Climatic Change (2024) 177:48
https://doi.org/10.1007/s10584-023-03646-6

Risks associated with global warming of 1.5 to 4 °C above pre-industrial levels in human and natural systems in six countries

R. Warren[1] · J. Price[1] · N. Forstenhäusler[1] · O. Andrews[2,3] · S. Brown[4] · K. Ebi[5] · D. Gernaat[6] · P. Goodwin[7] · D. Guan[8,9] · Y. He[1] · D. Manful[1] · Z. Yin[9] · Y. Hu[10] · K. Jenkins[1] · R. Jenkins[1] · A. Kennedy-Asser[2] · T. J. Osborn[11] · D. VanVuuren[6] · C. Wallace[11] · D. Wang[12,13] · R. Wright[1]

Received: 4 September 2020 / Accepted: 27 November 2023

Abstract
The Topical Collection "Accrual of Climate Change Risk in Six Vulnerable Countries" provides a harmonised assessment of risks to human and natural systems due to global warming of 1.5–4 °C in six countries (China, Brazil, Egypt, Ethiopia, Ghana, and India) using a consistent set of climate change and socioeconomic scenarios. It compares risks in 2100 if warming has reached 3 °C, broadly corresponding to current global greenhouse gas emission reduction policies, including countries' National Determined Contributions, rather than the Paris Agreement goal of limiting warming to 'well below' 2 °C and 'pursuing efforts' to limit to 1.5 °C. Global population is assumed either constant at year 2000 levels or to increase to 9.2 billion by 2100. In either case, greater warming is projected to lead, in all six countries, to greater exposure of land and people to drought and fluvial flood hazard, greater declines in biodiversity, and greater reductions in the yield of maize and wheat. Limiting global warming to 1.5 °C, compared with ~ 3 °C, is projected to deliver large benefits for all six countries, including reduced economic damages due to fluvial flooding. The greatest projected benefits are the avoidance of a large increase in exposure of agricultural land to severe drought, which is 61%, 43%, 18%, and 21% lower in Ethiopia, China, Ghana, and India at 1.5 °C than at 3 °C, whilst avoided increases in human exposure to severe drought are 20–80% lower at 1.5 °C than 3 °C across the six countries. Climate refugia for plants are largely preserved at 1.5 °C warming in Ghana, China, and Ethiopia, but refugia shrink in areal extent by a factor of 2, 3, 3, 4, and 10 in Ghana, China, India, Ethiopia, and Brazil, respectively, if warming reaches 3 °C. Economic damages associated with sea-level rise are projected to increase in coastal nations, but more slowly if warming were limited to 1.5 °C. Actual benefits on the ground will also depend on national and local contexts and the extent of future investment in adaptation.

Keywords Climate change · Risk · Human systems · Ecosystem services

Extended author information available on the last page of the article

1 Introduction and methods

Interdisciplinary climate change risk assessment is typically conducted either at a global scale, sometimes using a harmonised approach in terms of climate change and socioeconomic scenarios, and risk projection, but without exploring the implications for individual countries except for very large ones (for example Byers et al. 2018; Warren et al.2022; O'Neill et al. 2022). Nations, on the other hand, typically conduct their own independent interdisciplinary climate change risk assessments (for example Reidmiller et al. 2017; Betts and Brown 2021). Inevitably, different nations choose to use different approaches to selecting climate change and socio-economic scenarios, and use different models to projecting risk. Therefore, consistent sets of climate change risk assessments for different countries that are harmonised, utilising consistent sets of scenarios and methodological approaches, are in general, lacking. Without such studies, an objective comparison of levels of risk across countries at different levels of warming is challenging. In this study, such an approach is adopted for six countries.

This paper synthesises the harmonised assessment of projected future climate change risks in six countries provided by the Topical Collection, using a consistent set of climate change and socioeconomic scenarios and a single set of risk models. The countries were selected to span different levels of development, as well as different continents: Brazil, China, Egypt, Ethiopia, Ghana, and India. The analysis of risk is based on the projection of how hazard and exposure are projected to change under the scenarios considered. Vulnerability is assumed to remain constant except in the case of coastal flooding where adaptation is specifically modelled (Brown et al. 2021).

In the Topical Collection, many important potential future risks associated with alternative levels of global warming ranging from 1.5 to 4 °C above pre-industrial levels in the six countries were quantified for the year 2100 (Table S1). A case where human population remains constant at year 2000 levels, is compared with one where it evolves as in an established shared socioeconomic pathway (SSP2) (Riahi et al. 2017), with populations doubling or tripling in many African countries, but declining in China, leading to an overall global population increase from 7.2 billion in 2015 to 9.2 billion by 2100. These levels of warming span the goal set in the UNFCCC Paris Agreement of limiting warming to well below 2 °C and to pursue efforts to limit it to 1.5 °C, as well as higher levels of warming such as 3 °C which are consistent with the current national policies under the UNFCCC in terms of their Nationally Determined Contributions (NDCs) (Rogelj et al. 2016). Table S1 indicates the global climate change scenarios used, including the implications for the magnitude and rate of sea-level rise. The scenarios were generated using an established integrated assessment approach to create scenarios including or excluding different levels of climate change mitigation so as to reach approximately 1.5, 2, 3, and 4 °C warming by 2100 (Warren et al. 2021).

Risk indicators assessed in the Topical Collection include future exposure of agricultural land to drought, human exposure to drought (Price et al. 2022) and fluvial flooding (He et al. 2022), coastal flooding (Brown et al. 2021), changes in crop yields (Wang et al. 2021), and biodiversity loss (Price et al. 2020). The multi-sectoral findings from the Topical Collection are synthesised for each country, also including (for completeness) a brief summary of recent literature on heat stress, so the reader can gain a holistic picture of how climate change is expected to affect that country, and what the greatest benefits of limiting global warming (relative to pre-industrial levels) to 1.5 °C (Paris Agreement) as opposed to 3 °C (NDCs) would be.

The study facilitates a comparison of risk accrual with global warming in the six countries, and allows a comparison of levels of risk and relative increases in risk across countries and across metrics. However, it should be noted that adaptive capacity and vulnerability, which could not be included, also vary both nationally and locally. This means that a 5% change in exposure to a hazard in one country might have a more profound effect in one country than another. Similarly, there will be differential vulnerabilities to different types of hazards such that 5% change in one metric may have much larger or smaller implications than a 5% change in another.

To explore some aspects of differential vulnerability between countries, the regional economic implications of our simulated changes in crop yields and fluvial flooding were estimated within the Topical Collection (Wang et al. 2021; Yin et al. 2021) under both the constant population scenario and SSP2. In the latter case, estimates reflect changes in population, labour force, national GDP, and capital stock within SSP2 growth trajectories (2086–2115). Yin et al. (2021) estimate direct economic losses of fluvial flooding, assuming no adaptation, by linking the spatially explicit daily flood hazard data from He et al. (2022) with country and sector specific flood depth-damage functions. These values then input to an economic Input–Output model for the estimation of indirect losses. Indirect losses reflect business interruption losses of affected economic sectors, the spread of losses towards other initially non-affected sectors, and the costs of economic recovery.

The analysis encompasses scientific uncertainty in the regional spatial pattern of climate change projection at a given level of warming. It does so by utilising 21 alternative spatial patterns of regional climate change emerging from 21 alternative climate models. The percentage of additional risk accrual avoided with respect to the risk reference baseline period of 1961–1990, if global warming (above pre-industrial levels) is limited to a lower rather than a higher level, is calculated separately for each regional climate model pattern analysed. For each risk metric, the mean percentage avoided risk across these regional climate model patterns is derived. Applied methods and associated limitations, including the calculation of sea-level rise and associated coastal flooding, are described in the Supplementary Material (SM). Further details may be found in the sister publications within the Topical Collection.

Risk indicators were estimated for all scenarios, except that for the 1.5 and 2 °C levels of warming, analysis was in the case of fluvial flooding instead carried out for the scenarios 1b and 2b, that is < 1.5 °C and < 2 °C, in which there is 66% probability of warming remaining below these levels rather than 50% (see Warren et al. (2021) for further details). Throughout this synthesis, unless otherwise indicated all comparisons use the 'exact' 1.5 and 2 °C warming scenarios 1a and 2a, rather than 1b and 2b. Spatially explicit climate scenarios were produced for each country using pattern scaling as described in the Supplementary Information, including the scenarios 1a and 2a, which were produced by pattern scaling assuming these precise levels of warming in 2100.

Table S2 indicates the metrics used in this synthesis (see Supplementary Material for detail).

2 Results

The results allow comparison of risk accrual at different levels of synthesised in two ways:

(i) A cross-sectoral comparison within each of the six countries, identifying which of the climate-related risks are of greatest concern (Sect. 2.1).
(ii) A cross-country comparison within each of the six countries, assessing in which countries the risk in various sectors accrues the most as the climate warms, and which countries benefit the most from climate change mitigation (Sect. 2.2).

2.1 Risk accrual across sectors within each country

Figure 1 summarises our projections of multi-sectoral climate change related risk accrual for warming of 1.5–4 °C by 2100 by country, detailing projected changes in crop yields, agricultural land exposed to severe drought, and areas with increasing frequency of severe flooding. The numerical median and 10–90% ranges of various risk indicators are provided in Figures S1–S6 and Tables S3–8, with the latter also including projected changes in human exposure to flooding and drought for both population scenarios, and for some countries the land remaining suitable for growing some key cash crops.

Figure 2 shows the mean proportion of additional risk accrual avoided if warming is limited to 1.5 °C as compared with 3 °C or 2 °C by 2100. Metrics shown match those shown in Fig. 1 and represent avoided mean % changes in risk indicators relative to 1961–1990. In the majority of cases, there are substantial avoided risks although climate change is projected to benefit rice and soy yields in some countries. Limiting warming to 1.5 °C as compared with 3 °C is projected to deliver very large benefits in the avoidance of severe drought (SPEI12 – 1.5) exposure in all six countries, in terms of both agricultural land exposed, and people exposed. The reductions in exposure of agricultural land to severe drought are 61%, 43%, 18%, and 21% lower in Ethiopia, China, Ghana, and India, respectively. Human exposure to severe drought is reduced by 20–80% across countries in a constant population scenario in 2100 under SSP2. The findings for each country are detailed below and summarised in Table 1.

2.1.1 Brazil

Climate change projections for Brazil generally show a decrease in precipitation during the twenty-first century, with uncertainty in the magnitude and sign of the changes, and in small areas of the west precipitation may increase (He et al. 2022). Temperatures are projected to rise and heat stress vulnerable regions have been identified in metropolitan areas of Brazil (Lapola et al. 2019), with high heat stress conditions projected to increase regionally (Bitencourt et al. 2020). Population is projected to increase from 165 to 185 million between 2000 and 2100 in the SSP2 scenario. In other socioeconomic scenarios (SSPs), the projected population ranges from 142 to 264 million in 2100.

