid-century under different emission scenarios (e.g. SSP1–1.9 and SSP5-8.5). Increases are expected to be particularly pronounced in the high-latitude coniferous forests of the Northern Hemisphere in areas where tree growth is constrained by cold. In the latter half of the century, however, studies diverge in their projections. The divergence results from differences in the methodologies, datasets, and assumptions used regarding future forest responses under alternative emission scenarios. Projected outcomes range from continued increases in productivity (e.g. Fang *et al.*, 2024) to a declining, but still positive, increase in the rate of growth under most emission scenarios (except SSP3–7.0) and forest types (e.g. Yuxi *et al.*, 2024), to projections showing the transition to negative growth rates across the Northern Hemisphere's temperate and boreal forests occurring at different time intervals and latitudes under both low- and high-emission scenarios (Zhang *et al.*, 2022). The projected increase in forest growth rates in these studies is based on the observed positive response of forest growth to rising temperatures and atmospheric CO_2 concentrations in recent decades, as well as assumptions on tree acclimation to evolving climate regimes through the end of the century.

One implication of forests showing potential negative growth is that they will transition from being a carbon sink to becoming a net carbon source. For example, in northern South America, 7 percent of the region is projected to experience an abrupt forest dieback event for each degree of temperature rise above 1.5 °C of global warming (e.g. Parry *et al.*, 2022). However, a full collapse of the Amazon Forest is thought to be unlikely in the twenty-first century (e.g., Chai *et al.*, 2021). The impact of extreme heat events can be assumed to be included in the projected overall changes noted in the referenced studies. However, none of the studies attempted to single out the direct impacts of changes in the frequency, duration or severity of extreme heat, heatwaves, compound events, or the associate changes to regional fire regimes.

One of the findings of studies that do examine the future impacts of extreme heat on forests is that under all emission scenarios except SSP1–2.6, forest sensitivity to extreme heat will continue to increase in line with the growing frequency of extreme heat events through the end of the century (Yang *et al.*, 2024). Under the low-emission scenario forest sensitivities initially rise, then stabilize around the 2050s, before declining slightly in the 2090s. The identified sensitivities reflect forest productivity gains in northern latitudes and higher elevations, and declines in the tropics (e.g. Yuan *et al.*, 2021; Yang *et al.*, 2024). The projections of extreme losses in GPP, due either to excesses or deficit in precipitation and temperature, show that under the low-emission scenario (SSP1-2.6) productivity losses increase then stabilize around the 2050s, whereas losses continue to intensify to the 2090s under the high-emission scenario (SSP5-8.5) (Gao *et al.*, 2024). Although the frequency of extreme loss events declines slightly under both emissions scenarios towards the end of the century, the duration of events and magnitude of losses continue to increase under the high-emission scenario to 2100. For both emission scenarios and time periods, the role of extreme high temperature (over the 90th percentile) as a single driver of these events in markedly lower than that resulting from precipitation deficit. However, when considering the impact of compound events, extreme high temperature combined with precipitation deficit (hot-dry) is the most dominant driver, accounting for 51 percent of the total extreme GPP loss events under SSP1–2.6 and 48 percent under SPP 5–8.5. The impact of hot-dry compound events is more than double the impact of the highest individual driver (Gao *et al.*, 2024). As with studies considering impacts of extreme heat events in the observational period, studies that look forward rely on average monthly climate data, calling into question their ability to adequately identify extreme heat events that are typically of shorter duration.

The rise in wildfire risk is also linked to the potential increase in damages from extreme heat and compound hot-dry events. A global study of historical (1850–2014) and projected (2015–2100) trends in fire weather was undertaken using the Fire Weather Index (FWI) of the Canadian Forest Fire Danger Rating System (Van Wagner, 1987) and included the full ensemble of 28 CMIP6 earth system models, daily meteorological data and eight future emissions scenarios. The study found robust (greater than 80 percent model agreement) increases across all the indicators assessed (Quilcaille *et al.*, 2023). Reported in terms of degrees Celsius of warming, maximum FWI seasonal values are projected to increase by 37 percent under 1 °C of warming, and by 120 percent with 3 °C of warming. The number of days per season with extreme fire weather is projected to increase by 120 percent with 1 °C of warming and up to 400 percent under 3 °C of warming. The number of extreme fire weather days were projected to increase globally, reaching a global average of 28 days per year with 3 °C of warming. Similarly, the seasonal FWI average is projected to increase by 56 percent with 1 °C of warming and up to 250 percent with 3 °C of warming. The length of the fire season is anticipated to increase by 300 percent with 1 °C of warming and up to 1 400 percent with 3 °C. The global average length of the fire season is projected to increase to 45 days. The examination of severe events (defined as occurring at a frequency of once every ten years) found robust increases across all indices, with no declining trends. The number of days of extreme fire weather and length of the fire season show particularly strong increases. The number of days of extreme fire weather increased by 192 percent, and the length of the fire season increased by 177 percent. Regionally, North America, northern South America, Europe, southern Africa and Australia are projected to be most impacted. These findings are consistent with other studies using indices based on daily maximum temperature and precipitation that found an increase in the frequency and level of fire risk days (Gannon and Steinberg, 2021; He *et al.*, 2025b). Areas such as the western United States of America, Australia and the Amazon have been projected to experience increases of over 60 high risk days per year by mid-century, which, for some locations, is over double their historical baseline. A global study examining historical and projected trends in compound weather conditions and fire risk found that the increased frequency of days with extreme temperature and reduced relative humidity were the major drivers associated with the projected increasing trends in extreme compound fire weather days (Fan *et al.*, 2023). The prospect of increasing emissions from wildfires and the previously noted potential decline in productivity gains have obvious implications for the global carbon cycle and efforts to reach net-zero emissions by 2050. There is a particularly worrying possibility that increasing numbers of wildfires in the northern boreal forest could destabilize the carbon stored in the region’s permafrost (Natali *et al.*, 2021).

In addition to the potential impacts of reduced forest growth and wildfire loss, extreme heat has important long-term effects on forest composition through its influence on species’ suitable habitats. Referred to through climate or habitat suitability indices, structured around abiotic factors, the suitability of species’ habitats is primarily a reflection of the annual temperature and precipitation regimes. In cool climates, the effect of global warming results in suitability zones generally shifting poleward and to higher elevations, whereas in areas of the tropics forests transition from moist to dry forest types (Mauri *et al.*, 2022; Boonman *et al.*, 2025; Zhang *et al.*, 2023). In temperate and boreal environments, temperature extremes and associated disturbances are the primary drivers in pushing species out from locations where they once prospered along the trailing edge of suitability domains in transition. The rise in maximum low temperatures is largely responsible for opening up new areas on the leading edge of expanding suitability domains (e.g. Dyderski *et al.*, 2025). Changes in forest composition, however, occur at the biological pace of the dominant species involved and are subject to the influences of local climate refugia, soil conditions (especially ph), hydrologic regimes, natural and human physical barriers and disturbances (e.g. Lima *et al.*, 2024). In the case of temperate and boreal forests of North America, the pace of temperature change in inducing a northernly shift in the suitability zone of dominant tree species is estimated to be 900 to 9 000 percent (10 to 100 times) faster than the rate at which trees species are thought capable of migrating (Government of Canada, 2025). Estimations of tree migration potential is derived from consideration of a species' age at reproductive maturity, the time required to establish associated reproduction requirements, the frequency of good seed years and the means of seed dispersal in determining how far a species might 'travel' in a single generation. The same forces that influence the redefinitions of the suitability zones of species in natural forests also challenge the continued propagation of tree species in managed production systems.

The projected impacts of extreme heat directly affecting the productivity of orchard and plantation species are multifaceted. Measured in terms of impacts on productivity aligned with exceedance of cardinal temperature thresholds, orchard and plantation species face a variety of threats from temperature extremes throughout their growth cycle. For temperate fruit and nut species, for example, the accumulation of adequate chilling hours during the cold-season dormancy period is essential for normal reproduction in the following season. For plantings of species currently at the cold limit of their range, projected warming will allow further expansion and create opportunities for the introduction of new species (e.g. Sun *et al.*, 2022; Qian *et al.*, 2025; Sugiura *et al.*, 2024). For species located at the warm limit of their range, projected warming will lead to range retraction, rendering traditional production areas non-viable for continued production (e.g. Egea *et al.*, 2022). In the United States of America, for example, warming in California's central valley, which produces over half of the country's perennial fruit and nut production, projected warming will reduce areas suitable for production of major products (e.g. apricot, peach, plum, chestnut, pecan, walnut) to between 78 to 10 percent of the total area. Depending on the climate scenario, the areas suitable for some species (e.g. cherry, apple, pear) will be reduced to zero (Luedeling *et al.*, 2009). As species approach their minimum chill requirement threshold, incidents of extreme heat occurring during the dormancy period have increasingly serious impacts. Failure to meet a species' chill requirement in more than 10 percent of years is thought to render production economically non-viable (Luedeling *et al.*, 2011; Luedeling, 2012).

In both temperate and tropical environments, extreme temperatures during the main growing period have major implications for the future viability of traditional tree crop production areas. Research into the projected temperature impacts on widely grown commodities (e.g. bananas, cocoa, coffee and tea) found that by 2050 (2041–2070), the production of the 1.6 million small scale-farmers farmers across the tropics who participate in global Fairtrade supply chains will be negatively impacted by heatwaves under both medium- (RCP 4.5) and high- (RCP 8.5) emission scenarios (Malek *et al.*, 2022). There will be a reduction and a shift in the areas suitable for production, with some crops (e.g. banana) projected to lose 50 percent of its range. Other studies have found that coffee will also suffer a 50-percent reduction in suitable areas (Bunnet *et al.*, 2015). There will also be significant changes in the suitability ranges for coconut, oil palm, and rubber (Appelt *et al.*, 2023). In general, yield losses and increased yield variability can be expected, along with the potential for increased insect pest pressures and incidence of disease. Unlike large-scale and corporate producers, small-scale farmers have limited ability to shift their production to new areas that are less affected and will see their yields decline as conditions around them change.

Studies on of the impacts of extreme heat on the pest and diseases of orchard and plantation species are generally carried out at the level of individual species at national and subregional scales. Important tree crop pest species (e.g. coffee berry borer and olive fly) have been projected to significantly increase their range under future warming scenarios (e.g. Jaramillo *et al.*, 2009; 2011; Gutierrez *et al.*, 2009). The range of major diseases (e.g. banana black sigatoka and fusarium wilt) are also expected to expand (Malek *et al.*, 2022). As noted in previous sections, the potential for indirect extreme heat impacts from insect pests and disease outbreaks are influenced by multiple causal factors including the health status and unique temperature thresholds of host species, pest species, pest-predators and competitors, and disease vector species and pathogens (e.g. Raju *et al.*, 2024). The net effect of responses to temperature change can both accelerate or diminish the likelihood of incidence of outbreaks, making the projection of impacts highly uncertain (IPPC Secretariat, 2021). The uncertainty in outcomes is highlighted in a meta-analysis of research on the projected impacts of warming on 31 herbivorous insect pest species (annual crops and trees) where 41 percent of species show signs of a likely increase in damage; 4 percent show decline; and 55 percent show signs of both potential increases and declines (Lehmann *et al.*, 2020).

3.6 Agricultural workers

3.6.1 Vulnerabilities to extreme heat

The nature of agricultural labour means that workers are often exposed to extreme weather conditions. Extreme heat is a serious health issue for outdoor and indoor workers across the agricultural subsectors (crops, livestock, fisheries and aquaculture and forestry), including workers engaged in the post-production stages of agrifood value chains. Symptoms of heat exhaustion include heavy sweating, weakness, muscle spasms, dizziness, nausea, and headaches. If not addressed, heat stress can progress to dehydration, loss of consciousness, heatstroke and death (Flouris *et al.*, eds., 2024). Repeated exposure to heat stress over time can increase the risk of cardiovascular issues, kidney damage, and other long-term health problems. Agricultural workers who spend long periods of time outdoors and in non-air-conditioned indoor facilities may face higher risks of heat stress (e.g. El Khayat *et al.*, 2022). Elderly workers, pregnant women and their unborn children, children, and people with pre-existing medical conditions are particularly vulnerable (Rekha *et al.*, 2024). Workers who wear heavy clothing or thermal insulation for protective purposes (e.g. against agrochemicals) or those who are not provided with adequate hydration, rest, and cooling breaks are also more vulnerable than others. Labour

BOX 10. Extreme heat, food security, and nutrition in Pakistan

In the rain-fed rural areas of Punjab, Pakistan, increasingly frequent and severe heatwaves are disrupting agricultural systems and undermining household food security. A study by Habib *et al.* (2022) highlights how these events, identified by local communities as their main climate hazard, are resulting in cascading negative impacts on livelihoods heavily dependent on agriculture and livestock.

The effects of extreme heat on production are stark. Heatwaves have led to significant declines in crop yields. In high-rainfall zones of Punjab, fruit productivity has fallen by as much as 50 percent. Livestock are also severely affected. Large ruminants produce less milk under heat stress, and small ruminants face increased outbreaks of foot-and-mouth disease. The loss of agricultural output directly translates into reduced household income and diminishes the ability of families to purchase food. The problem is compounded by the accelerated spoilage of vegetables, dairy products and other perishable goods. Spoilage further reduces food availability and drives up local prices. Consequently, households face a dual burden: they obtain less diverse and nutritious food from their own production, and their reduced agricultural income does not purchase as much at markets. This double burden severely limits their access to healthy diets.

Although entire communities are affected, women generally bear a disproportionate share of this burden. Rural women in Punjab are deeply involved in harvesting, water collection and other physically demanding domestic tasks. As a result, they face high exposure to extreme heat and increased risk of heat-related illnesses. These health risks are particularly acute for pregnant and lactating women who have greater dietary needs that are often the first to be compromised during periods of food scarcity. Research indicates that each 1 °C rise in temperature is associated with a 4 percent increase in the likelihood of preterm birth, and the risk jumps to 26 percent during heatwaves (Lakhoo *et al.*, 2025).