Despite the uncertainties in precipitation changes, there is high agreement in the literature that warming is expected to drive increases in climate variability in the form of both drought (Montenegro and Ragab 2012; Penalba and Rivera 2016; Marengo et al. 2017) and fluvial flooding (Hirabayashi et al. 2013; Alfieri et al. 2017). In this study, we also find

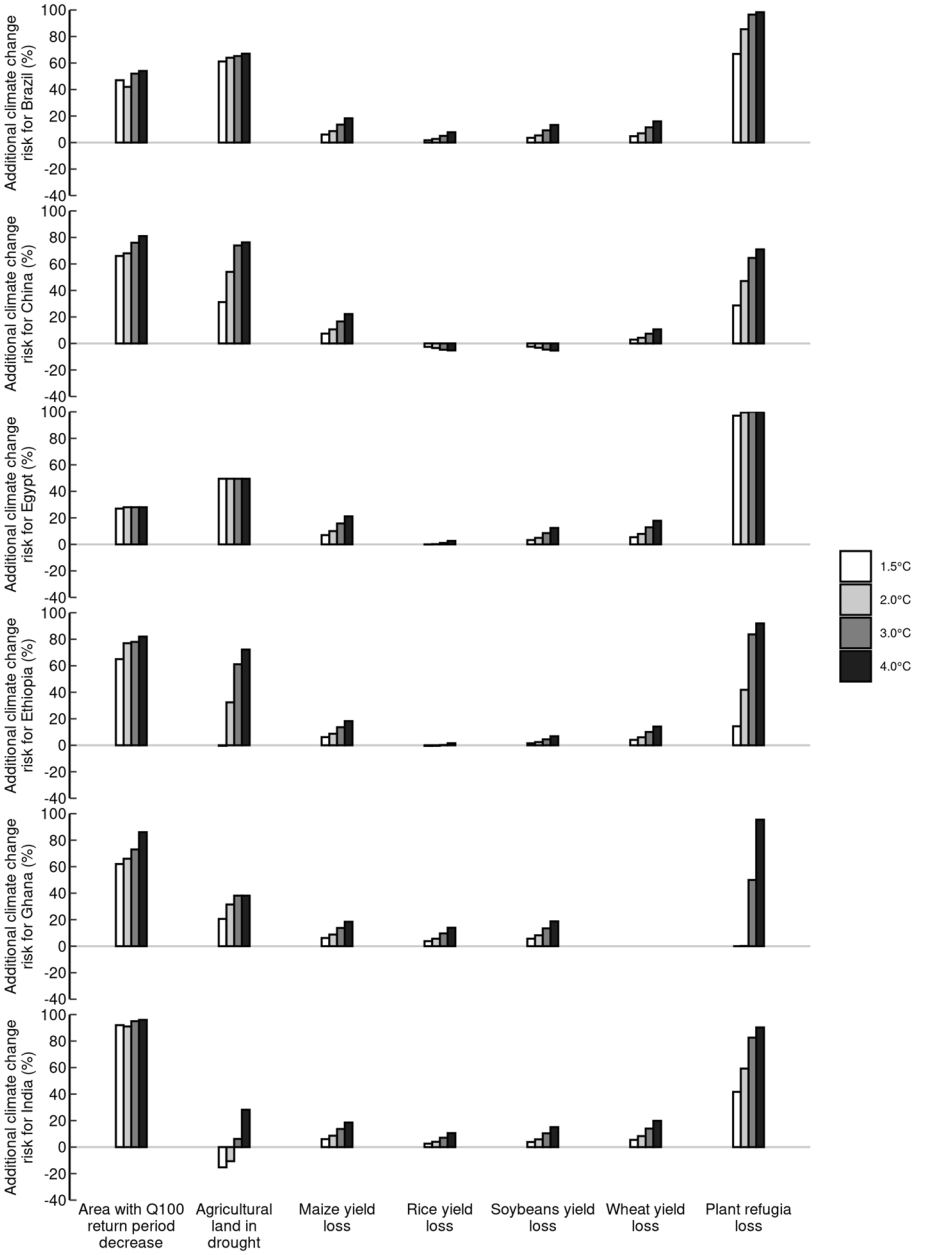

Fig. 1 Median growth in multi-sectoral additional climate change risk relative to 1961–1990, for global warming levels of 1.5–4 °C (above the 1850–1900 mean, a proxy for the pre-industrial baseline). Risk accrual is quantified using modelled percentage changes in risk indicators. Metrics shown are detailed in Table S2 and represent median changes as follows: loss of areal extent of climate refugia for plants, areal exposure of agricultural land to drought, areal exposure of land to decreasing Q100 return period, maize yield decline, rice yield decline, soybean yield decline, and wheat yield decline. Drought is defined as the probability that any given month will be classified as having a drought of magnitude − 1.5 (SPEI 12). Solid colour indicates risk levels at 4 °C global warming; dark grey, 3 °C warming; pale grey, 2 °C; and outlined, 1.5 °C

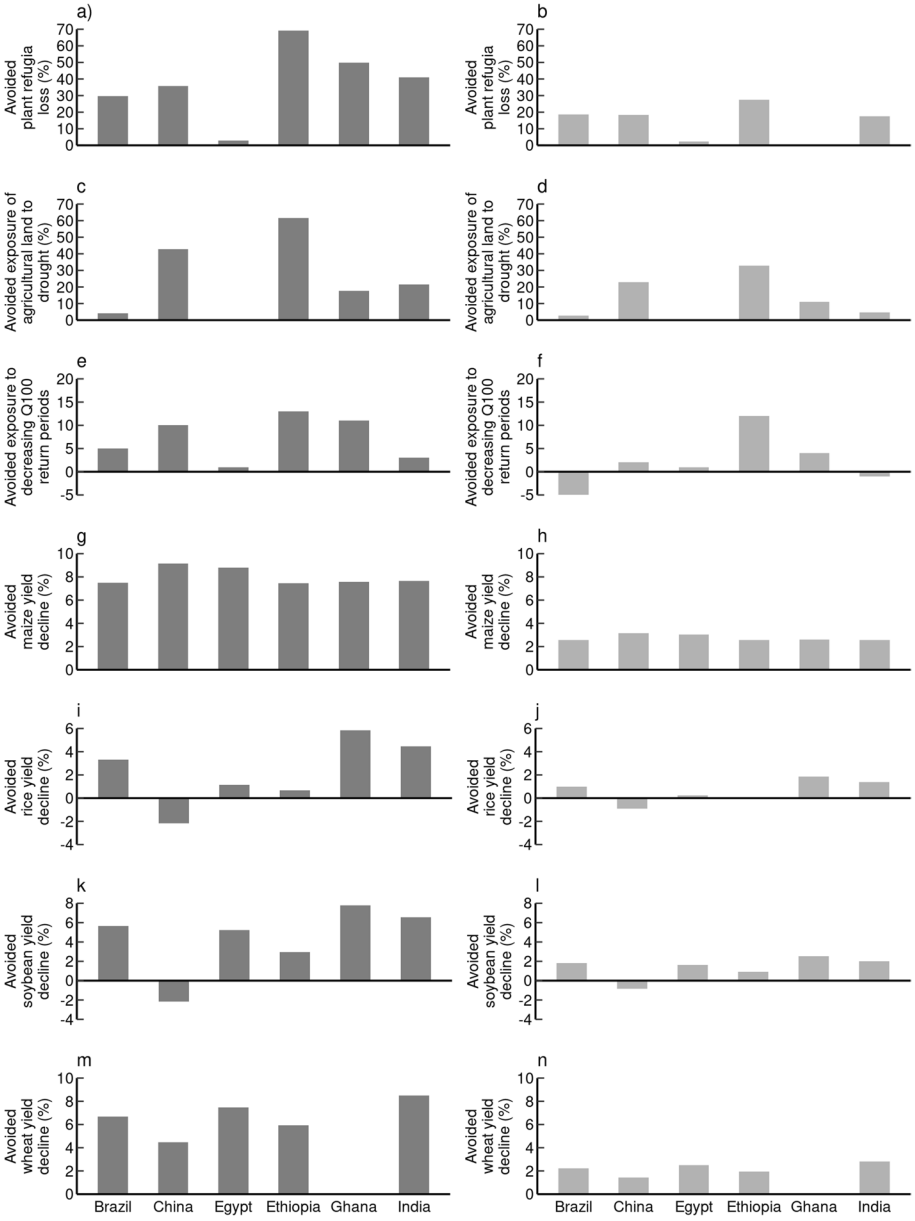

Fig. 2 Percentage of additional risk accrual avoided if warming is limited to 1.5 °C as compared with 3 °C (**a**, **c**, **e**, **g**, **i**, **k**, and **m**) or 2 °C (**b**, **d**, **f**, **h**, **j**, **l**, and **n**) by 2100. Metrics shown match those shown in Fig. 1 and represent avoided mean % changes in risk indicators relative to 1961–1990 as follows: loss of areal extent of climate refugia for plants (a and b), areal exposure of agricultural land to drought (b and d), areal exposure of land to decreasing Q100 return period (c and e), maize yield decline (d and f), rice yield decline (e and g), soybean yield decline (k and l), and wheat yield decline (m and n). Drought is defined as the probability that any given month will be classified as having a drought of magnitude – 1.5 (SPEI 12)

Table 1 Summary of projected changes in climate related risk indicators in the six countries. Risks are greater for higher levels of global warming, and are greatly reduced if warming is limited to 1.5°C rather than 2°C or 3°C. Limiting warming to 1.5°C rather than 3°C (or higher) reduces the adaptation required on the part of the human system, and allows biodiversity more time to adapt naturally. Because risks still remain at 1.5°C warming, adaptation will still be needed, but this will be much less challenging for 1.5°C warming than for higher levels. Exposure metrics refer to the constant population scenario.

PROJECTIONS FOR BRAZIL Climate change poses major risks to Brazil in terms of drought, biodiversity loss, and declines in crop yields. Limiting global warming to 1.5 °C rather than 3 °C avoids 65% of the increased human exposure to drought, and to reduce climate change induced crop yield loss by about a half. With 3 °C global warming there are very few climate refugia for plant biodiversity. Limiting global warming to 1.5 °C would allow Brazilian plant biodiversity to persist in climate change refugia on 33% of its area. The area suitable for growing a*rabica* and *robusta* coffee declines by two thirds relative to 1961–1990 for 3 °C global warming, as compared with approximately one third at 1.5 °C	PROJECTIONS FOR ETHIOPIA Climate change poses major risks to Ethiopia in terms of drought, fluvial flooding, biodiversity loss, and crop yield declines. Limiting global warming to 1.5 °C rather than 3 °C avoids 60% of the increased human exposure to drought and over half of the climate change induced crop yield loss that would otherwise occur. It also reduces fluvial flood risk, but even with 1.5 °C warming 65% of basins experience more frequent flooding. Limiting global warming to 1.5 °C rather than 2 °C or 3 °C allows most Ethiopian plant biodiversity to persist in refugia, with an estimated 87% of the country able to act as refuge for plant biodiversity at 1.5 °C warming, compared with 16% at 3 °C
PROJECTIONS FOR CHINA Climate change poses major risks to China in terms of drought, fluvial and coastal flooding, biodiversity loss, and coastal flood risk. Limiting global warming to 1.5 °C rather than 3 °C is projected to avoid 66% of the increased human exposure to drought and 10% of the increased areal exposure to fluvial flooding. With 3 °C warming two thirds of China's remaining natural areas are projected to lose half of their plant species, and 97% of agricultural land is projected to be exposed to severe drought at least once in a 30-year period. Limiting global warming to 1.5 °C or rather than 3 °C would avoid two thirds of the loss climate change refugia for plants, leaving three quarters of the country able to act as a plant refugium. It would also reduce the proportion of agricultural land exposed to severe drought to around 55% rather than 97%, and postpone coastal flood risks	PROJECTIONS FOR INDIA Climate change poses major risks to India in terms of fluvial flooding, drought, biodiversity loss, and crop yield declines. Limiting global warming to 1.5 °C compared to 3 °C is projected to avoid 70% of the increased human exposure to drought that would otherwise occur. At 3 °C, 90% of the Himalayan region is projected to experience drought lasting over a year. Fifty-three percent of the agricultural land is projected to be exposed to severe drought at 3 °C warming as compared with 32% at 1.5 °C. Limiting warming to 1.5 °C allows an estimated 58% the country to act as a safe refuge for biodiversity, compared with 17% at 3 °C
PROJECTIONS FOR EGYPT Climate change poses major risks to Egypt in terms of drought and declines in crop yields, as well as coastal flood risk in the Nile delta. With 3 °C global warming the probability of a given month's being within a 12-month drought is projected to rise to an average of almost 100%, with drought length reaching 4–5 years, additionally exposing approximately 92% of the country's population to drought compared to 6% in 1961–1990. Limiting warming to 1.5 °C is projected to avoid an estimated 20% of the increase in human exposure to drought, to allow cotton to continue to be grown in most areas and to halve the crop yield declines that would otherwise occur with 3 °C global warming	PROJECTIONS FOR GHANA Climate change poses major risks to Ghana, particularly in terms of increasing drought and declines in crop suitability and yields, particularly for cacao, and also through coastal flooding and erosion in the Volta delta. Limiting global warming to 1.5 °C is projected to avoid 80% of the increases in human exposure to drought that would occur with 3 °C warming. Limiting warming to 1.5 °C allows cacao to continue to be grown in many areas and halves the declines in crop yields that would occur with 3 °C warming. Limiting global warming to 1.5 °C or 2 °C rather than 3 °C allows most Ghanaian plant biodiversity to persist in refugia

that land exposure to severe drought increases with warming (Fig. 1) and also that human exposure to severe drought also increases with warming (Table S3a; Table S10). The probability of a given month being in an extreme drought (averaged across the country) triples in a 1.5 °C scenario, and is 5 and 7 times greater in 2 °C and 3 °C scenarios, respectively, exposing an additional 10% and 17% (respectively) of the population to drought under SSP2 assumptions in 2100 (Table S3a; Price et al. 2022). This probability reaches 50% at 4 °C warming, with some droughts exceeding 5 years in length (Price et al. 2022). The percentage of agricultural land exposed to droughts lasting for more than 1 year rises from 28 to 89% with 1.5 °C warming (Table S3b; Table S10; Price et al. 2022). With constant population, limiting warming to 1.5 °C avoids around 65% of the increase in human exposure to drought occurring with 3 °C warming (Table S10).

Despite widespread projected drought increases, projected flood risk also increases in many areas. We project that at 1.5 °C warming ~ 47% (median) of Brazil's river basins experience a decrease in return period of the twentieth-century one-in-100-year flood (Q100), ~ 54% (median) with 4 °C warming (He et al. 2022). The non-linear response of hydrological systems to increased forcing can result in flood frequency first increasing and then decreasing with warming or vice versa (Fig. 1, leftmost bars of uppermost panel). Limiting warming to < 1.5 °C avoids approximately 90% (SSP2) or 84%(constant population) of the additional total direct and indirect economic losses that are projected to occur by 2100 with 3 °C warming due to fluvial flooding (Table S9a, b; Yin et al. 2021).

Additional people at risk from coastal flooding without additional protection (climate change component only and with no socio-economic change) in 2100 range between 1.1 and 1.3% of national population per annum (from < 1.5 °C 50th percentile to 4.0 °C 50th percentile). Annual sea flood damage costs are projected to increase from 1.1% (1.5 °C 50th percentile) to 1.4% (4 °C 50th percentile) in 2100 (Brown et al. 2021) under the SSP2 scenario and without additional adaptation (Table S3a). Defences can reduce these costs. However, sea-level rise and subsequent salinisation still induce a risk to ecosystems in deltaic areas (e.g. the Amazon) if freshwater volumes or active sedimentation are not greater than the sea-level rise. Slower rates of sea-level rise (aligning to a 1.5 °C scenario) allows greater time to respond, and thus a reduction in risks to ecosystems.

Projected declines in maize (6, 13%), wheat (5, 12%), soybeans (4, 9%), and rice (2, 5%) for (1.5 °C, 3 °C) warming, respectively, relative to 1961–1990 (Table S3b), are consistent with earlier declining yield projections (Costa et al. 2009; Margulis and Dubeux 2011). Yield changes were projected to cause increasing declines in wheat production and loss to sectoral value added (showing the change in the contribution of a given sector to overall GDP). For wheat, sectoral value added declined by 1.3% at 1.5 °C and 3.9% at 4 °C (Wang et al. 2021). For rice, declines in production and sectoral value added were projected between 1.5 °C (0.19%) and 3 °C (0.30%), with losses then reducing in severity at 4 °C (0.27%) reflecting changes in both yields and commodity prices (Wang et al. 2021). Related changes to welfare were found to become increasingly positive, projected to be 1.4% at 1.5 °C and 12.8% at 4 °C, suggesting limited effects of changing rice and wheat domestic and import prices, although if the model were to consider changes in other dominant crops like soybean, then given projections from other studies (e.g. Margulis and Dubeux 2011) benefits to welfare may well weaken or become negative.

With 3 °C warming, the projected area of land suitable for growing a key cash crop, coffee, declines by about 66% for both the *arabica* and *robusta* varieties (Table S3b), as compared with approximately a 33% decline at 1.5 °C warming. This is consistent with existing literature projecting declines in suitability of between 25 and 60% by 2050 (Ovalle-Rivera et al. 2015; Tavares et al. 2018). Similarly, the area suitable for growing sugar cane is also

projected to decline (Table S3b), whilst the literature variously projects that sugar cane yields might either increase or decrease in Brazil depending on the role of changes in water use efficiency (Marin et al. 2013; Carvalho et al. 2015).

Similarly, changes in climate lead to large declines in plant refugia for biodiversity with 1.5 °C warming with only 33% projected to remain, but with additional declines by 2 °C, and further declines by 3 °C with only 3.6% refugia remaining (Figs. 1 and 2; Table S3b), with 80–100% of natural land exposed to droughts in excess of 1 year in length at 3 °C (Price et al. 2022). However, 33% of the plant refugia are projected to be preserved if global warming were limited to 1.5 °C rather than very few at 3 °C (Fig. 2a)..

2.1.2 China

Climate change projections for China show regionally differentiated mixed trends in precipitation during the twenty-first century, with uncertainty in the magnitude and sign of change. However, a consistent signal of projected increases in precipitation emerges in the North of the country, contrasting with parts of the South of the country where it is generally projected to decrease (He et al. 2022). Temperatures are projected to rise, with previous studies having attributed heat extremes in 2015 and 2016 to climate change (Imada et al. 2018; Sun et al. 2017) and projecting severe heat stress in China due to climate change by the 2040s (e.g. Lee & Min 2018). Despite uncertainties in precipitation changes, there is high agreement in the literature that warming is expected to drive increases in drought throughout the country, except the North (Wang and Chen 2014; Qin et al. 2014; Leng et al. 2015). Population is projected to decrease from 1.2 billion to 782 million between 2000 and 2100 in the SSP2 scenario. In other socioeconomic scenarios (SSPs), the projected population ranges from 1 billion to 580 million in 2100.

In this study, we find that regardless of changes in population, projected human exposure to drought increases greatly with warming (Table S4a). Regional warming increases evapotranspiration and can therefore offset the effects of small projected increases in precipitation. Across China, the probability of a given month being in severe meteorological drought triples in a 1.5 °C scenario, projecting droughts lasting more than2 years (Price et al. 2022). Severe drought probability quadruples at 2 °C. In a 4 °C scenario, the probability of drought in a given month has on average across the country risen to almost 50%, exposing approximately an additional 18% (range − 2 to + 51%) of the country's population to drought and drought length may exceed 5 years. Under 3 °C warming and SSP2 population growth an additional 8% of the country's population or 65 million (range 11.5–177.1 million) are projected exposed to severe drought than during 1961–1990 (Table S4a). Limiting warming to 1.5 °C is projected to avoid an estimated 66% of the increase in human exposure to drought occurring with 3 °C warming under a constant population scenario (Table S10), and 43% of the increase in exposure of agricultural land (Table S4b; Fig. 2). An important regional finding is that by 3 °C warming, 90% of areas with permanent snow and ice cover are projected to face severe droughts lasting longer than a year (Price et al. 2022).

The literature projects increases in flooding in China (Hirabayashi et al. 2013; Alfieri et al. 2017), although Vetter et al. (2017) highlight the discrepancies between hydrological models in the sign of projected changes in flow in major river basins. In this study, like Hirabayashi et al. (2013), we project large increases in flood risk in the North of the country, but in contrast to that study we find a mixed picture for the rest of the country. Overall, we project that with 1.5 °C warming, 66% (median) of China's major river

basins experience a decrease in return period of the one-in-100-year flood (Q100), 81% (median) experiencing a decrease in return period with 4 °C warming (He et al. 2022). Limiting warming to 1.5 °C reduces the area projected to undergo an increase in fluvial flooding by 10% as compared with 3 °C warming (Fig. 2). It avoids approximately 72% (SSP2) or 59% (constant population) of the additional total direct (and indirect) economic losses that could occur with 3 °C warming by 2100 due to fluvial flooding (Table S9a, b; Yin et al. 2021).