Additional social inequalities exacerbate women's vulnerabilities to extreme heat. Despite their critical role in farming, women often lack ownership of land and other assets, necessary to access credit and financial services that could aid adaptation. With limited access to climate information and early warning systems, they are often less prepared to respond to heat events. Their coping strategies, such as reducing their own food intake to prioritize other family members, which can further compromise their health and resilience, reflect broader patterns of gender discrimination that amplify their vulnerability in times of climate crisis (Lecoutere *et al.*, 2023).

Sources: See References.

intensity and the lack of access to cooling resources can exacerbate the symptoms of heat stress, and the chances of heat stroke.

Agriculture workers in tropical and subtropical latitudes are at higher risk of heat stress due to a combination of extreme temperatures and the high share of agriculture in total employment (Flouris *et al.*, eds., 2024). Meteorological conditions such as high humidity, low wind speed and high solar radiation can exacerbate heat stress. Work-related factors that further exacerbate the risk of heat stress among agriculture workers include the performance of intensive manual labour; piece-rate payment that can induce agricultural workers to work beyond safe and healthy limits and avoid taking breaks to rest or hydrate; and the lack of control over workplace health and safety practices that ensure adequate access to water, shade or rest breaks. These factors, when combined with periods of high temperature and humidity, make sweating, the principal mechanism for regulation of the human body temperature, less effective, and places workers at higher risk to health problems. In terms of mortality, agricultural workers were found to be 3 400 percent (35 times) more likely to die from occupational heat exposure than other workers, according to an analysis in the United States of America (El Khayat *et al.*, 2022; Gubernot *et al.*, 2015).

The time-sensitive nature of agricultural labour (e.g. the need to conduct outdoor activities even during usually warm periods) can make the avoidance of heat stress risk extremely difficult. In countries that rely heavily on agriculture for their economies, the avoidance of heat stress has implications for farm productivity, the incomes of individual agricultural workers, and the broader national economic well-being.

3.6.2 Observed impacts of extreme heat

A variety of studies have looked at extreme heat and its impacts on agricultural workers in terms of mortality, productivity, and other indicators. Heat exposure not only affects the health and well-being of agricultural workers but also their ability to work, which reduces labour productivity. The 2025 WMO-World Health Organization (WHO) report, *Climate Change and Workplace Heat Stress*, indicates that worker productivity drops by 2 to 3 percent for every additional degree above 20 °C. The 2022 Lancet Countdown report which looked at change in labour capacity as an indicator, found that during 2021, high temperatures reduced global potential labour hours by 470 billion, a 37-percent increase compared to the average annual loss that occurred during the 1990s (Romanello *et al.*, 2022).

Occupational heat exposure especially affects labourers in the agricultural sector of low-income countries. In countries with a Human Development Index score below 0.550, the vast majority of labour hour losses (87 percent) were in the agricultural sector (Romanello *et al.*, 2022). Agricultural work that requires hand harvesting with minimal access to mechanical equipment place workers at higher risk for heat stress. For example, sugarcane harvesters from Costa Rica, El Salvador, Nicaragua, and Thailand, have reported heat stress impacts (Boonruksa *et al.*, 2020). A study by Amoadu *et al.* (2023), which reviewed the impact of heat stress on workers, found that migrants, refugees, pregnant women and children were extremely vulnerable to heat stress. Their vulnerability was due primarily to lack of autonomy and worker-supervisor power imbalances that limited workers' access to hydrating fluids, breaks, toilet facilities and shade. In sub-Saharan Africa extreme heat can drive both adults and youth out of agricultural work and into non-agricultural work (FAO, 2025b). Migrant labourers and members of ethnic minorities that work outdoors have been found to be at high risk of heat-related vulnerability (Van Selm *et al.*, 2025). In a study that covered 43 countries from different regions, it was found that during the period 1991–2018, 37 percent of the warm-season heat-related deaths could be attributed to human-induced climate change (Vicedo-Cabrera *et al.*, 2021). The health of female agricultural workers is at particular risk from heat-related illnesses including heat cramps, heat edema, heat syncope, heat exhaustion and heat stroke. (Wheeler and Nye, 2025; Flocks *et al.*, 2013).

A review by El Khayat *et al.* (2022) that focused on agricultural workers and heat stress impacts identified the following risk factors: dehydration, heat strain (body's response to heat stress), inappropriate clothing, excessive workload, piece-rate payment, and hot environmental conditions. The extreme heat impacts are felt more by women. Female agricultural workers are often paid by piece. As a result, women avoid using restrooms, limit their water consumption, and experience frequent chronic delayed urination, which increase the risk of kidney diseases. Also, sanitation facilities in agricultural workplaces are often lacking or inadequate, which can discourage women from using them out of fear of sexual harassment or assault thus making them more vulnerable to heat stress. Heat stress damages the kidneys through repeated episodes of dehydration that reduces blood flow to the organs and activates harmful physiological responses, ultimately leading to chronic kidney disease (Chang and Yang, 2023). Kidney disease and heat-related illness are observed particularly in hot regions such as sub-Saharan Africa, the Middle East and North Africa, and Southeast Asia.

In a global study, Diaz *et al.* (2023), using wet-bulb temperature as an indicator, found that rice and maize crop farmers experienced the greatest increase in exposure to extreme heat. It was 1.8 times greater for rice farmers and 1.9 times greater for maize farmers for the 2001–2019 period compared to 1979–2000. The most vulnerable regions were Southeast Asia, equatorial South America, the Indo-Gangetic Basin, coastal Mexico, and the northern coast of the Gulf of Guinea.

A systematic review by Habibi *et al.* (2024) on heat stress of outdoor workers across various locations globally has found a lack of awareness about adaptation strategies and interventions for preventing and enhancing resilience to heat stress among workers in outdoor tropical and subtropical environments. An analysis by Wang *et al.* (2025a) of 1.2 billion social media posts from 157 countries found that temperatures above 35 °C make people's outlook 25 percent more negative in lower-income countries and 8 percent more negative in wealthier ones, which suggests extreme heat has an impact on mental as well as physical health.

Recent studies have indicated a possible connection between forest loss and the impacts of extreme heat on people. Tropical deforestation, which induces local warming, elevates heat stress in people, and reduces safe outdoor working hours, has resulted in an estimated 28 000 heat-related deaths per year across the tropics during 2001–2020; totaling more than half a million deaths over the two decades reviewed in the study (Reddington *et al.*, 2025). In regions of forest loss, local biophysical warming from deforestation may contribute to over one-third of the total climate heat-related deaths.

3.6.3 Projected impacts of extreme heat

The impacts of heat stress on agricultural workers are only expected to get worse. According to the AR6 WGII (IPCC, 2022a; Foster *et al.*, 2021), the number of days with climatically stressful conditions for outdoor workers could increase to 250 days per year by the end of the twenty-first century in some regions (e.g. much of South Asia, tropical sub-Saharan Africa and parts of Central and South America) under SSP5-8.5, while there will be small increases in South Asia and West Asia under the SSP1-2.6. In these estimates, conditions are considered climatically stressful when physical work capacity is less than 60 percent based on average daily air temperature and relative humidity. Physical work capacity is defined as the maximum physical work output that can be reasonably expected from an individual performing moderate-to-heavy work in a 'cool' reference environment of 15 °C.

In one of the most comprehensive reviews of heat stress and labour, Dasgupta *et al.* (2021) provide a global overview of the projected effects of temperature on labour supply and productivity. Under future warming, the agriculture and construction sectors are projected to experience the greatest losses in labour supply (working hours) and labour productivity (performance) compared to other sectors. Under a 3 °C warming scenario, there will be a decline in the combined measure of labor supply and productivity of approximately 33 percent in Africa, 25 percent in Asia and 17 percent in the Americas due to increasing heat stress. Combined changes in the number of hours worked (e.g. work stoppage during hot spells or the hottest hours of the day) and the productivity of the workers will have profound consequences for long-term economic growth and inequality.

Nelson *et al.* (2024) projected the impacts of extreme heat on agricultural physical work capacity, where 100 percent is equivalent to the work capacity possible with no heat stress, and zero percent indicates no work being possible due to heat stress. They found that by the end of the century (2081–2100), under the SSP5-8.5 pathway, labour capacity during the growing season will be reduced to 70 percent or less in Southeast and South Asia, West and Central Africa, and northern South America. In the worst affected areas, such as the Indo-Gangetic plains (Pakistan and India), average growing season physical work capacity (i.e. expected labour output) could fall below 40 percent. Under the SSP1-2.6, projected labour capacity would be 81 percent by the end of the century, with respect to 86 percent for the recent historical period used in the study (1991 to 2000).

Labour productivity, particularly in developing countries, will be a key factor in determining overall crop productivity, profitability and sustainability. Past studies on crop productivity under climate change consider extreme heat and other biophysical impacts on crops but not labour productivity responses to heat stress. Consequently, earlier studies likely underestimate the full impacts of climate change on crop productivity. More recently, studies (e.g. Sheng *et al.*, 2025) project that global agricultural labour productivity could decrease by 18 percent under RCP 6.0 by the end of the century, with Africa, South Asia, and Southeast Asia experiencing the greatest declines. Impacts on agriculture productivity resulting from crop and labour responses to climate change have been found to be highly sensitive to the choices of labour-heat response functions and global climate models, resulting in a 13-percentage point difference in global heat-induced labour productivity loss between lower and higher projections by 2100. In another study, heat stress associated with an additional 3 °C of global warming (relative to the 1986–2005 baseline) could reduce labour capacity and contribute to annual global losses of USD 136 billion and a 5 percent increase in crop prices due to higher labour cost and production losses (De Lima *et al.*, 2021).

BOX 11. Extreme heat stress on agricultural workers – impacts in Africa

A forthcoming FAO study has examined the changes in the number of agricultural workers under extreme heat stress globally. The findings from Africa indicate that the number of agricultural workers who are exposed to extreme heat stress is projected to increase over the next few decades. In West Africa, the number of workers exposed to extreme heat stress for the majority of the cropping season (June to August), which is climatologically rainy and relatively mild in terms of temperature within the year, will increase by 78 percent by mid-century under a high GHG concentration pathway compared to the current baseline. In East Southern Africa, during the cropping season that extends from December to February, the number of workers exposed to extreme heat will increase by 83 percent. In Central Africa, where the cropping season north of the equator extends from June to August, the number affected workers will more than double (greater than 118 percent). These rapid rates of increase across Africa reflect the accelerating pace of climate change. The growing population in the region and the projected increase in the number of farm workers (more than 12 percent in West Africa; more than 11 percent in Central Africa; and more than 6 percent in East Southern Africa) account for a minor part of the increase. The results underline the rapidly increasing number of agricultural workers in Africa under heat stress, and the need for adaptation measures as well as reduction in GHG emissions.

BOX 12. Compound events and cascading impacts in Morocco

Morocco's agricultural sector, which contributes around 10 percent to the national GDP, is dominated by rainfed cultivation, and is highly vulnerable to climate extremes. Climatic conditions from 2022 to 2024 were among the most challenging in recent history. While the country grappled with the compound impacts of a prolonged six-year drought a series of successive intense heatwaves struck. According to the *Etat du Climat Maroc 2024* (DGM, 2024), Morocco experienced multiple long-duration heatwaves during this period that broke numerous daily and monthly temperature records. Notable events included an exceptional 11-day heatwave in March 2023 and a 10-day event in July 2024. Temperatures during these heatwaves were among the highest ever observed for these months, with peak temperatures frequently exceeding 40 °C, which significantly amplified crop and livestock stress and elevated wildfire risk.

The dual challenge of extreme heat and water scarcity, brought on by the protracted drought, caused widespread agricultural losses. Cereal yields dropped precipitously, falling by 43 percent in 2023–2024 to a historic low. Wheat production fell to its lowest level in over 15 years. High-value perennial crops were also hit hard. Prolonged heatwaves and high night-time temperatures caused fruit drop and reduced oil content in olives. Citrus production and exports saw a significant decline. For livestock, the combination of direct heat stress and heat-induced forage shortages affected animal health, and reduced milk yields and meat productivity. In response, many farmers reduced planting areas or abandoned crops entirely, particularly in rainfed zones, which increased economic losses and household vulnerability in rural areas.

The severe climatic events triggered far reaching secondary impacts that cascaded through interconnected systems. Morocco's forests faced severe damage, with extreme heat and drought driving catastrophic wildfires. In 2022, a record 22 760 hectares burned, primarily in the Rif Mountains. The most critical consequences, however, were due to the compound impacts on water resources. By the summer of 2024, the combination of prolonged drought and intense heat-driven evaporation led to some of the lowest levels ever recorded in dam reservoirs and groundwater tables. The unprecedented decline in stored water severely disrupted the national water distribution system. The resulting conditions led to critical shortages for drinking water and forced widespread restrictions on irrigation, which had knock-on effects in terms of crops losses. Overall, these events underscored the vulnerability of Morocco's interconnected natural ecosystems and agricultural systems to intensifying climate extremes.

Source: **DGM** (Direction Générale de la Météorologie) [General Directorate of Meteorology]. 2024. *État du climat Maroc 2024 [State of Climate Morocco 2024]*. Casablanca, Morocco, DGM. https://www.marocmeteo.ma/fr/climat-2024

BOX 13. Compound events affecting cattle in Australia

Heat stress in livestock has been acknowledged by the animal industries as both a production and welfare issue for decades, particularly where cattle producers operate in warm and semi-arid climates. A number of issues have forced cattle producers, livestock and climate researchers to focus on managing heat stress in cattle. Areas that have been studied include the increase in climate variability and more frequent and extreme weather events; the increase in numbers of cattle housed in feedlots and the expected growth in feedlot numbers; and increased societal oversight of animal welfare (Brown-Brandl *et al.*, 2003; Wijffels *et al.*, 2013).

Both sustained periods of hot weather and abrupt heatwaves induce heat stress in livestock. However, because of the differences in animal responses to these two distinct phenomena, different management interventions are required to address them. In either case, unacclimatized animals, feedlot animals close to market weight, and high-producing dairy cows are particularly vulnerable (Hahn, 1999). The effects of extreme heat on livestock can be greatly compounded by simultaneous high levels of humidity.

The mass mortality event that occurred at a feedlot in the town of Texas, Queensland Australia, in February 1991 is a clear example of the hazard posed by a compound hot-humid event affecting livestock. A sharp increase in relative humidity, from 40 percent to 80 percent, occurred over two days. Humid conditions were further magnified by a lack of wind. Temperatures at the time ranged between 20 °C and 30 °C. Temperatures of this magnitude, are by themselves within cattle's ability to tolerant. However, on 8 February, due to the combination with extreme humidity and calm air, these temperatures were enough to send the heat load index to a value of 95 (out of 100), exceeding the 99th extreme percentile. Overall, 2 600 cattle, mainly Angus and Hereford breeds, died at the cattle feedlot during this event.

Sources: See References.

BOX 14. Compound impacts of extreme heat in Kyrgyzstan

In 2021, Kyrgyzstan experienced multiple severe heat events, first in the spring and again during a prolonged heatwave in July and August. According to Kyrgyzhydromet (the Hydrometeorological Service under the Ministry of Emergency Situations of the Kyrgyz Republic) maximum temperatures reached 41 °C in the Chuy, Batken and Jalal-Abad regions, 5 to 12 °C above the seasonal average. The summer heatwave lasted for up to 14 consecutive days. During this period, there was minimal night-time cooling. The heatwave was accompanied by a severe drought, which was further exacerbated by low reservoir levels and reduced river flows. The temperatures, well above historical norms, led to a sharp increase in evaporation and a critical reduction in the availability of irrigation water. Analysis of temperature anomalies from the Bishkek station confirmed the impact of the heatwave, which was visible in the remotely sensed Vegetation Health Index across the entire country.

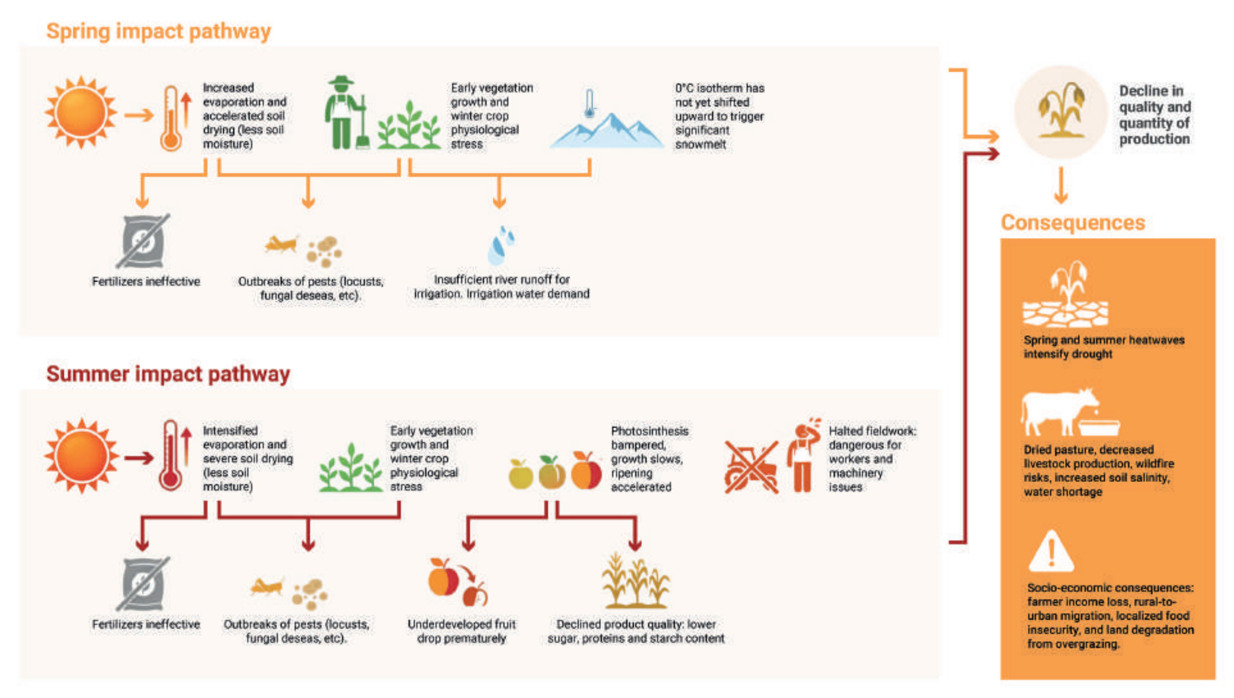
The agricultural impacts were devastating, particularly in the Chuy Valley and the northern regions of the country. Farmers reported complete crop failures in some areas, especially for maize, melons, and vegetables. Estimates indicated substantial yield reductions for key commodities. Wheat and barley yields declined by up to 40 percent in the Chuy and Talas Oblasts, and maize and potato production dropping by 25 to 35 percent. Livestock were also severely affected. Heat stress led to reduced milk production and increased mortality, particularly among small ruminants on lowland pastures. The broader environmental and social consequences included severe irrigation water shortages, with river flows in parts of the Naryn Basin decreasing by 15 to 20 percent (Vinokurov *et al.*, 2023). These pressures reportedly contributed to rising rural-to-urban migration, localized food insecurity, and land degradation from overgrazing on drought-affected pastures.

The chain reaction of impacts created by the heatwaves are depicted in Figure 11. The timing of each heatwave critically determined the nature of the damages created. In early spring, extreme heat led to a critical mismatch between water demand and supply. Higher temperatures accelerated an initial vegetation green-up but also enhanced evaporation and the rapid drying of soils before temperatures in the mountains had risen sufficiently to generate adequate snowmelt. As a result, river runoff remained below irrigation needs, inducing early-season moisture stress in crops. Farmers were forced to apply fertilizer under unfavourable conditions. Without adequate soil moisture, fertilizers cannot be absorbed effectively, which wastes critical inputs. In contrast, the extreme heat that occurred later in the growing season was sufficient to suppress photosynthesis, which slowed crop growth and accelerated ripening. This resulted in underdeveloped fruits and notable yield losses, and made fieldwork hazardous during peak heat periods.

The sequential heatwaves in 2021 are becoming an increasingly frequent pattern in Kyrgyzstan. The early-season depletion of water reserves due to elevate temperatures, followed by subsequent periods of summer heat intensifying irrigation demands, produces acute water deficits, and amplifies drought conditions. Evidence from Kyrgyzhydromet shows that drought in Kyrgyzstan is not simply a result of low precipitation but is being driven by temperature-induced water loss. Thus, extreme heat acts as a powerful amplifier of drought, magnifying its socio-economic consequences across the entire agricultural sector.

Source: **Vinokurov, E., ed.** 2023. *Efficient Irrigation and Water Conservation in Central Asia*. Reports and Working Papers 23/4. Almaty, Kazakhstan, Eurasian Development Bank. https://eabr.org/upload/iblock/632/EDB_2023_Report-4_Irrigation_eng.pdf

FIGURE 11. Impact pathway of extreme heat on agriculture in Kyrgyzstan



Authors’ own elaboration.

BOX 15. Compound events and compound outcomes of extreme heat in India in 2022

Indian agriculture continues to be vulnerable to weather extremes despite being self-sufficient in grain production. Heat waves cause physiological damage to crops, animals, poultry and fish; reduces water availability; increases demand of water and energy and reduces work efficiency. According to the report, *Heat Wave 2022: Causes, impacts and way forward for Indian Agriculture*, published by the Indian Council of Agricultural Research (ICAR) and Central Research Institute for Dryland Agriculture (CRIDA), March and April 2022 were the warmest months on record in India (Bal *et al.*, 2022). During this period, extreme temperatures were 8 to 10.8 °C higher than normal and rainfall was 60 to 99 percent below normal in 10 out of 36 meteorological subdivisions. That year will also be remembered as a classic example of the combined impacts of high temperatures and reduced rainfall felt throughout India's agricultural production systems, specifically in northern and central India. The abnormal increase in maximum and minimum temperatures during 2022 affected crops, fruits, vegetables and livestock and poultry in over one-third of India's states, including Punjab, Haryana, Rajasthan. Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, Madhya Pradesh, Bihar and Maharashtra.

Wheat yields were reduced by 9 to 34 percent. For maize, stunted growth and a fall armyworm attack led to yield reductions of up to 18 percent. The impacts on chickpeas included poor vegetative growth and poor pod set, wilting and shrivelling of grains.

The impacts of the heat on fruit crops were numerous. For apple and plum trees, there were viral infections and petal fall in both royal and spur type apples and low fruit set in plums. For lemons, there were drying of trees, high incidence of insect pests, sunburn, less fruit set, flower, and fruit drop.

The impact of the heat was particularly high for vegetables. Cabbage and cauliflower suffered from poor vegetative and stunted growth and a reduction of yields up to 50 percent compared to normal. For tomatoes, there were reductions in plant canopy, severe flower and fruit drop as well as forced ripening of fruits, fruit burning and sunscald resulting in yield reductions of 40 to 50 percent.

For dairy animals, the increased temperatures led to increased calf mortality and skin infections. The heat also contributed to a loss appetite and higher body temperatures, which led to reductions in milk yield of up to 15 percent.

For poultry, there was reduced egg production of up to 10 percent in laying hens during the initial two days of heat wave, and production remained four to 7 percent lower during the subsequent days. There was also increased mortality rates of layers up to 3.5 to 4.0 percent per month versus the regular monthly mortality rate of 0.5 percent. Another impact of the acute heat stress was the suppression of the birds' immune system which led to disease outbreaks.

Source: **Bal, S. K., Prasad, J.V.N.S. & Singh, V.K.** 2022. *Heat Wave 2022: Causes, impacts and way forward for Indian Agriculture*. Technical Bulletin No. ICAR/CRIDA/TB/01/2022. Hyderabad, India. The Indian Council of Agricultural Research (ICAR) - Central Research Institute for Dryland Agriculture (CRIDA). https://doi.org/10.13140/RG.2.2.15040.20482

4. ADAPTATION OF AGRICULTURE TO EXTREME HEAT

4.1 Types of technical adaptation options

The principal aim of adaptation action is to reduce the exposure and vulnerability of both natural and human systems to damaging weather events through informed decisions and by enhancing individual and collective capacities to respond. The IPCC, however, warns that adaptation efforts across most sectors and regions continue to rely on minor modifications to current practices and that, faced with intensifying climate extremes, including extreme heat, many human systems and coupled human-natural systems are approaching, or have already exceeded, their adaptive limits given current capacities (IPCC, 2022a).

Numerous adaptation strategies have been implemented in the agricultural sector, but they often address extreme heat only implicitly, considering it as a component of a broader set of climate-related challenges. Consequently, there are relatively few strategies designed specifically to address the direct and compound threats of extreme heat as a primary hazard. This historical focus means that despite the increasing frequency and severity of heatwaves, and damages from rising temperatures generally, the threats emanating from extreme heat have not been systematically evaluated on their own terms in policy settings and planning fora. Furthermore, there is limited evidence as to the effectiveness of various adaptation options in reducing risks that are specifically heat-related across the agricultural sector despite the fact that temperature (heat) is the primary controller of most organisms and biological systems.

Reviews have identified a range of technical agricultural adaptation options and other broader non-technical risk management strategies in response to extreme heat (e.g. Parent and Tardieu, 2012). These options include: the introduction of tolerant crop varieties and livestock breeds; water and soil management practices; farmer training and knowledge transfer; agrometeorological services and early warning systems; financial schemes and risk insurance; and migration (e.g. Grigorieva *et al.*, 2023; FAO, 2021; Alvar-Beltrán *et al.*, 2021).

Technical adaptation options can be organized into three general categories of adaptive actions that serve to reduce vulnerability to the growing threat of extreme heat by altering exposure or sensitivity (Simpson, 2016; FAO, 2021). The first category involves the use of genetics, the inherent traits of varieties, breeds and species, to avoid or reduce the threats posed by extreme heat. Options in this category include the cultivation of varieties or crops with shorter or longer maturation periods, to avoid the occurrence of acute stresses that may align with critical stages in crop development during the growing season (e.g. reproduction and grain filling). Another option involves switching varieties or crops, or livestock breeds and species to those that better tolerate or even thrive under the emerging weather patterns. This may even involve switching from crops to livestock.

The second category are adaptation options that involve altering the production environment. Adaptation actions in this category change how certain features of the farm function so that critical stresses can be avoided, reduced or eliminated. Technologies range from adding simple shade structures to reduce livestock exposure to the sun during hot periods, to investments in irrigation to eliminate drought stress and improve the tolerance of crops to heat stress.

The third category of adaptation options are knowledge-based management decisions. These options are distinct from the other options but often support changes in the way genetic resources and environmental features on the farm are used. Examples of options in this category include adjusting planting dates to avoid potential extreme heat exposure during critical stages of crop develop later in the season and changing livestock feeding times to cooler periods of the day to ensure that animals' digestive metabolic heat load does not peak during the hottest part of the day. Knowledge-based management decisions greatly benefit from access to agrometeorological advisories and seasonal forecasts of potential extreme heat so that farm managers can plan for and undertake adaptive actions. For human safety and health under extreme heat, the International Labour Organization (ILO) has sectoral instruments that provide guidance, such as the Safety and Health in Agriculture Convention (No. 184; ILO, 2021a) and its Recommendation (2001; No. 192; ILO, 2021b). These instruments cover occupational safety and health measures to be implemented in the agricultural sector, and include the establishment of a national surveillance system, risk assessment, policies, and preventive and control measures (e.g. shades, rest breaks, drinking water, clothing, adjustments in working hours).