The number of people exposed to coastal flood risk increases with warming, even for low levels of warming. Additional people at risk from flooding without additional protection (SSP2) in 2100 range from 5.5 to 6.5% of national population per annum (from < 1.5 °C 50th percentile to 4.0 °C 50th percentile) (Table S4a). Without additional adaptation, annual flood costs are projected to be 15.4% (1.5 °C 50th percentile) to 19.3% (4 °C 50th percentile) per year in 2100 (SSP2; Brown et al. 2021). These flood costs are particularly high due to many megacities situated in low-lying coastal areas, including deltas (e.g. Shanghai (Du et al. 2020)). Impacts and costs of sea-level rise are exacerbated by high rates of land subsidence (Fang et al. 2020), particularly in deltaic areas. Coastal protection in China is already significant in length in low-lying areas, but would need to dramatically increase in highly exposed areas even with a modest rise in sea level under a scenario of aggressive climate change mitigation. This could decrease total flood costs to approximately 0.1% across all scenarios (Brown et al. 2021).

Projected climate changes lead to projected declines in the % of the country land area suitable for growing tea (from 15% in 1961–1990 to 9% with 1.5 °C warming and only 4% with 3 °C warming; Table S4b). Changes in climate were also projected to lead to declines in maize (20–24%) and wheat (9–12%) by 4 °C, accompanied by increases in the yield of soybeans (3–6%) and rice (5–6%) (Fig. 1; Table S4b). The literature contains mixed projections (both positive and negative) for the effects of climate change on wheat, rice, and maize in China owing to differing model parameterisations especially in relation to the treatment of CO_2 fertilisation (Tao and Zhang 2013; Chen et al. 2013; Xiao et al. 2018; Geng et al. 2019). However, for rice, despite potential increases in yield, concurrent offsetting declines in protein and micronutrient content are also projected (Myers et al. 2014; Zhu et al. 2018).

Yield changes were projected to cause increasing declines in wheat production and loss to sectoral value added. For wheat, sectoral value added declined by 0.02% at 1.5 °C and by 0.32% at 4 °C. For rice, an increase in production was seen with an increase in sectoral value added of 0.14% at 1.5 °C and 0.27% at 4 °C, although the additional economic benefits become more marginal from 3 to 4 °C (Wang et al. 2021). Related changes to welfare were initially positive, increasing at 1.5 °C and 2 °C by 0.47% and 0.48% (equivalent to US$400 m million), before declining at 3 °C to 0.14%. At 4 °C, projected negative impacts lead to welfare decreasing by 0.68%, reflecting the trade-off between decreasing rice prices, increasing wheat prices, and increasing import prices for rice and other commodities at higher warming levels.

Climate change is projected to lead to large declines in plant refugia for biodiversity between 1.5 °C and 2 °C, and further declines between 2 °C and 3 °C (Fig. 1) (Price et al. 2020). If warming were limited to 1.5 °C 77% of the country can act as a refugium for plants, rather than only 23% at 3 °C (Fig. 2; Table S4b).

Considerable benefits could accrue if warming were limited to 1.5 °C compared with 3 °C or higher (Fig. 2), especially for drought exposure, wheat and maize yields, and biodiversity conservation. This limits the amount of adaptation otherwise required on the part of the human system, and allows biodiversity more time to adapt naturally.

2.1.3 Egypt

Climate change projections for northern and central Egypt generally show a decrease in precipitation during the twenty-first century, whilst precipitation in the south may increase (He et al. 2022). Temperatures are projected to rise and existing studies have identified an influence of climate change on elevated heat stress during individual heatwave events over Egypt (e.g. Mitchell 2016). Further, Ceccherini et al. (2017) showed that heat waves became more widespread across Africa, particularly from 2006 to 2015, compared to 1981 to 2005, including affecting a greater proportion of Egypt. Population is projected to increase from 67 to 130 million between 2000 and 2100 in the SSP2 scenario. In other socioeconomic scenarios (SSPs), the projected population ranges from 97 to 191 million in 2100.

Few studies have projected changes in drought risk for Egypt. Hoegh-Guldberg et al. (2018) showed that an increase in the number of consecutive dry days in Egypt is likely with future climate change, whilst Schewe et al. (2014) projected significant reductions in precipitation across much of Egypt with 5 GCMs at 2 °C warming. Population is projected to increase from 67 to 130 million between 2000 and 2100 (SSP2).

In this study, we find that regardless of changes in population, human exposure to drought increases with warming as compared with 1961–1990. Averaged across Egypt, the probability of a given month being in a severe meteorological drought (SPEI12) increases considerably even with 1.5 °C warming (Price et al. 2022). This puts an additional 70% of the population (40–100 million people depending on socioeconomic scenario) (Table S5a) and 100% of the agricultural land (Tables S5b and S10) projected to be exposed to drought of at least 1 year in length. Drought probability is projected to reach 90% with 2 °C warming with severe droughts reaching 2 years. By 3 °C, the probability of a given month's being within a 12-month drought has on average across the country risen to almost 100%, with severe drought becoming the new normal condition, additionally exposing over 90% of the population to drought irrespective of population growth scenarios (Table S5a). These projections are indicative of large increases in projected drought in Egypt, despite the known issues concerning the potential tendency of the drought metric used in our study in arid regions such as Egypt to overestimate potential changes (Cook et al. 2014). Limiting warming to 1.5 °C avoids an estimated 20% of the increase in human exposure to drought that would otherwise occur with 3 °C warming (constant population) (Table S10). In practice, Egypt's ability to withstand meteorological drought will depend greatly on the management of the Nile watershed.

Studies generally also project increased fluvial flood risk in the Nile basin, especially at higher levels of warming (Hirabayashi et al. 2013; Dankers et al. 2014; Alfieri et al. 2017; Dottori et al. 2018). Here, we project that at 1.5 °C warming only around 27% (median) of Egypt's major river basins experience a decrease in return period of the one-in-100-year flood (Q100), 28% (median) with 4 °C warming (He et al. 2022). The Q100 return periods along the Nile river show higher occurrence of floods (in agreement with Hirabayashi et al. 2013) with low to moderate agreement, although these are relatively insensitive to the level of warming. The increasing flood risk along the Nile river within Egypt is likely due to the increasing precipitation projected in the south of Egypt and its upstream countries such as Sudan and Ethiopia, even though precipitation is projected to decrease in a large part of Egypt, in particular the north (He et al. 2022). Limiting warming to < 1.5 °C is projected to avoid approximately 70% (SSP2) or 60% (constant population) of the additional total direct and indirect economic losses

that could occur with 3 °C warming by 2100 due to fluvial flooding (Table S9a, b; Yin et al. 2021).

Risks to coastal flooding simultaneously increase, particularly in the northern coast and around the Nile delta, where salinisation could be a growing issue with sea-level rise. People at risk from flooding without additional protection (SSP2) in 2100 range from 8.8 to 10.9% of the national population per annum (from < 1.5 °C 50th percentile to 4.0 °C 50th percentile). Without additional adaptation, annual sea flood damage costs are projected to be between 9.5% (1.5 °C 50th percentile) and 13.9% 4 °C (4.0 °C 50th percentile) of GDP in 2100 (SSP2). Adaptation could reduce these costs to less than 0.1% of GDP per year. However, it is likely those at risk and costs without protection will be lower than projected here as higher flood defence standards around the Nile delta have not been accounted for.

Only 2% of the country is classified as natural land (as compared to bare ground), but even within this very small extent, the potential extent of climate refugia for plants declines with warming (Table S5b; Price et al. 2020). The projected climate change also leads to projected declines in crop yields, notably for wheat and rice (Wang et al. 2021) ranging from 0 to 7% for 1.5 °C warming, compared with 2–18% at 3 °C warming, consistent with earlier projections of declining yields (Figure S1b; Table S6b) (Jones and Thornton 2003; Liu et al. 2008). These yield changes were projected to cause increasing declines in the production of wheat and rice, with sectoral value added declining 1.4% at 1.5 °C and 4.0% at 4 °C for wheat and 0.1% at 1.5 °C and 0.5% at 4 °C for rice (Wang et al. 2021). Egypt is projected to suffer impacts to welfare due to negative impacts of climate change on rice and wheat yields, subsequent production, and increasing crop prices. Welfare losses range from 4.6% at 1.5 °C to 17.4% at 4 °C. Whilst trade can mitigate impacts of decreasing agricultural production at a country level, as countries can import more goods, it will provide less of a buffer for major food-importing countries such as Egypt, who will face the impacts of declines in domestic production alongside increasing global food prices. Areas of the country suitable for growing cotton are also projected to decline (Table S5b). Limiting warming to 1.5 °C as compared with 3 °C would deliver benefits to agriculture (Fig. 2), limiting the amount of adaptation otherwise required.

2.1.4 Ethiopia

Climate change projections for Ethiopia generally show an increase in precipitation during the twenty-first century with strong consistency across climate models but large variance (He et al. 2022). Temperatures, particularly daytime and warm extremes, are projected to rise (Gebrechorkos et al. 2019), with associated increases in human exposure to heat stress (e.g. Andrews et al. 2018) and associated implications of future heat stress conditions for livestock production in Ethiopia, by varying amounts across the country depending on livestock type (Rahimi et al. 2021). Population is projected to increase from 63 to 191 million between 2000 and 2100 (SSP2). In other SSPs, the projected population ranges from 135 to 287 million in 2100.

Few studies have projected changes in drought risk for Ethiopia, but Niang et al. (2014) argued that risk of drought will decrease across East Africa in the future due to projected increases in precipitation. We find that exposure of agricultural land and of humans to drought both increase strongly with warming (Fig. 1; Table S6a, b; Table S10). The probability of a given month's being in a meteorological drought exceeding a year in length doubles with 2 °C warming, exposing 58% of the agricultural land to drought (Table S6a; Table S10; Price et al. 2022). The probability of drought reaches 20% with 3 °C warming

and 27% with 4 °C warming, with drought lengths reaching 3–4 years in length with 3 °C warming, additionally exposing approximately an additional 12% (1–42%) of the country's population (22 million; 1.1–68.6; SSP2) (Table S6a; Table S10).

Fluvial flood risk in Ethiopia is currently low. Several studies project increased flood risk in Ethiopia, especially at higher levels of warming (Hirabayashi et al. 2013; Dankers et al. 2014; Müller et al. 2014; Gosling and Arnell 2016; Winsemius et al. 2016; Alfieri et al. 2017) but inconsistencies exist in the sign of the change in risk, especially at lower levels of warming (Vetter et al. 2017). In this study, we project increasing flood frequency in the south-east and decreasing frequency in south-west, with a more mixed pattern in the north-west. We project that at 1.5 °C warming, around 65% (median) of Ethiopia's major river basins experience a decrease in return period of the one-in-100-year flood (Q100), with 82% (median) experiencing a decrease in return period with 4 °C warming (He et al. 2022). Limiting warming to < 1.5 °C is projected to avoid approximately 60% (SSP2) or 54% (constant population) of the additional total direct and indirect economic losses that could occur by 2100 with 3 °C warming due to fluvial flooding (Table S9a, b; Yin et al. 2021).

Projected climate change leads to projected declines in yields of maize and wheat (ranging from 3 to 8% for 1.5 °C warming as compared with 10–21% at 3 °C warming (Table S6b), consistent with earlier projections of declining yields (Jones and Thornton 2003; Liu et al. 2008; Araya et al. 2015; Abera et al. 2018). Yield changes were projected to cause increasing declines in the production of wheat, with sectoral value added declining by 0.66% at 1.5 °C and by 1.2% at 4 °C. For rice, a significant increase in production is projected, with value added increasing by between 4.6% at 1.5 °C and by 18.1% at 4 °C (Wang et al. 2021). This reflects the smaller effects of climate on rice yields, but large increases in the price of domestic and imported rice, driving increased rice production. Welfare is projected to decline, due to increasing prices, with losses of 2.9% at 1.5 °C and 8.4% at 4 °C. Whilst trade can mitigate impacts of decreasing agricultural production at a country level, as countries can import more goods, it will provide less of a buffer for major food-importing countries such as Ethiopia, which will face the impacts of declines in domestic production alongside increasing global food prices.

Ethiopia has large tracts of natural land, with 75% of the country being classified as natural, meaning it provides a very important refuge for biodiversity as climate changes especially at < 2 °C warming (Fig. 1 and Table S6b; Price et al. 2020). With 3 °C warming and above, there is much greater biodiversity loss in the country, although some refugia are still projected to remain, especially in montane areas.

Limiting warming to 1.5 °C rather than 3 °C avoids around 65% of the loss of plant refugia that would otherwise occur (Fig. 2), 60% of the increase in human exposure to drought relative to 1961–1990 occurring with 3 °C warming under a constant population scenario and 61% of the increase in drought exposure in agricultural land (Table S10; Fig. 2). Considerable benefits could therefore accrue if global warming were limited to 1.5 °C as compared with 3 °C or higher (Fig. 2), especially for drought exposure and crop yields, limiting the amount of adaptation otherwise required.

2.1.5 India

The population is projected to increase from 1 to 1.6 billion between 2000 and 2100 (SSP2). In other SSPs, the projected population ranges from 1.2 to 2.56 billion in 2100. Previous literature has identified observed heat stress events in India to be exacerbated by

climate change (Wehner et al. 2016). Furthermore, large increases of extreme heat waves and heat stress conditions in India are projected due to climate change by the end of the century (Im et al. 2017; Murari et al. 2015).

Climate change models generally project increasing precipitation across India, except in very small areas (He et al. 2022). Correspondingly, we project increasing flood frequency nearly countrywide, with moderate to strong agreement across models, with 1.5 °C warming, with 92% of major river basins affected. However, in parts of the Himalayas, flood frequency is projected to decline. However, our approach does not capture floods associated with the melting glaciers. Limiting warming to < 1.5 °C is projected to avoid approximately 87% (SSP2) or 84% (constant population) of the additional total direct and indirect economic losses that could occur with 3 °C warming due to fluvial flooding (Table S9a, b; Yin et al. 2021). Our findings are consistent with existing literature (Hallegatte et al. 2010; Ranger et al. 2011; Dankers et al. 2014; Gosling and Arnell 2016; Winsemius et al. 2016; Alfieri et al. 2017; Dottori et al. 2018).

Despite the projected increase in precipitation and fluvial flooding, droughts are projected to last as long as 2 years with 1.5 °C warming, the monthly SPEI12 probability doubling with 2 °C warming (Price et al. 2022). Human exposure to drought is also projected to increase on average across the country (Table S7a), due to changes in climate variability and also because regional warming increases evapotranspiration offsetting smaller projected precipitation increases. This is consistent with earlier studies (Mujumdar et al. 2020) using SPEI. Limiting warming to 1.5 °C avoids 70% of the increase in human exposure to drought risk occurring with 3 °C warming with constant population (Table S10) and 21% of the increase in exposure to agricultural land (Fig. 2). An important regional finding is that by 3 °C warming 90% of areas with permanent snow and ice cover are projected to face severe droughts lasting longer than a year (Price et al. 2022) with 3-year droughts possible with 2 °C warming, and 4-year-long droughts with 4 °C warming (Table S10).

We project declines in crop yields of 8–21% for wheat, maize, rice, and soybeans between 1961 and 1990 and 3 °C warming (Table S7b). Yields are projected to decline by 1–7% in a 1.5 °C scenario. Hence, limiting warming to 1.5 °C could avoid over half of the reductions otherwise occurring by 3 °C warming (Fig. 2). These declines in the production of rice and wheat are estimated to decrease value added by 1.1% at 1.5 °C and 3.8% at 4 °C for wheat, and by 1.2% at 1.5 °C and 4.3% at 4 °C for rice (Wang et al. 2021). The domestic prices of rice and wheat increase significantly from the baseline, in line with findings from other studies (Bandara and Cai 2014; Ren et al. 2018) resulting in welfare losses of 1.9% at 1.5 °C and 6.9% at 4 °C. Projected climate changes also lead to projected declines in the percentage of the country suitable for growing tea (from 7% in 1961–1990 to 5% with 1.5 °C warming; 3.5% with 3 °C), sugar cane (from 6% in 1961–1990 to 4% with 1.5 °C warming to 3% with 3 °C warming), and also the *hirsutum* variety of cotton (Table S7b). Existing work has projected declines in yield of cotton (Hebbar et al. 2013) and in the sucrose content of sugar cane (Sonkar et al. 2020) due to warming.

Coastal flood risks in India are projected to increase due to sea-level rise leading to the potential of increases in flooding and erosion (Table S7a). In deltaic areas, flood risk will potentially be further enhanced by subsidence, unless there are sufficient rates of sedimentation. People at risk from flooding without additional protection (SSP2) in 2100 range from 1.8 to 2.2% of national population per annum (from < 1.5 °C 50th percentile to 4.0 °C 50th percentile). Annual flood costs as a proportion of GDP in 2100 are projected to be between 3.1% (50th percentile scenario 1.5 °C) and 4.0% (50th percentile scenario 4.0 °C), with costs concentrated in urban areas (SSP2). With protection, total annual costs could decline to less than 0.1% across all scenarios. Further non-monetary costs or impacts may

evolve through secondary impacts, including people flooded, or changes in livelihoods due to increased salinisation. Cyclones can greatly increase flood risk, but improved warning (Iwasaki 2016) has helped reduce this. Autonomous adaptation at a local scale is likely to reduce long-term risk, simultaneous to national-level support (Brown et al. 2018).

There are large declines of plant biodiversity in India projected between 1.5 and 2 °C warming, and further between 2 and 3 °C warming (Fig. 1; Table S7b). Many of the areas that could act as plant refugia in India are already in agricultural use, but there are still important refugia remaining in the Western Ghats and the Himalayas. Limiting warming to 1.5 °C could avoid much of the plant refugia loss otherwise projected to occur by 3 °C warming (Fig. 2).

2.1.6 Ghana

Temperature averages and extremes have previously been shown to be increasing in the Gulf of Guinea and Sahel region (Ringard et al. 2016). Previous sectoral analyses for Ghana have shown that past impacts of extreme heat on healthcare have been further amplified by urban heat island effects and thermal inertia of buildings (Codjoe et al. 2020), whilst some adaptation methods have been implemented in response to increasing heat in the agriculture and mining sectors (Nunfam et al. 2019). Precipitation projections are inconsistent, but still indicate a clear south-north divide: areas in the south of the country projected to experience decreasing precipitation and areas in the north projected to experience increases (He et al. 2022). The population is projected to increase from 19 to 57 million between 2000 and 2100 (SSP2). In other SSPs, the projected population ranges from 40 to 88 million in 2100.

Few previous studies have examined potential drought in Ghana due to climate change, but Oguntunde et al. (2017) projected increased drought likelihood and areal extent. Consistent with this, our simulations project steady increases in monthly SPEI-12 drought probability, doubling with 2 °C warming and reaching 23% with 3 °C warming (Table S10; Price et al. 2022). Drought length may exceed 2 years with 1.5 °C warming, exceed 3 years with 2 °C warming, and be close to 4 years at 3 °C warming (Table S10). Human exposure to drought affected 7% of the population in 1961–1990 in our simulations, with an additional 12% of the population (or 7.1 million, range 3.9–26.4 million people) with 3 °C warming (Table S8a) and 15% (range 9–65%) (or 9.3 million, range 4.9–36.6 million people) with 4 °C warming (SSP2). Limiting warming to 1.5 °C rather than 3 °C avoids around 80% of the increase in human exposure to drought relative to 1961–1990 (constant population; Table S10) and avoids an additional 18% of agricultural land being exposed to drought (Table S10; Fig. 2).

Our simulations mostly project decreasing exposure to flood risk in the south of the country where precipitation is projected to fall, and increasing exposure in the north where precipitation is projected to rise. Overall, a net increase in human exposure to flood risk in the country occurs with additional warming, with 62% of major river basins at increased flood risk for 1.5 °C warming and 86% at 4 °C warming (Table S8a). Our finding of decreased flood risk in the south is consistent with some studies (Müller et al. 2014) but inconsistent with others (Hirabayashi et al. 2013). Limiting warming to < 1.5 °C is projected to avoid approximately 85% (SSP2) or 81% (constant population) of the additional total direct and indirect economic losses that could occur with 3 °C warming by 2100 due to fluvial flooding (Table S9a, b; Yin et al. 2021). Overall, the literature contains mixed projections for future flood risk in Ghana, including both increases and decreases either

locally or overall (McCartney et al. 2012; Hirabayashi et al. 2013; Dankers et al. 2014; Müller et al. 2014; Gosling and Arnell 2016; Alfieri et al. 2017), probably due to the large uncertainties in changes in precipitation.

Although our projections of increasing coastal flood risks in the country appear small in percentage terms (Table S8a), this masks a serious local problem. In Ghana, a major threat is flooding and erosion in the Volta delta as 88% of the delta is below 5 m in elevation (Brown et al. 2018). Erosion of the delta and other shores is currently a major issue due to natural processes, but also enhanced erosion through sand mining. In Ghana, people at risk from flooding without additional protection (SSP2) in 2100 range from 1.6 to 2.0% of national population per annum (from < 1.5 °C 50th percentile to 4.0 °C 50th percentile). In 2100 and without additional adaptation, annual sea flood costs are projected to be between 2.2% (5th percentile scenario 1.5 °C) and 3.1% (50th percentile 4 °C) of GDP (Brown et al. 2021; SSP2). With protection, total annual costs are projected to decline to less than 0.1% regardless of scenario. Hence, in Ghana adapting to sea-level rise must go hand-in-hand with wider development and livelihood improvements.