In support of these technical adaptation options, there are a range of financial services and other mechanisms that can reduce household financial risks and compensate household for losses. These additional adaptive options include cash transfers, insurance and payment schemes, and longer-term migration plans. Access to financial services underpins all categories of adaptation options. Small-scale producers often lack risk finance and can become trapped in downward spirals of disaster and poverty. Shock-responsive social protection schemes, contingency funds, savings and loan mechanisms, and risk-sharing arrangements can help protect livelihoods, reduce vulnerability, and enable investment in adaptation measures. Risk insurance further supports resilience by removing the risk of income loss and reducing uncertainty, thereby encouraging producers to adopt improved seeds, technologies, and climate-smart practices that reduce their vulnerability to and possible impacts of extreme heat events.

4.2 Timescales of technical adaptation options

Along with financial risk reduction and compensation measures, the categories of technical adaptation options (genetic, environmental, and knowledge-based management) and the mechanisms through they work (avoidance, reduction, removal) provide a framework for working with farmers to navigate the challenges of responding to threats posed by extreme heat (FAO, 2021). To guide the systematic identification of viable adaptation actions, these categories and mechanisms can be combined into a matrix and used to query the range of possible actions to alter the exposure and sensitivity of an agricultural system to extreme heat in developing national adaptation frameworks. Higher-level policy decisions, however, require another perspective that includes consideration of the temporal and spatial scale of options for investment planning purposes. Policy planning involves three general timeframes:

- tactical (short-term),
- strategic (medium-term) and
- transformational (long-term) (see Table 1).

Consideration must also be given to the areas with greatest vulnerability and the geographic concentration of production activities, and the necessary phasing of actions, including the

Table 1. Adaptation matrix for extreme heat in the agriculture sector

Technical options	Tactical	Strategic	Transformative
Genetic	Using available varieties with shorter or longer maturation periods to avoid periods of heat stress	Developing new stress tolerant varieties and breeds	Planning shifts in concentrated zones of production; switching to different, unaffected species
Environmental	Altering use of different fields and pastures (e.g. higher elevation) to avoid heat stress locations	Adding on-farm irrigation for crops, shade, fans, wind breaks for livestock, and aeration of fishponds	Investing in largescale irrigation systems and temperature-controlled indoor production units
Management	Planting earlier or later in the season; altering feed composition; feeding during cool periods of the day; following the guidance from climate and agrometeorological information services	Optimizing the diversification of crop and species	Ceasing production of affected species; abandoning affected locations

identification and removal of barriers to ensure that all non-technical enabling conditions are in place.

Tactical actions are short-term response interventions to emergent conditions. Tactical interventions are characterized by their need for immediate action within the course of a single season, or period between successive seasons. Actions often involve knowledge-intensive responses that have high-impact outcomes. Tactical actions tend to rely on local or immediately accessible resources and are aimed mainly at implementing quick fixes. Less attention is given to resolving the root causes of vulnerability. By definition, tactical responses are not amenable to direct policy interventions. However, they are strengthened through strategic investments in education, training, early warning information systems, other support services and safety nets.

One of the most effective tools for supporting farmers in responding to intra-seasonal events are agrometeorological advisory services that can inform farmers on pending extreme heat conditions and their potential compound impacts. Early warning systems integrate agrometeorological data with forecasting tools to issue timely alerts and advisories to farmers, livestock producers, and fisherfolk. The design of an early warning system relies on four essential elements:

- risk knowledge (i.e. hazard prediction, as well as exposure and vulnerability);
- detection and monitoring (i.e. verification);
- warning dissemination and communication (i.e. decision support); and
- preparedness, anticipation and response capabilities (i.e. short-term adaptation).

To be effective, early warning systems must have the appropriate resolution, domain and outputs; their accuracy and reliability must be verified against observations; and the forecasts must be relevant for risk-informed decision making, interpretable by end-users, and delivered in a practical format. Ultimately, the forecasts and agrometeorological advisories must be used wisely, which requires agencies issuing advisories to clearly communicate the forecasts' uncertainties and the full range of plausible outcomes to users (e.g. Pacchetti *et al.*, 2023). Operational agrometeorological advisory services can enhance farmers' ability to make smart on-farm management decisions during heatwaves and other weather events. However, extreme heat events can exceed farmers' ability to respond, especially in the short-term and in the case of novel compounding events. In these instances, anticipatory actions (see Box 16) can reduce the impacts on agriculture and livelihoods from serious extreme heat events.

Strategic actions involve moving beyond immediately available and known technologies, services and capacities. Strategic actions require planning, investment and a shift in perspective that includes an increased consideration of anticipated threats. Strategic investments focus on broadening and deepening resilience within the framework of existing socioeconomic systems. Implementation is typically carried out over a 3 to 10-year timespan. Examples of strategic investing include:

- Investments in changes in school curriculum to improve awareness of the health and productive dangers of extreme heat;
- investments in climate services to communicate relevant information and warnings on extreme heat events and responses; and
- investments in agricultural research to support development of new varieties, breeds and management practices that are more tolerant and responsive to extreme conditions.

Transformative actions involve particularly large-scale investments in novel technologies. These actions may require changes to core socioeconomic systems that demand concerted actions in policies and programmes spread over a decade or more. Transformative actions involve not only making changes in the way things are done, but increasingly doing different things. Examples include making whole-sale changes in the crop, tree or livestock species grown, even in how food is produced; investing in large-scale landscape restoration and rehydration projects; fundamentally changing market structures, national grain reserves, land tenure systems; and perhaps even changing the way farm labour is conducted. These actions have the greatest capacity to directly address the underlying drivers of vulnerability and can be assumed to require large investment budgets, careful analysis of the breadth of potential future threats, and thorough assessments of new vulnerabilities that may be created.

BOX 16. Anticipatory actions

Anticipatory actions are disaster risk reduction measures that protect agricultural production and livelihoods from the impact of specific shocks (e.g. drought, floods, and heatwaves). The actions are pre-planned, risk-informed, and forecast-based. They are initiated based on an early warning trigger and are implemented ahead of the materialization of a hazard, such as a heatwave. An anticipatory action approach shifts the focus from reactive to proactive crisis management and can be particularly effective when embedded within national climate risk management strategies (Isaev *et al.*, 2024). For example, anticipatory actions can provide small-scale water infrastructure and feed for livestock in response to anticipated increased water demands and reduced water and feed supply during or following heatwaves or compound hot-dry events. In so doing, livestock mortalities can be reduced as well as the need for farmers to engage in negative coping strategies after the events (e.g. selling productive assets or skipping meals to compensate for lost income streams).

Anticipatory actions can be considered tactical responses, carried out on a short-term basis or seasonal timeframe. While forecasting of extreme heat is possible, the window of opportunity for the implementation of anticipatory actions is limited as it sits between an early warning trigger and the moment in which the hazard materializes or its impacts are felt. It is critical to note that effective implementation of anticipatory actions depends on the functionality of an early warning system or other forecasting indicators; the ability to anticipate specific local needs; and the speed of acquisition and positioning of needed resources in locations likely to be impacted. In considering the use of anticipatory actions it is essential to invest in medium-longer term capacity development of agencies from national government to extension workers in operating early warning systems and implementing anticipatory actions. To this end, the Early Warnings for All initiative, launched by the United Nations and coordinated by WMO and other partners including FAO, plays a critical role in ensuring that early warning systems are strengthened so that everyone is protected by 2027. Anticipatory action is integrated as a priority in Pillar 4 of the Early Warnings for All initiative.

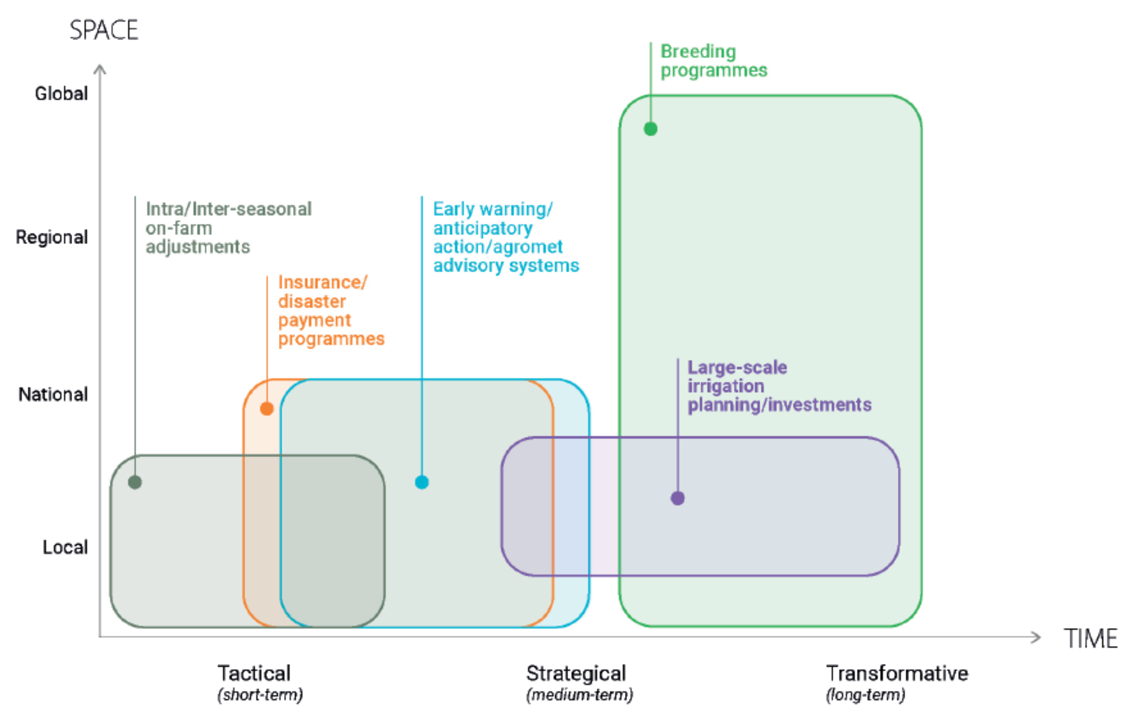
Source: **Isaev, E., Jones, C., Goncalves, M., Parkinson, E., Moniz, T. & Soares, R.** 2024. *Exploring the application of Artificial Intelligence for triggering drought anticipatory action: A Timor-Leste case study*. Technical Working Paper.Dili, Timor-Leste, FAO. https://doi.org/10.4060/cd1173en

Extreme heat and compound hot-dry extreme events are becoming an increasingly common and severe threat to agricultural productivity in many parts of the world. The expanding severity and extent of these events are impacting breadbasket regions (Alizadeh *et al.*, 2020; Biess *et al.*, 2024) and require concerted actions at various temporal and spatial scales to respond (see Figure 12). Short-term adaptation actions focus on anticipating the occurrence of extreme heat events and responding to their immediate local impacts within the course of a single agricultural season or between seasons. Due to the need for rapid decision-making in which high-impact outcomes often hang in the balance, responses are highly dependent on the knowledge and management skills of agricultural producers, as well as timely access to accurate, relevant information. Response options may be limited to the use of existing or readily available resources. Enhancing the capacities of agricultural producers in making short-term decisions regarding extreme heat responses generally requires investments in medium-term support services. Additional options and support may come from long-term investments. Education, awareness raising, access to extension services and information are among the factors most highly correlated with decision-making for extreme heat adaptation and will need to be central to any overarching planning framework (Ruzzante *et al.*, 2021; Arslan *et al.*, 2022).

4.3 Barriers to adaptation and synergies with mitigation

The successful implementation of any adaptation strategy will likely face multiple barriers. Many of the perennial socioeconomic challenges (e.g. weak governance structures and technical capacities, lack

FIGURE 12. **Temporal and spatial scales of investment adaptation options**



Source: Authors' own elaboration.

of training opportunities and extension systems, and the low income of farmers in developing countries) will continue to impede successful implementation of adaptation options (Van Maanen *et al.*, 2023). Furthermore, agriculture adaptation is currently not strongly supported by the financial sector. Agrifood systems received only 4 percent of total climate-related development finance in 2023 (FAO, 2025c). The context framed by these conditions highlights the fact that while technical solutions may exist, their deployment depends on ensuring the presence of supportive socioeconomic policies, financial investment, organizational capacities and overcoming knowledge deficits and other barriers. In response, fully integrating climate change adaptation planning into traditional planning frameworks will be required to move from tactical to transformative response formulation. This integration will be key to ensuring lasting impacts and a shift away from short-term solutions that are prone to setbacks due to a lack of coherency and sustainability.

As noted, current funding is vastly insufficient, with agrifood systems receiving only a meagre portion of the available climate finance (FAO, 2025c). The substantial underfunding of agriculture must be addressed to support the necessary changes within the sector. Closing the financing gap requires establishing innovative financing mechanisms and public-private partnerships and directing capital towards strategic and transformative actions that build long-term resilience, especially for small-scale agricultural producers. Focusing on these areas can ensure that funding is used effectively to create meaningful and sustainable change.

Adaptation actions for extreme heat may have synergies with broader agricultural development objectives and adaptation measures responding to other stressors. However, it is also true that adaptation actions may also involve trade-offs, and that new vulnerabilities may emerge that must be identified and managed. For example, introducing irrigation to reduce water stress during extreme heat and drought risks aquifer depletion and soil salinization. Switching to more resilient species to extreme heat may result in reduced genetic diversity, increasing the vulnerability of crops and livestock to large-scale losses due to a narrower genetic base. Shifting to new locations (e.g. higher elevations) can increase deforestation. Effective adaptation policy requires integrated and well-informed planning that acknowledges and mitigates potential negative consequences across environmental, social, and economic domains.