Climate changes are projected to drive declines in yields of maize, rice, and soybean, with declines of 3–8% for 1.5 °C warming, 8–17% for 3 °C, and 11–19% for 4 °C (Figure S1b; Table S8b). Limiting warming to 1.5 °C avoids on average around two thirds of the decline in yields projected to occur with 3 °C warming (Fig. 2). Yield changes were projected to cause increasing declines in the production of rice, with sectoral value added declining by 0.52% at 1.5 °C and 1.54% at 4 °C (there is no cultivation of wheat in Ghana) (Wang et al. 2021). This results in negative changes to welfare, with projected losses of 2.2% at 1.5 °C and 3.7% at 4 °C. As climate warms, the area of land suitable for growing the most important cash crop, cacao (ingredient of chocolate), declines from 39% presently to 24% with1.5 °C warming and only around 13% with 3 °C warming (Table S8b).

Climate refugia for plants are projected to persist strongly in Ghana, especially for lower levels of warming (Fig. 1). Limiting warming to 1.5 °C or 2 °C rather than 3 °C could allow most Ghanaian biodiversity to persist in refugia (Fig. 2). However, some 50% of these refugia are in use for agriculture, but the rest remain presently as natural land.

2.2 Cross-country comparison of risk-accrual with global warming

In all six countries, exposure of agricultural land to drought, the frequency of severe fluvial flooding and coastal flooding, and risks to biodiversity are all projected to increase with global warming (Fig. 1); crop yields generally decline. The risk metrics that increase most dramatically with warming are the proportion of agricultural land in drought and the loss of climate change refugia for plants (Fig. 1). Hence, limiting warming to 1.5 °C rather than 3 °C reduces risks of biodiversity loss (as indicated by the loss of plant refugia), exposure to drought, fluvial and coastal flooding, and (in general) declines in crop yield (Fig. 2). Furthermore, India and China both have large areas under 'permanent' ice and snow cover, and by 3 °C global warming, 90% of these areas are projected to face severe droughts lasting longer than a year. Because risks still remain at 1.5 °C warming, adaptation will still be needed, but this will be much less challenging for 1.5 °C warming than for higher levels.

Due to increased climate spatial heterogeneity, and the interaction of temperature with evapotranspiration, many countries such as Brazil and China display simultaneous increases in flood risk as well as drought. Fluvial flood hazard, as measured by the Q100 index, increases strongly with warming in Ghana, Ethiopia, and China. Limiting warming to 1.5 °C rather than 3 °C avoids 71–96% of the increase in population exposure to

flood risk under a constant population scenario (Table S11) although the proportions of the countries' populations exposed to flood risk are small. At 1.5 °C warming, 47%, 66%, 27%, 65%, 62%, and 92% of the major basin areas in Brazil, China, Egypt, Ethiopia, Ghana, and India, respectively, experience a decrease in the return period of the twentieth-century 1-in-100-year flood, rising to 54%, 81%, 28%, 82%, 86%, and 96% with 4 °C warming (He et al. 2022; Table S12). The decrease in return periods leads to increased human exposure to flood risks, particularly with 4 °C warming, where exposure in the major river basin areas in Brazil, China, Egypt, Ethiopia, Ghana, and India increases by 589%, 202%, 5662%, 254%, 624%, and 2765% relative to the 1961–1990 reference period, respectively (He et al. 2022).

These trends create regional economic risks. Assuming no adaptation, fluvial flood risk is projected to cause an increase in total (direct + indirect) economic damages for all countries between < 1.5 and 4 °C, particularly when considering socio-economic change, due to increases in the assets exposed directly to flooding and the potential for large indirect losses due to business interruption losses which cause a slowdown in the growth rate of the economy from its potential trajectory. For both the climate change only and climate change and socioeconomic scenarios, total economic losses are projected to be largest in China and India when expressed in absolute terms, reflecting increasing flood risk as well as increasing population and economic assets at risk. However, when expressed as a relative share of national GDP, Egypt faces the largest indirect losses (up to 3% loss to GDP at 4 °C) when considering socioeconomic change. Importantly, all countries could benefit from reduced flood damages this century if warming is limited to < 1.5 °C compared to 3 °C and 4 °C (Yin et al. 2021). In particular, under the constant population scenario, India and Brazil's avoided flood damages are projected to be 87% and 90% lower, respectively, when warming is limited to < 1.5 °C compared to 3 °C, and as high as 93% and 95% when compared to 4 °C (Table S9a, b and Supplementary Material).

With 1.5 °C global warming, the probability (averaged across the country) of a 12-month severe drought is projected to triple in Brazil; double in China, Ethiopia, and Ghana; and substantially increase in Egypt (Table S10). By 2 °C warming, the length of droughts in all countries except India may exceed 3 years. With 3 °C warming, more than 50% of the agricultural area in each country could be exposed to droughts of longer than 1 year (80–100% in Brazil, China, Egypt, and Ethiopia) whilst with 1.5 °C warming the percentages drop considerably to 55% in China and 25% in Ethiopia (Table S10). India and China both have large areas under 'permanent' ice and snow cover. With 3 °C warming, 90% of these areas are projected to face severe droughts lasting longer than a year (Price et al. 2022). Other natural areas are similarly impacted. Brazil, China, Egypt, and Ethiopia all show that 80–100% of land classified as natural as being under severe droughts lasting longer than 1 year, 60–80% in Ghana and India.

Crop yields, with some exceptions, are also generally projected to decline (Fig. 1). Projected changes in crop yields and subsequent production of rice and wheat can also increase economic risks. Wheat production and sectoral value added is projected to decline in all countries, with more severe reductions at higher warming levels. For wheat, losses to sectoral value added are most severe in India, Brazil, and Egypt. Projections for rice are more mixed. China and Ethiopia are both projected to see an increase in rice production and sectoral value added, whilst losses are projected for the other countries. Overall, changes in both rice and wheat yields lead to marginal benefits to GDP and welfare in China up to 3 °C, although at 4 °C this trend reverses and losses to GDP are recorded. The remaining countries face negative impacts on GDP, which are largest in India. Welfare is also projected to decline in India, Ghana, Ethiopia, and

Egypt, with Egypt facing particularly severe impacts compared to the other countries (Wang et al. 2021). These estimates do not consider the projected decline in nutrient content of crops as climate warms (Zhu et al. 2018).

Concurrently, we project large declines in the climate suitability for important cash crops in several countries (such as cacao (chocolate) in Ghana, coffee in Ghana and Brazil, sugar cane in Brazil and India, and tea in China and India) (Tables S3–8b). This is generally consistent with the existing literature, although there are very few studies on tea. One study for China and India (Beringer et al. 2020) suggests that climate change could generally increase yields, but this is based on simulations that assumes CO_2 fertilisation, and this is not borne out by recent observations of climate-change related yield declines of tea yield in the Assam region of India (Duncan et al. 2016).

Across the six countries, climate refugia for biodiversity declines with warming, e.g. between 1.5 and 2 °C, and further between 2 and 3 °C, with plant refugia declining faster than vertebrate (animal) refugia (Figs. 1 and 2; Price et al. 2020). Climate refugia persist to a great extent at lower levels of warming in Ghana, China, and Ethiopia, but very few refugia remain under 4 °C warming except in China. Extensive refugia persist in Ghana with 2 °C and even 3 °C warming, but many of the remaining refugia are not in protected areas. India has already lost most of its climate change refugia for biodiversity to land use change. In contrast, Ethiopia has large tracts of natural land, with 75% of the country being classified as natural, and can provide an important refuge for biodiversity as the climate changes. Even at 1.5 °C warming, biodiversity loss is already significant in Brazil (Fig. 1) and our previous work (Warren et al. 2018) has highlighted the importance of facilitating natural adaptation in Amazonia by protecting large areas.

For coastal flood risk, Egypt and China are projected to have the greatest proportion of people at risk from sea-level rise without additional adaptation. In Egypt, especially around the Nile delta and Alexandria, protection levels are higher than the remainder of the coast (Hinkel et al. 2012), so the number of people affected is likely to be lower. For the five coastal countries, these results indicate that China is likely to experience the greatest impacts of sea-level rise due to densely populated cities located in low-lying areas with relatively low standards of protection. This follows previous assessments of the impacts of sea-level rise, including developing nations (e.g., Brown et al. 2019; Dasgupta et al. 2009). Throughout all countries studied, non-climatic factors are also important in influencing impacts. These include the use of a portfolio of approaches to adaptation to reduce impacts including land claim, sediment availability which can be restricted through damming or removed through beach mining, and recognition and action into land subsidence which can exacerbate sea-level rise. Adaptation to sea-level rise must go hand-in-hand with socio-economic development, including livelihood protections (Brown et al. 2018) for which so many living and working on the coast depend. Due to the commitment to sea-level rise, many of these risks and projected levels of people at risk will happen regardless of future actions to mitigate against climate change. Potential impacts do increase from a < 1.5 to a 4 °C in a 2100 global warming scenario in all countries assessed. The lower the rate and magnitude of sea-level rise, the lower the risk of flooding and the potential for people to move away from the coast. Adaptation (e.g. building dikes) can reduce the potential number of people flooded, or those who may need to move away from at-risk locations. Furthermore, mitigating climate change reduces potential damage and adaptation costs. However, it is the longer locked-in centennial-scale implications of rising sea-levels that pose a greater threat to populations (Goodwin et al. 2018; Brown et al. 2018; Nicholls et al. 2018) justifying stringent climate change mitigation.

3 Discussion and conclusions

The necessity of selecting metrics to quantify risks creates inevitable limitations. For example the index used for drought, SPEI12, may be over-sensitive to increasing evapotranspiration in areas of high aridity, whilst the choice of Q100 (the return period of the twentieth-century 1-in-100-year flood) as an index for flood risk focuses the analysis on very large floods. Existing or planned flood defences or dams that may exist on rivers are not included, nor are potential additional defences against coastal flooding. Our statistically based projections of crop yields exclude potential positive effects of CO_2 fertilisation and also negative effects of declines in crop nutrient content and increases in pests/disease. The assessment of climate change on biodiversity does not capture the potential additional effects of changes in climate variability, and for this reason we also quantified the exposure of natural land to drought (Price et al. 2022). Importantly, a full assessment of the potential role of adaptation in reducing climate change risks was beyond the scope of this study. For a further discussion of limitations, see Supplementary Material.