Technical solutions are necessary, but by themselves they will be insufficient if the pervasive socioeconomic barriers to adaptation in low- and middle-income countries are not addressed. Key obstacles include:

- limited awareness and access to information, education, and training;
- a lack of credit and risk insurance for agricultural producers that prevents them from investing in new technologies and innovation;
- a weak research and extension services;
- weak risk governance structures (e.g. early warning systems); and
- and land tenure insecurity.

It is also important to note that adaptive capacity varies widely both within and between countries. Even where adaptation options exist, they are not equally accessible and relevant in all countries or to all agricultural producers or value-chain actors within countries. The uneven landscape of individual and organizational capacity further limits uptake of available solutions. The spatial scale of extreme heat events, which often span thousands of kilometres, can also undermine localized adaptation efforts and overwhelm institutions and communities with limited resources. Overcoming these barriers is a prerequisite for the widespread adoption of adaptation strategies and requires parallel policy initiatives that ensure producers have access to financial, credit and risk insurance services, and basic infrastructure (e.g. water and irrigation systems).

Adaptation and risk reduction actions are urgently needed and will continue to be required for the foreseeable future. However, mitigation actions must also be increased to slow and eventually reverse the persistent rise in global temperatures and the associated increase in the occurrence and severity of extreme weather events. Some risk reduction and adaptation practices may directly contribute to climate change mitigation goals including:

- adjusting livestock feed rations to reduce low-quality roughage intake that elevates both metabolic heat and methane production;
- reducing tillage and introducing soil and water conservation measures that lower the use of synthetic inputs and improve carbon sequestration and at the same time increase heat resilience through improved soil moisture conservation; and
- reducing fossil-fuel use in aquaculture systems by switching to renewable energy sources to maintain water quality.

Ihe bulk of adaptation actions that contribute to mitigation gains, however, result indirectly from loss avoidance by reducing the need to bring additional land under cultivation to compensate for losses from extreme heat. Achieving and sustaining these gains in the agricultural sector is particularly challenging, as it depends on the independent decisions of over two billion producers and the fragile nature of mitigation benefits that tied to above ground and soil carbon sequestration.

4.4 Extreme heat risk governance across agricultural subsectors and beyond

Effective risk governance of extreme heat risk in the agricultural sector requires moving beyond discrete on-farm technical solutions to address systemic barriers, hard limits, and the need for transformative change within and across other sectors in the economy. Heatwaves are a systemic risk, closely linked to drought stress. The stressors from heatwave events ripple through entire supply chains, beginning with on-farm impacts, and affect local and national food security, water resources, public health, economic and political stability. A coherent risk governance framework must therefore integrate horizontal coordination across government departments and sectors and vertically align national policy with local actions.

An essential starting point for risk governance of extreme heat threats lies in recognizing that adaptation has limits. Identifying the constraints and limits to adaptation is critical to understanding the extent to which human and natural systems can successfully reduce risks and adapt to climate change. A systematic review of 1 682 academic studies for different regions, sectors, hazards, and actors revealed a fundamental lack of literature focused on exploring the limits to adaptation (Thomas *et al.*, 2021). Limits are categorized as being either ‘soft’ (i.e. they can be overcome with more resources or innovation) or ‘hard’ (those that insurmountable, regardless as to the resources applied). Technological, infrastructure, and ecosystem-based adaptation options suggest more evidence of hard limits than other types of responses. Crucially, finance, governance, institutional, and policy constraints are most prevalent at the global level, and represent soft limits related to innovation and commitment. A better understanding of the limits to adaptation is important for guiding financial decision-making and proactive risk governance regarding food security and has the closest ties to mitigation action.

The IPCC has reinforced the importance of identifying adaptation limits, stating that sectors or communities may exceed adaptation limits well before the end of the century (IPCC, 2022a). For example, limits in adaption to extreme heat relate not only to agriculture, forestry and other sectors with known hard limits to adaptation, but also to the ability of health systems to cope with increasing levels of heat stress and the sustainability of fishing communities that rely on coral reef environments. In addition to meeting the direct challenges of extreme heat, all groups can be adversely affected by maladaptation, and safeguards need to be put in place to prevent this.

With regards to vertical alignment of adaptation action, governance mechanisms must be tailored to local agrifood systems and livelihoods. A one-size-fits-all approach will not respond to the diversity of contexts and needs. Gaining a better understanding of the adaptation strategies of small-scale agricultural producers is of paramount importance. A long history of research shows significant differences in farming strategies used among distinct social groups and household clusters (e.g. Touch *et al.*, 2024). To enhance the adaptive capacity of small-scale producers, policies must target interventions that balance economic growth with social justice and environmental sustainability. Interventions also must be tailored to specific needs, including promoting the adoption of climate-resilient agricultural practices, investing in water management infrastructure, enhancing access to accurate climate information, and implementing social protection measures.

Effective risk governance of extreme heat risk requires a transformative and integrated approach that moves horizontally bridging sectoral and ministerial silos. Extreme heat is a silent killer and a systemic risk. It has the potential to trigger impacts that cascade within and across sectors, and thus demands coordinated horizontal policy development and vertical implementation coordination across levels that is beyond the sole purview of ministries of agriculture and national meteorological and hydrological services alone (Global Heat Health Network *et al.*, 2025; Field, 2025). The first United Nations Disaster Risk Reduction report noted that integrated approaches foster interdisciplinary research and development of intersectoral policy tools that are supported by reliable and risk-informed metrics and strong environmental and social safeguards (Global Heat Health Network *et al.*, 2025). The report also suggested that by adopting integrated approaches, agricultural production systems can become more resilient, resource-efficient, and economically viable. Advances that help to pave the way for food security and environmental health for all.

A primary obstacle in this regard is fragmented institutional responsibility. Without a mandated lead agency to drive extreme heat coordination, heat risk becomes everyone's problem and therefore no one's responsibility. Avoiding such an outcome requires high-level political commitment to establish clear objectives, shared metrics, and formal horizontal and vertical coordination mechanisms.

In summary, governing extreme heat risk response is about managing connectivity within and between sectors, between policy levels, and between public and private actors. Effective governance depends not only on the coordination among public institutions, but on the active engagement of all stakeholders, including producers, extension services, local authorities, private sector actors, research institutions, and civil society. Participatory approaches (e.g. the co-creation of knowledge, joint response planning, community-based risk assessments, and inclusive decision-making processes) help ensure that risk information is grounded in local realities and that proposed solutions are both feasible and widely supported.

By strengthening participatory mechanisms and ensuring transparent, two-way communication, risk information can flow more freely to those who need it; actions can become more synergistic and risk-informed; and the entire agrifood system can evolve to become more agile and resilient in the face of extreme heat and other climate threats.

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5. CASE STUDY: COMPOUND IMPACTS OF EXTREME HEAT IN BRAZIL

5.1 Introduction

From late 2023 through 2024, large parts of Brazil endured a severe and prolonged extreme heat event. This chapter presents an analysis of the impacts of this event across Brazil's key agricultural subsectors (crops, livestock, fisheries and aquaculture, and forestry) and the health of agricultural workers. By examining climate and other data, the analysis demonstrates how a single primary hazard—extreme heat—can trigger a wide range of compound impacts, revealing the profound and interconnected vulnerability of the entire agrifood system to extreme heat.

5.2 Data and methodology

For all the analyses presented in this case study, except for Figure 14, ERA5 (Hersbach *et al.*, 2020), the fifth-generation reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) was used. ERA5 provides hourly estimates of a wide range of climate variables at a 0.25° horizontal resolution (approximately 25 km at the Equator) from 1940 onwards. Based on an advanced data assimilation system that integrates historical observations with a numerical weather prediction model, ERAS ensures consistent spatial and temporal coverage, and is the most detailed and widely used reanalysis product for climate research and applications.

The data used in the analysis of fire incidence and areas burned were obtained from the BD Queimadas (Burned Area Database) of the National Institute for Space Research and are available through the TerraBrasilis Platform.3 This database provides consistent, satellite-derived records of fire counts and burned areas across Brazil and serves as the primary national reference for monitoring wildfire dynamics, assessing burned extent, and supporting fire management and environmental policy actions.

To evaluate the impacts of extreme heat across different sectors several indices were used. The Agricultural Stress Index (Van Hoolst *et al.*, 2016) is a quick-look indicator that facilitates the early identification of cropped land with a high likelihood of water stress (drought). The Index is based on the integration of the Vegetation Health Index (Kogan, 1995; Singh *et al.*, 2003) in temporal and spatial dimensions. These two dimensions are critical in the assessment of a drought event in agriculture. The first step of the Agricultural Stress Index calculation is a temporal averaging of the Vegetation Health Index, which assesses the intensity and duration of dry periods occurring during the crop cycle at the pixel level. This calculation includes the use of crop coefficients, which introduces sensitivity of a crop to water stress during each phenological phase. The second step determines the spatial extent of drought events by calculating the percentage of pixels in arable areas that have a Vegetation Health Index value below 35 percent. This value was identified as a critical threshold in assessing the extent of drought (Kogan, 1995). To facilitate the quick interpretation of results, each administrative area is classified according to the percentage of the affected area.

Based on the empirical study of temperature effects on crop yields (e.g. Schlenker and Roberts, 2009), we used 30 °C for soy and 29 °C for maize as the temperature threshold above which high temperatures are considered harmful for the yields.

The Temperature–Humidity Index (THI) is a bioclimatic indicator that combines air temperature and relative humidity to assess the level of heat stress experienced by animals (NRC, 1971). It is widely used in livestock research and management as a simple and robust metric to quantify conditions of thermal comfort. In this report, THI values from different livestock species (dairy cattle, beef cattle, sheep, goats, poultry and swine) and calculated with the number of days in which THI values fell into three risk categories (mild, moderate and severe) based on literature values. In particular, for dairy cattle, THI values between 72 and 78 correspond to the mild category; between 78 and 88 to moderate; and above 88 to severe (Armstrong, 1994). For swine, THI values between 23.33 and 26.11 correspond to the mild category; between 26.11 and 28.88 to moderate; and above 28.88 to the severe category (Cross *et al.*, 2018; Cross *et al.*, 2020). Monitoring the frequency of days within each category provides a practical means of evaluating environmental heat load on the animals, which can impact their feed intake, growth, reproduction, and overall welfare.

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[3] BD Queimadas database is available at: https://terrabrasilis.dpi.inpe.br/queimadas/portal/

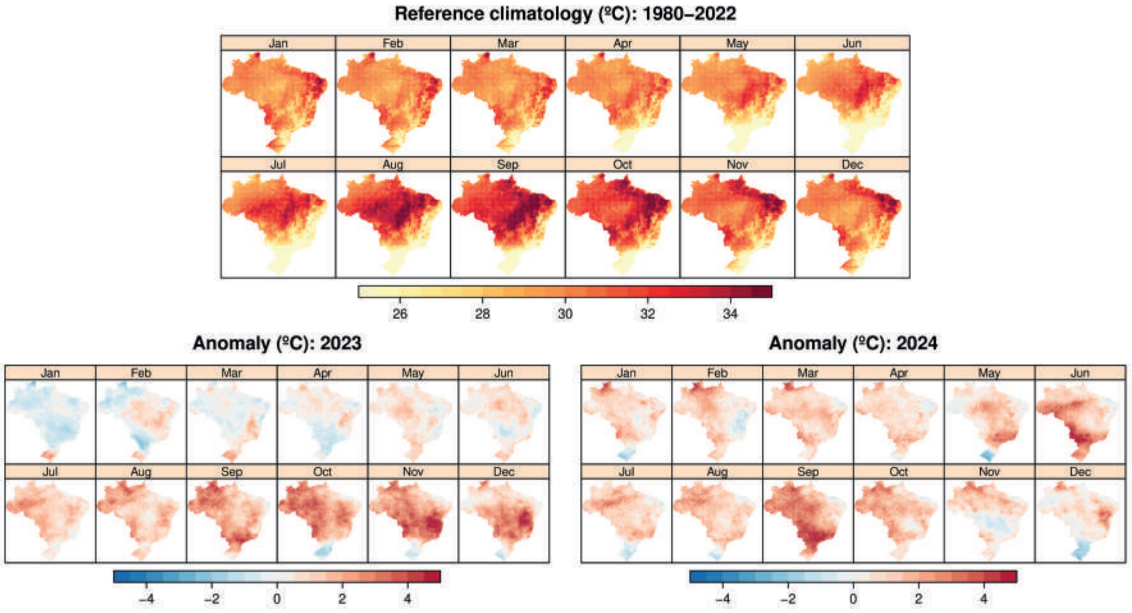
The Fire Weather Index (FWI), a component of the Canadian Forest Fire Weather Index System, is designed to estimate fire danger based on meteorological conditions (Van Wagner, 1987). It integrates temperature, relative humidity, wind speed, and precipitation to provide a numeric rating of fire intensity. It has been used at global and regional scales. In this report, the number of days in which the FWI exceeded a value of 30 were calculated during the months of August, September, and October, the main fire season in Brazil. Surpassing this threshold has been correlated with increased wildfire occurrence and intensity in various Brazilian biomes (e.g., Silva *et al.*, 2024). Analysis using FWI can help to anticipate wildfire events, guide fire management strategies, and support policies aimed at reducing fire-related impacts on ecosystems.

The Wet Bulb Globe Temperature (WBGT) is an empirical index that integrates air temperature, humidity, wind speed, and solar radiation to assess heat stress in humans in different environments. Several approaches to calculate the WBGT have been proposed in the literature. In this case study, the approach introduced by Liljegren *et al.* (2008), widely used in assessing heat stress risks for agricultural workers and other outdoor workers, was used. According to International Organization for Standardization (ISO) Standard 7243, Ergonomics of the thermal environment, a WBGT exceeding approximately 26 °C indicates a potentially hazardous condition for workers performing moderate-intensity tasks without scheduled breaks (ISO, 2017). The number of days in which the WBGT surpassed this threshold is used as a means of monitoring changes in potential extreme heat exposure in the field, which can help to inform occupational health measures and heat mitigation interventions (e.g. work-rest cycles, and hydration strategies).

5.3 Results

From late 2023 through 2024, large parts of Brazil endured a severe and prolonged extreme heat event. For some locations and over a course of months, daytime maximum temperatures exceeded 5 °C above the climatological mean value (from 1980 to 2022) (Figure 13). During this period, there were multiple heatwave episodes. Particularly severe episodes occurred between 17 and

FIGURE 13. Monthly daytime maximum temperature anomalies during Brazil heatwave (2024–2025)



Monthly daytime maximum temperature anomalies, in °C, in 2023 (bottom row, left) and 2024 (bottom row, right), relative to the climatological mean values for the period 1980–2022 (top row). In the bottom row, positive values indicate warmer-than-average conditions, while negative values indicate cooler-than-average conditions.

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in these maps.

Source: Authors' own elaboration.

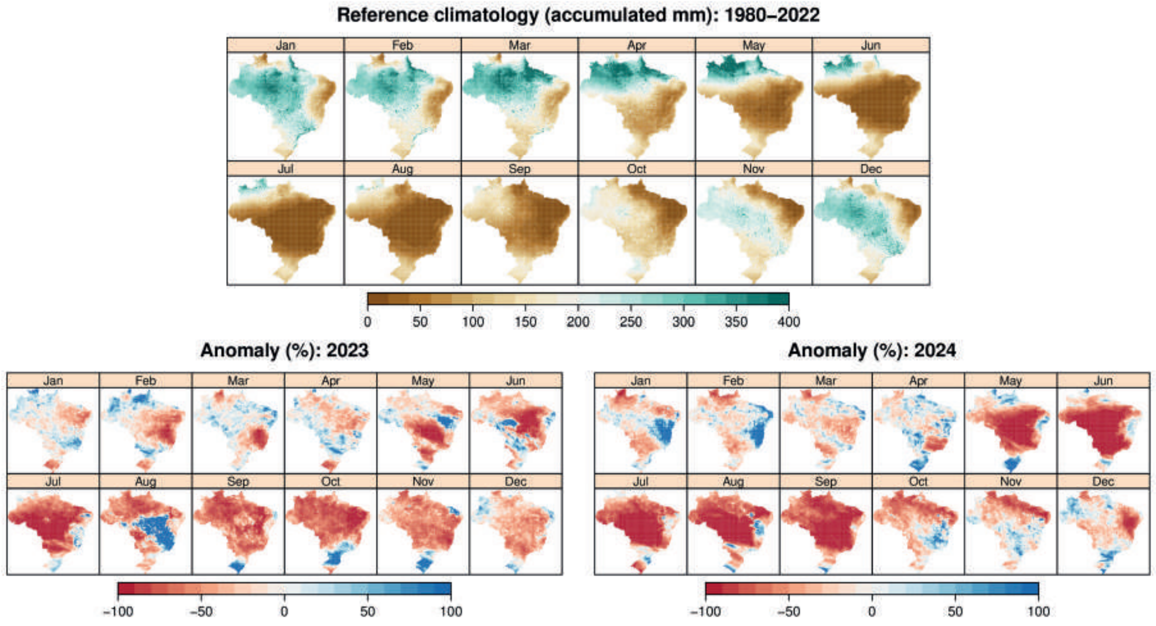
27 September and 11 and 18, November 2023, in Central-West and Southeast Brazil. These prolonged periods of high temperatures were caused by a large-scale weather pattern, characterized by an anomalous persistent high-pressure system, that trapped warm air over the region (Pampuch *et al.*, 2025; Marengo *et al.*, 2025). An analysis of large-scale meteorological conditions in the first three months of 2024 suggested that two types of weather patterns were responsible for bringing extreme heat to the region (Moreira *et al.*, 2024). The first weather pattern was an anticyclonic condition of an oceanic origin with the presence of a maritime tropical air mass and a subtropical Atlantic high-pressure centre. The second was the advancement of hot equatorial continental air masses, with both dry and wet days recorded, depending on atmospheric instability.

From 15 to 18 March, 2024 a record-breaking heatwave affected southern Brazil. On 27 April 2024, a severe heatwave struck central and southern Brazil and lasted five days. Between late August and the first week of September, parts of western central Brazil experienced heatwaves, with temperatures 7 °C above normal (WMO, 2025c).

These underlying meteorological conditions were amplified by a strong El Niño event, which typically brings warmer (drier) than usual conditions to southern (northern) Brazil. From September 2023 onwards, abnormally warm conditions were initially accompanied by lower-than-normal precipitation, leading to a meteorological drought that was particularly strong in the Amazon region (see Figure 14) (Pampuch *et al.*, 2025).

A critical finding from the analysis conducted on the Brazil heatwaves is the distinction between heat stress and water stress as the primary drivers of agricultural damage. Meteorological drought was widespread across vast parts of the country (as shown in Figure 15 and Marengo *et al.*, 2026). However, the Agricultural Stress Index, a measure of remotely sensed vegetation health, indicated that agricultural drought in croplands was confined to localized areas in Eastern Brazil (Figure 15) and in selected months from late 2023 to early 2024. This suggests that the negative impacts experienced

FIGURE 14. Monthly precipitation anomalies during Brazil heatwave (2024–2025)



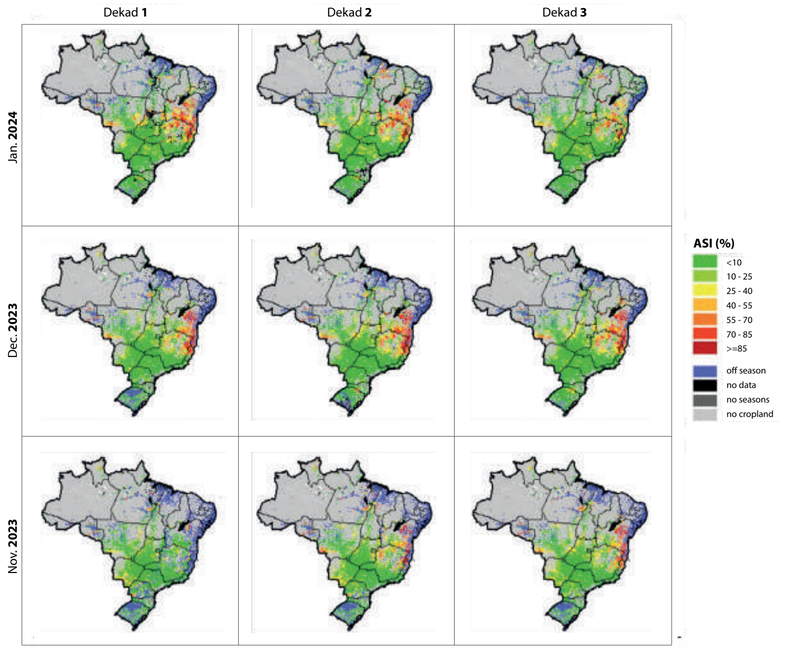
Monthly precipitation anomalies, in percent, in 2023 (bottom figure, left) and 2024 (bottom figure, right), relative to the climatological mean values for the period 1980–2022 (in mm/month; top figure). In the bottom figures, positive values indicate wetter-than-average conditions, while negative values indicate drier-than-average conditions.

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in these maps.

Source: Authors' own elaboration.

FIGURE 15. **Percentage of cropland areas affected by severe agricultural drought during Brazil heatwave (2024–2025)**

Percentage of cropland areas affected by severe agricultural drought as indicated by the Agricultural Stress Index, for November 2023 (bottom), December 2023 (middle), and January 2024 (top); and for the first 10-day (dekad 1; left), middle 10-day (dekad 2; middle), and the remainder (dekad 3; right) of each month. The other months from the second half of 2023 through 2024 did not have large areas with a high percentage of cropland under severe agricultural drought.



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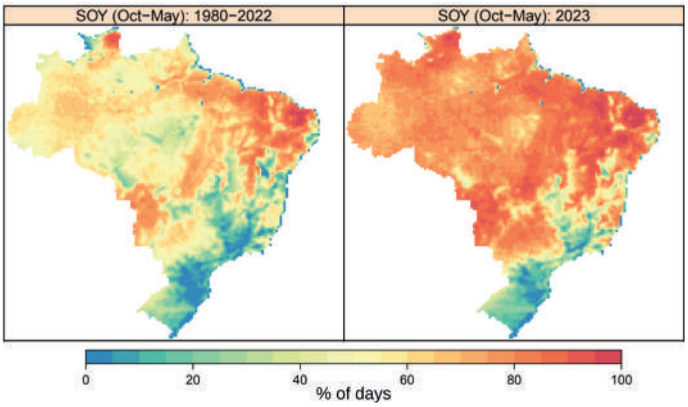
Source: Authors' own elaboration.

during the 2023–2024 season were driven more by direct extreme heat stress on crops than by widespread water scarcity, except for the eastern region.

The impacts on Brazil's primary crops (soy and first season maize) in the October 2023 to May 2024 season were significant, as the heatwaves coincided with the growing cycles in the major production areas in the Northeast, Central-West, and Southeast. Analysis shows that daytime maximum temperatures exceeded the critical threshold for soy (30 °C) on more than 60 percent of days between October 2023 and May 2024 in most areas except southern Brazil (Figure 16). Normally, such an elevated percentage is experienced only in the northeast. At the monthly time scale, significant temperature anomalies (with respect to the 1980–2022 reference period) were found throughout the entire growing season in most of the country except the southern region (Figure 17). Strikingly, even daily mean temperatures, which typically remain below 30 °C, surpassed the threshold on as many as 20 percent of the days early in the cropping season (October-December; not shown). Soy is most sensitive to high temperatures during the reproductive and grain filling stages, when excessive heat can cause flower abortion, pod drop, poor grain formation, which reduces overall grain yields. Losses can be greater for crops planted under conventional tillage (ploughing and harrowing) due to soil moisture loss and elevated soil temperatures. In São Paulo State, soybean crops grown in fields under no-till management, especially on sugarcane straw, suffered less from the effects of high temperatures and dry spells. The straw mulch acted as a thermal insulator, maintaining a suitable temperature for crop development and soil microorganisms, while also reducing soil moisture loss. Initial forecasts from Brazil's National Supply Company, CONAB, which is under the Ministry of Agriculture, Livestock and Food Supply, projected a record crop of 162 million metric tonnes. However, partly due to the relentless heat stress, by May 2024, the estimate was slashed to 147.7 million metric tonnes, a reduction of nearly 10 percent from initial expectations (CONAB, 2023; 2025). At the subnational level, the impact was even greater. For example, the reduction in soy yield was estimated to be more than 20 percent in the state of São Paulo (Vegro *et al.*, 2024). In the October 2023 to May 2024 season, similar impacts were observed for the first season maize crop. The estimated yield decrease in the state of São Paulo was more than 10 percent (Vegro *et al.*, 2024). For soy and maize, in many cases areas of a high heat stress during the growing season months

FIGURE 16. **Percentage of days in which the daytime maximum temperature exceeded the critical threshold of 30 °C during the growing season for soy during Brazil heatwave (2024–2025)**

Percentage of days in which the daytime maximum temperature exceeded the critical threshold of 30 °C during the growing season for soy (from October to November). The left-hand map shows the average for the period 1980–2022, and the right-hand map shows October 2023 to May 2024.

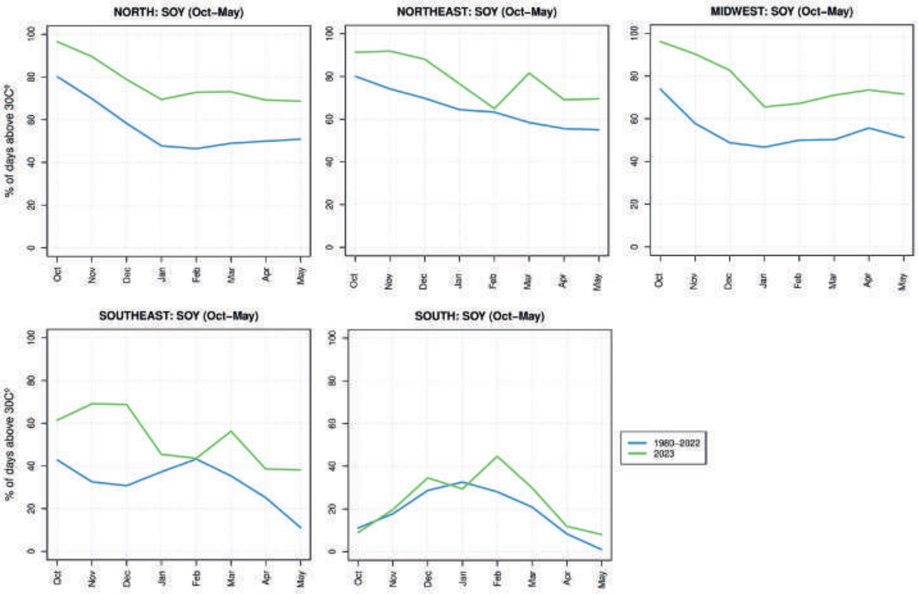


Note: Refer to the disclaimer on the copyright page for the names and boundaries used in these maps.

Source: Authors' own elaboration.

FIGURE 17. **Temporal evolution, month by month, of the percentage of days in which the daytime maximum temperature exceeded the critical threshold of 30 °C during the growing season for soy during Brazil heatwave (2024–2025)**

Temporal evolution, month by month, of the percentage of days in which the daytime maximum temperature exceeded the critical threshold of 30 °C during the growing season for soy (from October to May). Each panel corresponds to a different region within Brazil: north, northeast, midwest, southeast and south. Within each panel, the blue line corresponds to the average for the period 1980–2022, and the green line corresponds to October 2023 to May 2024.