Despite these limitations, the study has identified important trends in climate change risk in the six countries studied. With a few exceptions, increasing warming leads to greater exposure to drought, fluvial and coastal flooding, and greater declines in biodiversity and crop yields. All countries except India are projected to experience large increases in both drought frequency and length, and hence, in terms of risk magnitude, the benefits of limiting warming to 1.5 °C rather than 3 °C are greatest in terms of reduced exposure to drought. All nations experience an increase in hazards due to sea-level rise, which is projected to rise globally, even if temperatures stabilise. However, stabilisation reduces the rate of sea-level rise, potentially reducing human migration from inundated areas as compared with the case that temperatures continue to increase globally.

This study was limited to exploration of two population scenarios: one in which population does not change and one following a middle-of-the-road scenario (SSP2). Human exposure to risks such as drought are considerably higher in Africa in the SSP2 scenario as compared with the constant population scenario, owing to the doubling or tripling of human populations in some African countries projected in this scenario by 2100. Future research might usefully explore the implications of other socioeconomic scenarios, in particular the SSP3 scenario in which populations in Egypt, Ethiopia, Ghana, and India reach 191, 287, and 256 million and 2.56 billion, respectively. Whilst increased levels of development (in some of the SSPs) could potentially reduce human vulnerability to some climate change risks, potentially by facilitating additional adaptation (for example in coastal cities; Brown et al. 2019), many risks remain large even at higher levels of development and some are unaffected or may even be exacerbated by development (for example risks to biodiversity).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-023-03646-6.

Author contribution R. Wa. wrote the paper and coordinated the project; O. A., S. B., N. F., Y. He., D. M., Z. Y., Y. Hu., K. J., A. K.-A., and D. W. conducted the model simulations and contributed to writing the paper; D. G., D. V. V., T. O., C. W., and P. G. provided the underlying driving climate change and sea-level scenarios and data; K. E. and D. G. advised; N. F. and R. Wr. collated and processed the model output and drew the figures and tables; and R. J. and N. F. collated the references.

Funding This research leading to these results received funding from the UK Government, Department for Business, Energy and Industrial Strategy, as part of the 1.5–4 °C warming project under contract number UKSBS CR18083-S2.

Data availability This publication is based on the extraction of data from an existing well-established database, and hence, code availability is not applicable. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate N/A.

Competing interests The authors declare no competing interests.

References

Abera K, Crespo O, Seid J, Mequanent F (2018) Simulating the impact of climate change on maize production in Ethiopia East Africa Environ. Syst Res 7:4. https://doi.org/10.1186/s40068-018-0107-z

Alfieri L, Bisselink B, Dottori F et al (2017) Global projections of river flood risk in a warmer world. Earths Future 5:171–182. https://doi.org/10.1002/2016EF000485

Andrews O, Le Quéré C, Kjellstrom T et al (2018) Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study. Lancet Planet Health 2:e540–e547. https://doi.org/10.1016/S2542-5196(18)30240-7

Araya A, Hoogenboom G, Luedeling E et al (2015) Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. Agric Meteorol 214–215:252–265. https://doi.org/10.1016/j.agrformet.2015.08.259

Bandara JS, Cai Y (2014) The impact of climate change on food crop productivity, food prices and food security in South Asia. Econ Anal Policy 44:451–465. https://doi.org/10.1016/j.eap.2014.09.005

Beringer T, Kulak M, Müller C et al (2020) First process-based simulations of climate change impacts on global tea production indicate large effects in the world's major producer countries. Environ Res Lett 15:034023. https://doi.org/10.1088/1748-9326/ab649b

Betts RA, Brown K (2021) Introduction. In: Betts RA, Haward AB, Pearson K (eds) The Third UK Climate Change Risk Assessment Technical Report. Prepared for the Climate Change Committee, London

Bitencourt DP, Muniz Alves L, Shibuya EK et al (2020) Climate change impacts on heat stress in Brazil—past, present, and future implications for occupational heat exposure. Int J Climatol 41:E2741–E2756. https://doi.org/10.1002/joc.6877

Brown S, Nicholls RJ, Lázár AN et al (2018) What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? Reg Environ Change 18:1829–1842. https://doi.org/10.1007/s10113-018-1311-0

Brown S, Nicholls RJ, Pardaens AK et al (2019) Benefits of climate-change mitigation for reducing the impacts of sea-level rise in G-20 countries. J Coast Res 35:884–895. https://doi.org/10.2112/JCOASTRES-D-16-00185.1

Brown S, Jenkins K, Goodwin P et al (2021) Global costs of protecting against sea-level rise at 1.5 to 4.0 °C. Climatic Change 167:4. https://doi.org/10.1007/s10584-021-03130-z

Byers E, Gidden M, Leclère D et al (2018) Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ Res Lett 13:055012. https://doi.org/10.1088/1748-9326/aabf45

de Carvalho AL, Menezes RSC, Nóbrega RS et al (2015) Impact of climate changes on potential sugarcane yield in Pernambuco, northeastern region of Brazil. Renew Energy 78:26–34. https://doi.org/10.1016/j.renene.2014.12.023

Ceccherini G, Russo S, Ameztoy I et al (2017) Heat waves in Africa 1981–2015, observations and reanalysis. Nat Hazards Earth Syst Sci 17:115–125. https://doi.org/10.5194/nhess-17-115-2017

Chen Y, Wu Z, Okamoto K et al (2013) The impacts of climate change on crops in China: a Ricardian analysis. Glob Planet Change 104:61–74. https://doi.org/10.1016/j.gloplacha.2013.01.005
Codjoe SNA, Gough KV, Wilby RL et al (2020) Impact of extreme weather conditions on healthcare provision in urban Ghana. Soc Sci Med 258:113072. https://doi.org/10.1016/j.socscimed.2020.113072
Cook BI, Smerdon JE, Seager R, Coats S (2014) Global warming and 21st century drying. Clim Dyn 43:2607–2627. https://doi.org/10.1007/s00382-014-2075-y
Costa LC, Justino F, Oliveira LJC et al (2009) Potential forcing of CO_2, technology and climate changes in maize (*Zea mays*) and bean (*Phaseolus vulgaris*) yield in southeast Brazil. Environ Res Lett 4:014013. https://doi.org/10.1088/1748-9326/4/1/014013
Dankers R, Arnell NW, Clark DB et al (2014) First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. Proc Natl Acad Sci 111:3257. https://doi.org/10.1073/pnas.1302078110
Dasgupta S, Laplante B, Meisner C et al (2009) The impact of sea level rise on developing countries: a comparative analysis. Clim Change 93:379–388. https://doi.org/10.1007/s10584-008-9499-5
Dottori F, Szewczyk W, Ciscar J-C et al (2018) Increased human and economic losses from river flooding with anthropogenic warming. Nat Clim Change 8:781–786. https://doi.org/10.1038/s41558-018-0257-z
Du S, Scussolini P, Ward PJ et al (2020) Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. Glob Environ Change 61:102037. https://doi.org/10.1016/j.gloenvcha.2020.102037
Duncan JMA, Saikia SD, Gupta N, Biggs EM (2016) Observing climate impacts on tea yield in Assam, India. Appl Geogr 77:64–71. https://doi.org/10.1016/j.apgeog.2016.10.004
Fang J, Lincke D, Brown S et al (2020) Coastal flood risks in China through the 21st century — an application of DIVA. Sci Total Environ 704:135311. https://doi.org/10.1016/j.scitotenv.2019.135311
Gebrechorkos SH, Hülsmann S, Bernhofer C (2019) Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int J Climatol 39:18–30. https://doi.org/10.1002/joc.5777
Geng X, Wang F, Ren W, Hao Z (2019) Climate change impacts on winter wheat yield in northern China. Adv Meteorol 2019:2767018. https://doi.org/10.1155/2019/2767018
Goodwin P, Brown S, Haigh ID et al (2018) Adjusting mitigation pathways to stabilize climate at 1.5 °C and 2.0 °C rise in global temperatures to year 2300. Earths Future 6:601–615. https://doi.org/10.1002/2017EF000732
Gosling SN, Arnell NW (2016) A global assessment of the impact of climate change on water scarcity. Clim Change 134:371–385. https://doi.org/10.1007/s10584-013-0853-x
Hallegatte S, Ranger N, Bhattacharya S, et al. (2010) Flood risks, climate change impacts and adaptation benefits in Mumbai. OECD Environment Working Papers No. 27. OECD, France
He Y, Manful D, Warren R, et al (2022) Quantification of impacts between 1.5 and 4 °C of global warming on flooding risks in six countries. Climatic Change 170. https://doi.org/10.1007/s10584-021-03289-5
Hebbar KB, Venugopalan MV, Prakash AH, Aggarwal PK (2013) Simulating the impacts of climate change on cotton production in India. Clim Change 118:701–713. https://doi.org/10.1007/s10584-012-0673-4
Hinkel J, Brown S, Exner L et al (2012) Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Reg Environ Change 12:207–224. https://doi.org/10.1007/s10113-011-0249-2
Hirabayashi Y, Mahendran R, Koirala S et al (2013) Global flood risk under climate change. Nat Clim Change 3:816–821. https://doi.org/10.1038/nclimate1911
Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F, Guiot J, Hijioka Y, Mehrotra S, Payne A, Seneviratne SI, Thomas A, Warren R, Zhou G (2018) Impacts of 1.5ºC global warming on natural and human systems. In: global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 175-312. https://doi.org/10.1017/9781009157940.005
Im E-S, Pal JS, Eltahir EAB (2017) Deadly heat waves projected in the densely populated agricultural regions of South Asia. Sci Adv 3:e1603322. https://doi.org/10.1126/sciadv.1603322
Imada Y, Shiogama H, Takahashi C et al (2018) Climate change increased the likelihood of the 2016 heat extremes in Asia. Bull Am Meteorol Soc 99:S97
Iwasaki S (2016) Linking disaster management to livelihood security against tropical cyclones: a case study on Odisha state in India. Int J Disaster Risk Reduct 19:57–63. https://doi.org/10.1016/j.ijdrr.2016.08.019
Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Change 13:51–59. https://doi.org/10.1016/S0959-3780(02)00090-0