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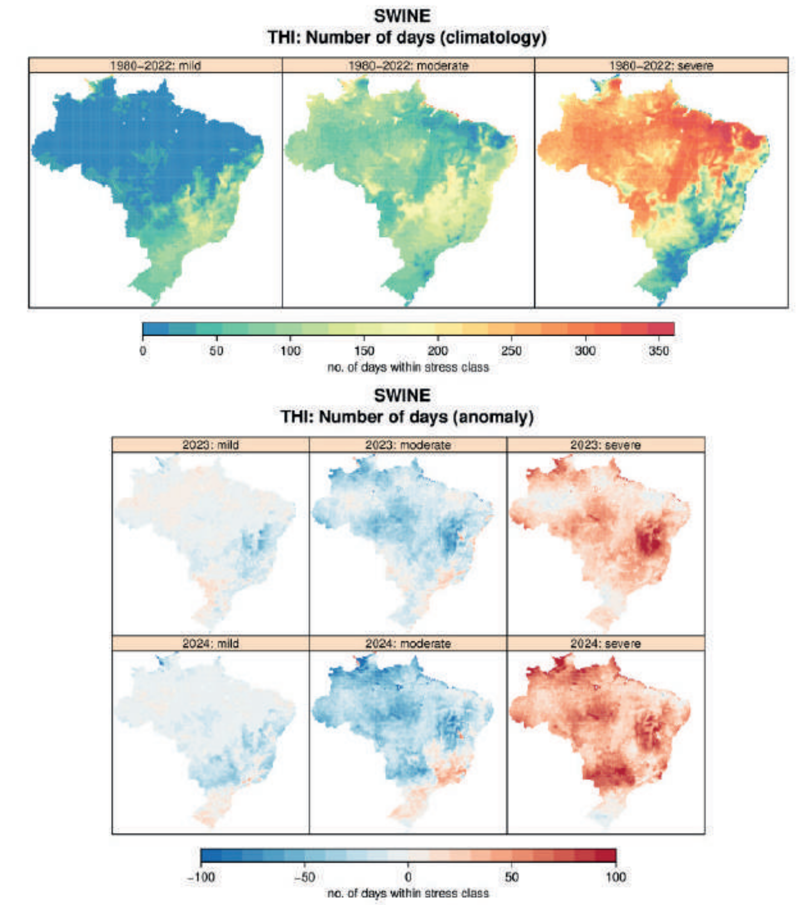
overlapped with areas of high concentration of crop production. Examining the extent of heat effects on crops at a closer spatial scale (e.g. in the state of Sao Paulo), there have been reports of damages to various crops due to extreme heat. For example, peanuts suffered from flower abortion and reduced number of pods. Maize, potato, soybean, sugarcane, common beans faced an increase in pests and diseases (e.g. whiteflies and *Macrophomina phaseolina*). Perennial crops that were affected included arabica coffee, olives, cashew and ipê.

The livestock sector also faced severe pressure. Pigs (swine), one of the most heat-sensitive animals, were under severe heat stress for 20 or more days each month throughout most of the 2023–2024 period in the hard-hit Central-West region according to the THI for swine. Under average conditions, pigs are under mild and moderate heat stress conditions in Central-West, Southeast and South regions, whereas for the northern parts of the country, severe stress conditions prevail (top row in Figure 18). However, in 2023 (starting in July), and more significantly in 2024 (until September), almost every region in Brazil experienced a major shift in stress categories. Mild conditions became moderate, or even severe, and moderate stress became severe. This change can be seen in the reduction in number of days under mild and moderate stress, and the significant increase in days of severe stress in bottom row in Figure 18 and Figure 19. The shift in stress levels meant pigs were under severe stress conditions throughout 2023 and 2024 across most of the country. Similarly, in agreement with the results obtained from the analysis of the THI for swine, the same analysis for dairy (not shown), indicated a significant impact on dairy animal health and productivity, particularly in the Southeast, where one-third of the dairy industry is concentrated. Heat stress in pigs causes a slowdown in feed intake and weight gain. These effects can be compensated for by lengthening their growth cycle, although this incurs additional costs. For dairy cattle, heat stress leads to reduced milk production, and these losses cannot be regained. Sustained periods of extreme heat exposure for both species can lead to physiological damages that persist for the lifetimes of the animals and can lead to offspring with reduced performance, which represent additional irreversible economic loss for farmers.

The 2023–20224 heat event triggered further compound outcomes, including catastrophic wildfires and hazardous conditions for workers. In 2024, the Fire Weather Index (FWI) was abnormally high compared to the long-term average (1980–2022).

FIGURE 18. The number of days falling in three risk categories for swine during Brazil heatwave (2024–2025)

The number of days falling in three THI risk categories for swine (mild, moderate, and severe) for the years 2023 (bottom panel, top row) and 2024 (bottom panel, bottom row), expressed as the difference in the number of days in each category, relative to the climatological mean values corresponding to the period 1980–2022 (top panel). In the bottom panels, positive (negative) values indicate more (less) days than the climatological mean in the corresponding risk category.



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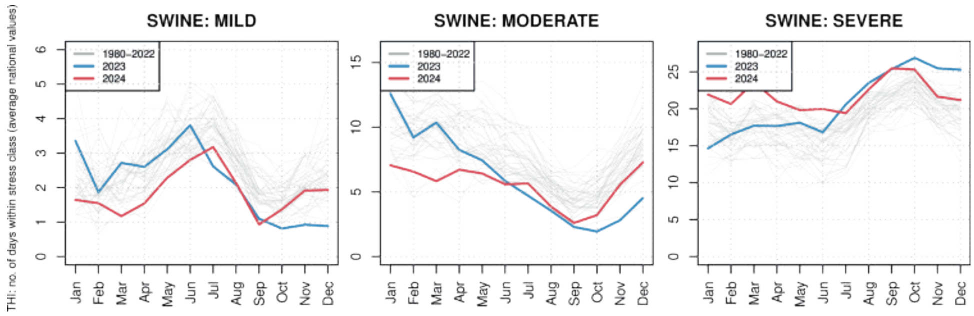
Source: Authors' own elaboration.

The Midwest region was particularly hard hit, with the percentage of days in a year that exceeded the FWI threshold of 30 increased by as much as 40 percent point (or 150 days; Figure 20). FWI, which takes into account temperature, humidity, wind speed, and precipitation, also captured the meteorological drought conditions that were prevalent (Marengo, 2026). The high FWI values are reflected in the

FIGURE 19. The number of days falling in three risk categories for swine spatially averaged over the entire country during the Brazil heatwave (2024-2025)

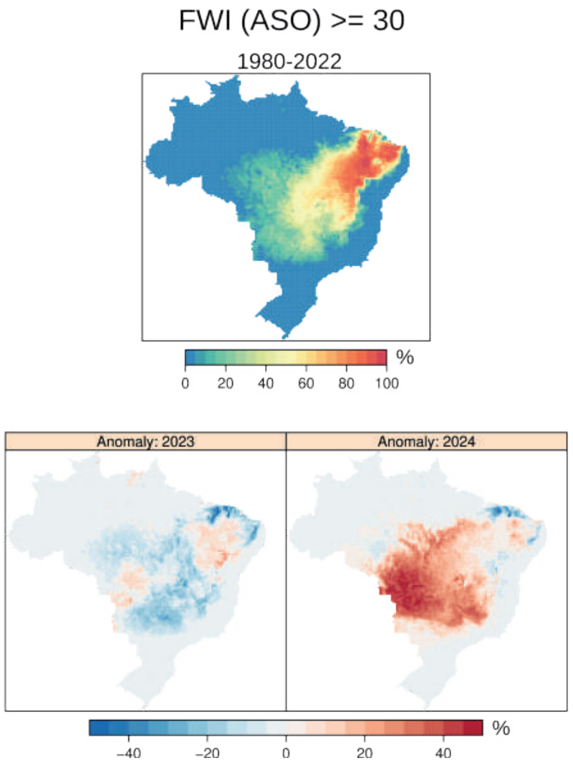


The number of days falling in three THI risk categories for swine (mild, moderate, and severe), spatially averaged over the entire Brazil, in each month. For a given panel/category, each pale grey line corresponds to a different year within the period 1980–2022. The blue lines correspond to the year 2023 and the red lines to 2024.

Source: Authors' own elaboration.

FIGURE 20. The percentage of days on which Fire Weather Index values exceeded the threshold of 30 during the Brazil heatwave (2024–2025)

The percentage of days in a year on which FWI values exceeded the threshold (30) during the August-September-October (ASO) fire season, for the years 2023 and 2024 (bottom row). Values in the lower row are expressed as the difference in the percentage points relative to the mean climatological value corresponding to the period 1980–2022 (top row). In the bottom row, positive (negative) values indicate more (less) days than the climatological mean.



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Source: Authors' own elaboration.

extend of areas burned; wildfires devastated an area equivalent to the size of Italy and caused severe air pollution from microparticles (≤ 2.5 micrometers in diameter). The spikes in fire risks in 2024 were most evident in Central-West Brazil, followed by Northeast and Southeast, and show sharp contrasts compared to the long-term average for each region. Over the last 20 years, these two regions exhibit an increasing percentage of days with elevated fire risk (i.e. an FWI value above 30) as well as increasing interannual variability (Figure 21).

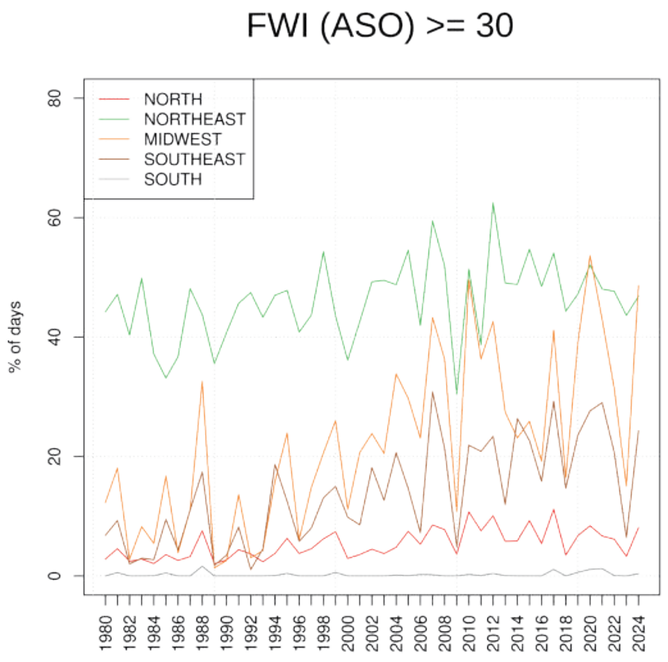
The increased fire risks evident in elevated FWI values translated into major fire disasters in 2024. In terms of observed fire counts and burned area across Brazil from 2002 to 2024 (Figure 22), there was substantial year-to-year variability with marked peaks associated with extreme climatic events. The first panel, representing total fire counts, indicates elevated fire frequency in the early 2000s (especially between 2003 and 2007) and again during major drought years such as 2010, 2020, and 2024. These years were severely affected by extreme heat. In contrast, the lowest fire counts occurred between 2009 and 2013, a period that coincided with stronger fire control efforts and stricter public policies that effectively reduced fire activity nationwide.

The second panel (Figure 22), showing total burned area (km²), broadly mirrors the fluctuations in fire count and the underlaying climatological conditions. Extreme years in the number of fires (e.g. 2007, 2010, and 2024) produced the highest burned extent (exceeding 490 000 km²), while years with lower fire numbers were also characterized by smaller burned areas. This suggests generally that the ignition and spread of fires was a result of the combined effects of fuel availability and meteorological conditions.

The year 2024 is notable for having the highest number of both fire counts and burned area since 2010. This also coincides with the increased weather-related fire risks from extreme heat. Especially during El Niño events such as in 2024, heat, meteorological drought, and fire activity were connected, which indicates the high climatic sensitivity of the ecosystems impacted.

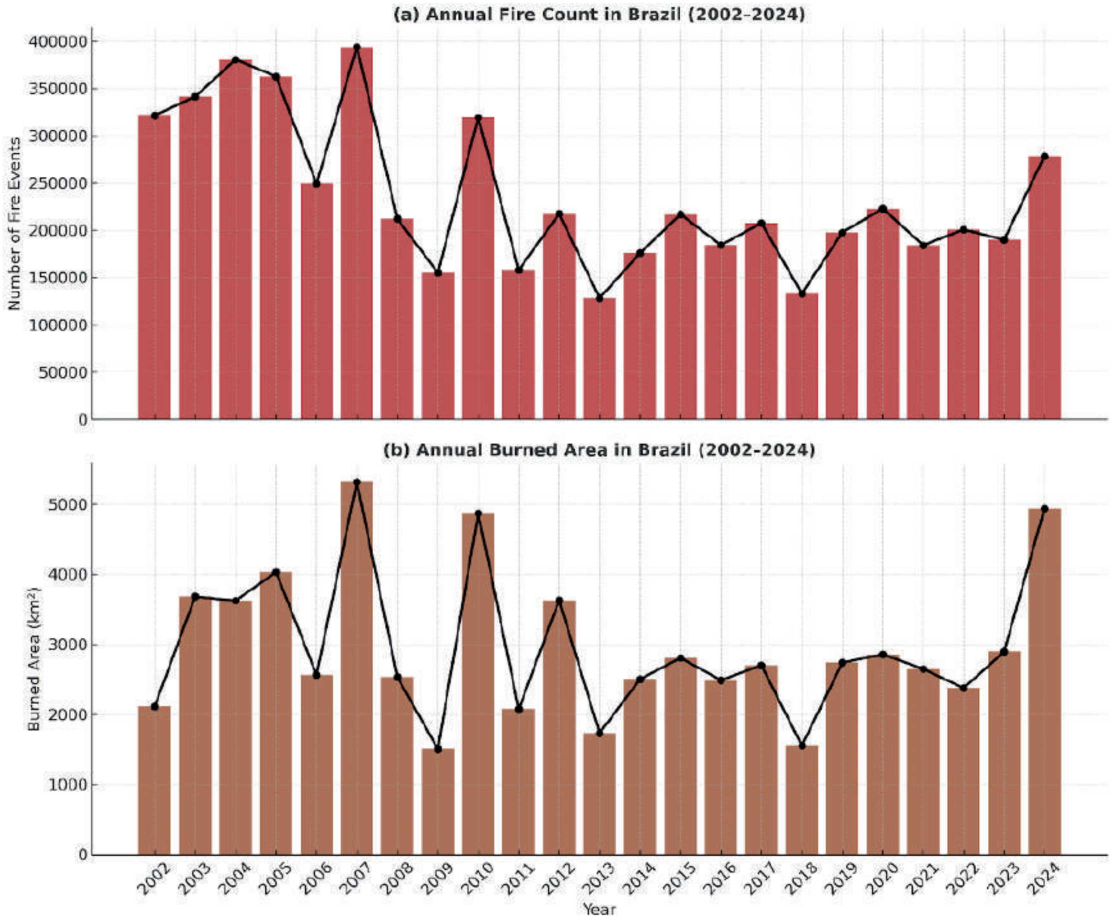
FIGURE 21. Temporal evolution of the percentage of days in a year with Fire Weather Index exceeding 30 in Brazil during the August-September-October season for the period 1908–2024

Temporal evolution of the percentage of days in a year with FWI exceeding 30 during the August-September-October season for the period 1908-2024. Each line corresponds to a different region within Brazil: North (red), Northeast (green), Central-West (yellow), Southeast (brown) and South (grey).



Source: Authors' own elaboration.

FIGURE 22. **Annual number of fire events and annual burned area in km^2 in Brazil from 2002 to 2024**



Source: Authors' own elaboration.

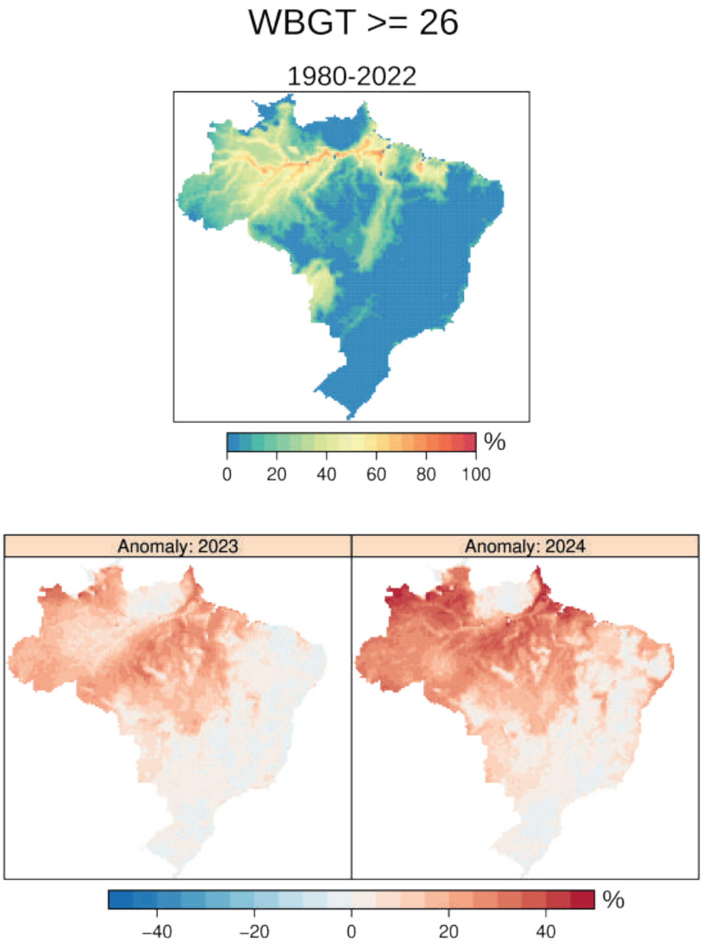
Agricultural workers in the North, Northeast, and Central-West were also exposed to extreme heat stress. Wet Bulb Globe Temperature exceeded the safety threshold of 26 °C on a large percentage of days (top row in Figure 23), which compromised worker health and productivity. In North and Central-West, 2024 set the record for the highest percentage of days with WBGT values of 26 or more during the 45-year period covered in this analysis (Figure 24).

Salmon farming is also susceptible to extreme heat. In Brazil rainbow trout and Atlantic salmon are near their upper threshold for high temperatures. As water temperatures rise, these species experience a double stress as warmer water contains less oxygen, while simultaneously increasing fish metabolism thus elevating their oxygen demand. Under greater physiological stress, fish feed less and are more susceptible to diseases caused by opportunistic microorganisms. During 2023 and 2024, water temperature reached the highest level in ten years (since 2015) at the salmon farming experimental station in Campos do Jordão. The elevated temperatures caused high mortality rates in the fish, from their early stages of development (embryos) to adult breeding stock.

In addition to these negative impacts the extreme heat conditions also contributed to another devastating compound event in the south. From April to May 2024, an atmospheric cold front was blocked by the prevailing heat dome to the north,

FIGURE 23. **The percentage of days in a year with Wet Bulb Globe Temperature more than 26 °C in Brazil for the years 2023 and 2024**

The percentage of days in a year with WBGT more than 26 °C for the years 2023 and 2024 (bottom row). Values are expressed as the difference in percentage points, relative to the mean climatological value corresponding to the period 1980–2022 (top row). In the bottom row, positive (negative) values indicate more (less) days than the climatological mean.



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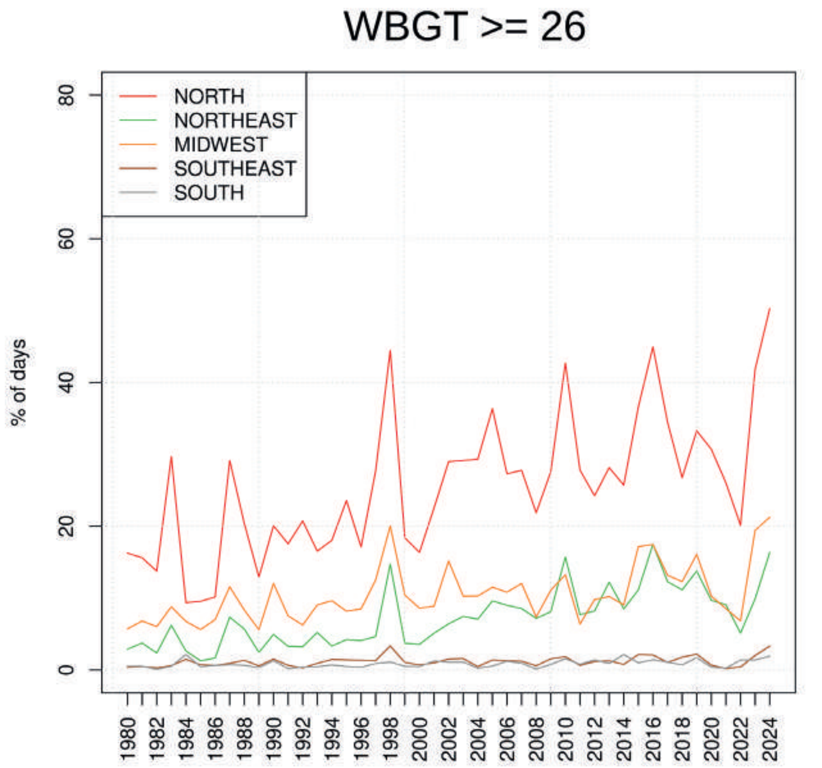
Source: Authors' own elaboration.

resulting in catastrophic rainfall and flooding in the southern state of Rio Grande do Sul (Simoes-Sousa *et al.*, 2025). Between 22 April and 6 May 2024, total precipitation exceeded 500 mm in many parts of Rio Grande do Sul, with some municipalities receiving over 700 mm (Nóia-Júnior *et al.*, 2025). Rio Grande do Sul, which accounts for over 70 percent of Brazil's rice output, saw productivity reduced by 3.6 percent over the previous harvest. The human toll was even more severe, as the floods claimed 183 lives and displaced over 600 000 people. It is also reported that the flood led to the destruction of up to 2 million tonnes of soybeans that were left unharvested (Nóia-Júnior *et al.*, 2025). Another source reported that the agricultural losses amounted to 1.2 billion Brazilian real (equivalent to more than USD 200 million) and that 600 000 hectares of pastures were seriously damaged (WMO, 2025). The flooding also affected Patos Lagoon, a vital area for wildlife and fishing. The boats, equipment, and fishing grounds of local small-scale fishers were destroyed. The floods also disrupted the supply chains and markets across Brazil for pink shrimp, 30 percent of which comes from the Patos Lagoon (WMO, 2025c). These impacts illustrate how meteorological conditions causing extreme heat can be linked to multiple, seemingly contradictory compounding hazards such as drought and heavy rainfall.

The extreme heat events in 2023 and 2024 in Brazil occurred within the larger context of warming trends in South America and globally

FIGURE 24. **Temporal evolution of the percentage of days in a year with Wet Bulb Globe Temperature exceeding 26 °C in Brazil during the period 1980–2024**

Temporal evolution of the percentage of days in a year with WBGT exceeding 26 °C, during the period 1980–2024. Each line corresponds to a different region within Brazil: North (red), Northeast (green), Central-West (yellow), Southeast (brown) and South (grey).



Source: Authors' own elaboration.

and the strong 2023–2024 El Niño event. Since 1979 there had been a significant increase in the frequency and intensity of heatwaves in tropical and subtropical regions of Brazil. The heatwaves were felt in areas that had not previously been subject to heatwaves, such as the Amazon and northeastern Brazil (Marengo *et al.*, 2026). By the end of the century an extreme heat event with the daily maximum temperature of at least 40.6 °C (as experienced in the city of Rio de Janeiro on November 18, 2023) will become much more likely. Under SSP2-4.5, the return period for such a heatwave would be 19 years, and just 4 years for SSP5-8.5 (Ivanovich *et al.*, 2024). The extent to which human-driven climate change is contributing to the occurrence of these extreme weather events has been quantified by attribution studies carried out by the World Weather Attribution and others. Fires similar to those that occurred in June 2024 in Pantanal would have been 10 000 percent less frequent without climate change (Barnes *et al.*, 2024). Climate change increased the likelihood of severe heavy rainfall events that have occurred in southern Brazil more than 100 percent and amplified the intensity by 6 to 9 percent (Clarke *et al.*, 2024a). Due to climate change, the likelihood of the meteorological drought experienced by Brazil in the second half of 2023 increased 1 000 percent (Clarke *et al.*, 2024b).

The 2023–2024 period in Brazil serves as a stark example of the breadth and severity of compound impacts that can be triggered by a primary extreme heat event. On top of a warmer baseline shaped by climate change and amplified by El Niño, the heatwave simultaneously impacted crops, livestock, forests, fisheries, and human health. The interconnected failures highlight the profound vulnerability of the entire agricultural sector and the grave implications such events have for the livelihoods and food security of the millions who depend on it.

6. CONCLUSION

The evidence presented throughout this report on the many direct and indirect impacts of extreme heat and the interconnected nature of compound events and complex compound impacts makes it clear that a business-as-usual, siloed response to the growing risk of extreme heat is insufficient. A risk analysis focused on a single crop's response to a single hazard will inevitably underestimate the profound challenges that must be addressed to strengthen the resiliency of agrifood systems globally. The challenges of responding to extreme heat demand a transformative approach grounded in proactive adaptation, integrated governance, and ambitious climate change mitigation.

As the frequency and intensity of extreme heat events continue to increase with climate change, building systemic resilience through adaptation and dedicated risk reduction is imperative. The path forward requires a shift from reactive crisis management to proactive risk reduction, beginning with the empowerment of agricultural producers by giving them access to essential information and tools. A key opportunity lies in leveraging the high predictability of heat. Agrometeorological advisories and early warning systems linked to anticipatory action protocols represent a highly promising and widely applicable adaptation measure. These systems enable farmers, pastoralists, and fisherfolk to implement tactical, on-farm responses and are a critical first line of defence.

However, technical on-farm solutions alone are insufficient. Effective risk governance requires a transformative and integrated approach that moves horizontally across sectoral silos and aligns vertically from national policy to local action. Extreme heat is a systemic risk that demands coordinated systemic policy development involving ministries of agriculture, health, water, labour, disaster risk authority, and others. A primary obstacle is often fragmented institutional responsibility. Overcoming this requires high-level political commitment to establish clear mandates and coordination mechanisms, such as integrating agricultural resilience into national heat action plans, to support the diverse needs of local agricultural systems.

Even with strong governance, it must be acknowledged that there are the profound barriers and limits to adaptation. The successful implementation of even proven strategies is in many contexts hindered by substantial financing gaps, weak institutional capacities, and socioeconomic barriers that disproportionately affect the most vulnerable. While many of these are 'soft' limits that can be overcome with resources and political will, there are also 'hard' physiological and ecological limits that no amount of adaptation can surmount.

While this report outlines a path toward enhanced resilience, solutions and opportunities are not infinite. Alongside robust adaptation and risk reduction strategies, the only durable solution to the escalating threat of extreme heat lies in ambitious, multilateral climate change mitigation. Protecting the future of agriculture and ensuring global food security will require not only building on-farm resilience but also exercising international solidarity and collective political will for risk sharing, and a decisive transition away from a high-emissions future.

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