Lapola DM, Braga DR, Di Giulio GM et al (2019) Heat stress vulnerability and risk at the (super) local scale in six Brazilian capitals. Clim Change 154:477–492. https://doi.org/10.1007/s10584-019-02459-w
Lee S-M, Min S-K (2018) Heat stress changes over East Asia under 1.5° and 2.0 °C global warming targets. J Clim 31:2819–2831. https://doi.org/10.1175/JCLI-D-17-0449.1
Leng G, Tang Q, Rayburg S (2015) Climate change impacts on meteorological, agricultural and hydrological droughts in China. Glob Planet Change 126:23–34. https://doi.org/10.1016/j.gloplacha.2015.01.003
Liu J, Fritz S, van Wesenbeeck CFA et al (2008) A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. Clim Change Desertification 64:222–235. https://doi.org/10.1016/j.gloplacha.2008.09.007
Marengo JA, Torres RR, Alves LM (2017) Drought in Northeast Brazil—past, present, and future. Theor Appl Climatol 129:1189–1200. https://doi.org/10.1007/s00704-016-1840-8
Margulis S, Dubeux C, Marcovitch J (2011) The economics of climate change in Brazil: Costs and Opportunities. University of Sao Paulo
Marin FR, Jones JW, Singels A et al (2013) Climate change impacts on sugarcane attainable yield in southern Brazil. Clim Change 117:227–239. https://doi.org/10.1007/s10584-012-0561-y
McCartney M, Forkuor G, Sood A, Amisigo B, Hattermann F, Muthuwatta L (2012) The water resource implications of changing climate in the Volta River Basin. Colombo, Sri Lanka: International Water Management Institute (IWMI), (IWMI Research Report 146) p 40. https://doi.org/10.5337/2012.219
Mitchell D (2016) 14. Human influences on heat-related health indicators during the 2015 Egyptian heat wave. Bull Am Meteorol Soc 97:S70–S74
Montenegro S, Ragab R (2012) Impact of possible climate and land use changes in the semi arid regions: a case study from North Eastern Brazil. J Hydrol 434–435:55–68. https://doi.org/10.1016/j.jhydrol.2012.02.036
Mujumdar M, Bhaskar P, Ramarao MVS, Uppara U, Goswami M, Borgaonkar H, Niyogi D (2020) Droughts and floods. In: Krishnan R, Sanjay J, Gnanaseelan C, Mujumdar M, Kulkarni A, Chakraborty S (eds). Assessment of Climate Change over the Indian Region. Springer, Singapore
Müller C, Waha K, Bondeau A, Heinke J (2014) Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. Glob Change Biol 20:2505–2517. https://doi.org/10.1111/gcb.12586
Murari KK, Ghosh S, Patwardhan A et al (2015) Intensification of future severe heat waves in India and their effect on heat stress and mortality. Reg Environ Change 15:569–579. https://doi.org/10.1007/s10113-014-0660-6
Myers SS, Zanobetti A, Kloog I et al (2014) Increasing CO_2 threatens human nutrition. Nature 510:139–142. https://doi.org/10.1038/nature13179
Niang I, Ruppel OC, Abdrabo MA et al (2014) Africa. In: Barros VR, Field CB, Dokken DJ et al (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. contribution of working group II to the fifth assessment report of the intergovernmental panel of climate change. Cambridge University Press, Cambridge, pp 1199–1265
Nicholls RJ, Brown S, Goodwin P et al (2018) Stabilization of global temperature at 1.5 °C and 2.0 °C: implications for coastal areas. Philos Trans R Soc Math Phys Eng Sci 376:20160448. https://doi.org/10.1098/rsta.2016.0448
Nunfam VF, Van Etten EJ, Oosthuizen J et al (2019) Climate change and occupational heat stress risks and adaptation strategies of mining workers: perspectives of supervisors and other stakeholders in Ghana. Environ Res 169:147–155. https://doi.org/10.1016/j.envres.2018.11.004
Oguntunde PG, Abiodun BJ, Lischeid G (2017) Impacts of climate change on hydro-meteorological drought over the Volta Basin, West Africa. Global Planet Change 155:121–132
O'Neill B, van Aalst M, Zaiton Ibrahim Z et al (2022) Key risks across sectors and regions. In: Pörtner H-O, Roberts DC, Tignor M et al (eds) Climate Change 2022: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 2411–2538
Ovalle-Rivera O, Läderach P, Bunn C et al (2015) Projected shifts in *Coffea arabica* suitability among major global producing regions due to climate change. Plos One 10:e0124155. https://doi.org/10.1371/journal.pone.0124155
Penalba OC, Rivera JA (2016) Regional aspects of future precipitation and meteorological drought characteristics over Southern South America projected by a CMIP5 multi-model ensemble. Int J Climatol 36:974–986. https://doi.org/10.1002/joc.4398
Price J, Warren R, Forstenhäusler N (2020) Biodiversity losses associated with global warming of 1.5 to 4 °C above pre-industrial levels in six countries. Submitted
Price J, Warren R, Forstenhäusler N et al (2022) Quantification of meteorological drought risks between 1.5 °C and 4 °C of global warming in six countries. Clim Chang 174:12. https://doi.org/10.1007/s10584-022-03359-2
Qin Z, Tang H, Li W et al (2014) Modelling impact of agro-drought on grain production in China. Int J Disaster Risk Reduct 7:109–121. https://doi.org/10.1016/j.ijdrr.2013.09.002

Rahimi J, Mutua JY, Notenbaert AMO et al (2021) Heat stress will detrimentally impact future livestock production in East Africa. Nat Food 2:88–96. https://doi.org/10.1038/s43016-021-00226-8
Ranger N, Hallegatte S, Bhattacharya S et al (2011) An assessment of the potential impact of climate change on flood risk in Mumbai. Clim Change 104:139–167. https://doi.org/10.1007/s10584-010-9979-2
Reidmiller DR, Avery CW, Easterling DR, et al (2017) Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. https://doi.org/10.7930/NCA4.2018
Ren X, Weitzel M, O'Neill BC et al (2018) Avoided economic impacts of climate change on agriculture: integrating a land surface model (CLM) with a global economic model (iPETS). Clim Change 146:517–531. https://doi.org/10.1007/s10584-016-1791-1
Riahi K, van Vuuren DP, Kriegler E et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob Environ Change 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009
Ringard J, Dieppois B, Rome S et al (2016) The intensification of thermal extremes in west Africa. Global Planet Change 139:66–77. https://doi.org/10.1016/j.gloplacha.2015.12.009
Rogelj J, den Elzen M, Höhne N et al (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534:631–639. https://doi.org/10.1038/nature18307
Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB, Dankers R, Eisner S, Fekete BM, Colón-González FJ, Gosling SN (2014) Multimodel assessment of water scarcity under climate change. Proc Natl Acad Sci 111:3245–3250
Sonkar G, Singh N, Mall RK et al (2020) Simulating the impacts of climate change on sugarcane in diverse agro-climatic zones of northern India using CANEGRO-Sugarcane model. Sugar Tech 22:460–472. https://doi.org/10.1007/s12355-019-00787-w
Sun Y, Song L, Yin H et al (2017) Human influence on the 2015 extreme high temperature events in western China. Bull Am Meteorol Soc 97:S102–S106. https://doi.org/10.1175/BAMS-D-16-0158.1
Tao F, Zhang Z (2013) Climate change, wheat productivity and water use in the North China Plain: a new super-ensemble-based probabilistic projection. Agric Predict Using Clim Model Ensembles 170:146–165. https://doi.org/10.1016/j.agrformet.2011.10.003
Tavares P da S, Giarolla A, Chou SC et al (2018) Climate change impact on the potential yield of Arabica coffee in southeast Brazil. Reg Environ Change 18:873–883. https://doi.org/10.1007/s10113-017-1236-z
Vetter T, Reinhardt J, Flörke M et al (2017) Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Clim Change 141:419–433. https://doi.org/10.1007/s10584-016-1794-y
Wang L, Chen W (2014) A CMIP5 multimodel projection of future temperature, precipitation, and climatological drought in China. Int J Climatol 34:2059–2078. https://doi.org/10.1002/joc.3822
Wang D, Jenkins K, Forstenhäusler N et al (2021) Economic impacts of climate-induced crop yield changes: evidence from agri-food industries in six countries. Climatic Change 166:30 (10/gkc7xp)
Warren R, Andrews O, Brown S et al (2022) Quantifying risks avoided by limiting global warming to 1.5 or 2 °C above pre-industrial levels. Climatic Change 172:39. https://doi.org/10.1007/s10584-021-03277-9
Warren R, Hope C, Gernaat DEHJ et al (2021) Global and regional aggregate damages associated with global warming of 1.5 to 4 °C above pre-industrial levels. Clim Chang 168:24. https://doi.org/10.1007/s10584-021-03198-7
Warren R, Price J, VanDerWal J et al (2018) The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. Clim Change 147:395–409
Wehner M, Stone D, Krishnan H et al (2016) S16. The deadly combination of heat and humidity in India and Pakistan in summer 2015. Bull Am Meteorol Soc 97:S30–S32
Winsemius HC, Aerts JCJH, van Beek LPH et al (2016) Global drivers of future river flood risk. Nat Clim Change 6:381–385. https://doi.org/10.1038/nclimate2893
Xiao D, Bai H, Liu LD (2018) Impact of future climate change on wheat production: a simulated case for China's wheat system. Sustainability 10. https://doi.org/10.3390/su10041277
Yin Z, Hu Y, Jenkins K et al (2021) Assessing the economic impacts of future fluvial flooding in six countries under climate change and socio-economic development. Climatic Change 166:38 (10/gmhbf6)
Zhu C, Kobayashi K, Loladze I et al (2018) Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci Adv 4:eaaq1012. https://doi.org/10.1126/sciadv.aaq1012

This article is part of the topical collection "Accrual of Climate Change Risk in Six Vulnerable Countries", edited by Daniela Jacob and Tania Guillén Bolaños.

Authors and Affiliations

R. Warren[1] · J. Price[1] · N. Forstenhäusler[1] · O. Andrews[2,3] · S. Brown[4] · K. Ebi[5] · D. Gernaat[6] · P. Goodwin[7] · D. Guan[8,9] · Y. He[1] · D. Manful[1] · Z. Yin[9] · Y. Hu[10] · K. Jenkins[1] · R. Jenkins[1] · A. Kennedy-Asser[2] · T. J. Osborn[11] · D. VanVuuren[6] · C. Wallace[11] · D. Wang[12,13] · R. Wright[1]

✉ R. Warren
r.warren@uea.ac.uk

[1] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia (UEA), Norwich NR4 7TJ, UK

[2] Bristol Research Initiative for the Dynamic Global Environment (BRIDGE), University of Bristol, Bristol, UK

[3] Department of Environment and Geography, Wentworth Way, University of York, Heslington, York, UK

[4] Department of Life and Environmental Sciences, Bournemouth University, Bournemouth, UK

[5] University of Washington Centre for Health and the Global Environment, Seattle, WA, USA

[6] PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands

[7] School of Ocean and Earth Science, University of Southampton, Southampton, UK

[8] Department of Earth System Science, Tsinghua University, Beijing, China

[9] The Bartlett School of Sustainable Construction, University College London, London, UK

[10] School of Economics and Management, Southeast University, Nanjing, China

[11] Climatic Research Unit, School of Environmental Sciences, University of East Anglia (UEA), Norwich, UK

[12] School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai, China

[13] Department of Geography, King's College London, London, UK