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OPINION

Climate change research and action must look beyond 2100

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Abstract

Anthropogenic activity is changing Earth's climate and ecosystems in ways that are potentially dangerous and disruptive to humans. Greenhouse gas concentrations in the atmosphere continue to rise, ensuring that these changes will be felt for centuries beyond 2100, the current benchmark for projection. Estimating the effects of past, current, and potential future emissions to only 2100 is therefore short-sighted. Critical problems for food production and climate-forced human migration are projected to arise well before 2100, raising questions regarding the habitability of some regions of the Earth after the turn of the century. To highlight the need for more distant horizon scanning, we model climate change to 2500 under a suite of emission scenarios and quantify associated projections of crop viability and heat stress. Together, our projections show global climate impacts increase significantly after 2100 without rapid mitigation. As a result, we argue that projections of climate and its effects on human well-being and associated governance and policy must be framed beyond 2100.

KEYWORDS
adaptation, climate change, climate models, crop projections, heat stress

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1 | INTRODUCTION

When climate models were first used in the 1980s and 1990s, the year 2100 was seen as a suitably distant horizon for climate projections. However, this benchmark is now just one human lifespan away, and opportunities to readily curb emissions in line with the Paris Agreement are dwindling (IPCC, 2018). Anthropogenic activity is already altering atmospheric carbon dioxide concentrations at a rate that generally exceeds those known in Earth archives (Burke et al., 2018; Kemp et al., 2015; Zeebe et al., 2016), generating changes deleterious for humans and ecosystems (Ford et al., 2019; IPBES, 2019; Pascale et al., 2020). Obtaining insights into anthropogenic effects on the Earth system that support human existence is therefore critical for designing governance and policy structures that can mitigate these effects, which are predicted to continue well beyond 2100 (Riahi et al., 2017).

Since 1990, the three Working Groups (WG) of the Intergovernmental Panel on Climate Change (IPCC) have produced periodic Assessment Reports, including the 2021–2022 publication of the sixth incarnation. Central to future climate projections are socioeconomic scenarios, including estimates of future fossil fuel consumption, land-use change, industrial activity, and associated greenhouse gas and short-lived pollutant emissions (Riahi et al., 2017).

The core scenarios prepared for IPCC's Fifth Assessment Report (AR5) were termed Representative Concentration Pathways (RCPs) and covered four emissions trajectories. RCPs ranged from a global scale reduction on fossil fuel reliance and achievement of net-negative CO_2 later this century (RCP 2.6), to a high-emission scenario that included substantial new investments in fossil fuels and lack of global climate policy and governance (RCP8.5) (van Vuuren et al., 2011). The newer Shared Socio-Economic Pathways (SSPs) include five development 'storylines' that capture emission scenarios and pair them with socioeconomic scenarios (O'Neill et al., 2020; Pedde et al., 2020; Riahi et al., 2017). The primary time horizon for both RCP and SSP scenarios is 2100.

However, it is now clear that without deep and rapid reductions in greenhouse gas emissions, climate change will continue for centuries into the future. Efforts to extend projections beyond 2100 exist but are limited. For example, emission and greenhouse gas concentration projections to 2300 are provided for each RCP scenario in CMIP5, which were further extended to 2500 by Meinhausen et al. (2011). Similar long-term projections exist to 2500 for Shared Socioeconomic Pathways (SSPs) in CMIP6 (Meinshausen et al., 2020). However, no complex climate model results from CMIP5 or CMIP6 are available beyond 2300. Although several CMIP5 models ran projections to 2300, at present very few CMIP6 models have done so, requiring the IPCC's Sixth Assessment Report to base longer-term projections primarily on simpler models (Lee et al., 2021). Indeed, many studies that focus on time horizons beyond 2100 have used reduced complexity or intermediate complexity Earth System models (Goodwin et al., 2018; Palmer et al., 2020; Zickfeld et al., 2013) due to a combination of additional computational cost in running models beyond 2100 and the small number of Earth System Models that have performed the experiments. Perhaps even more critically,

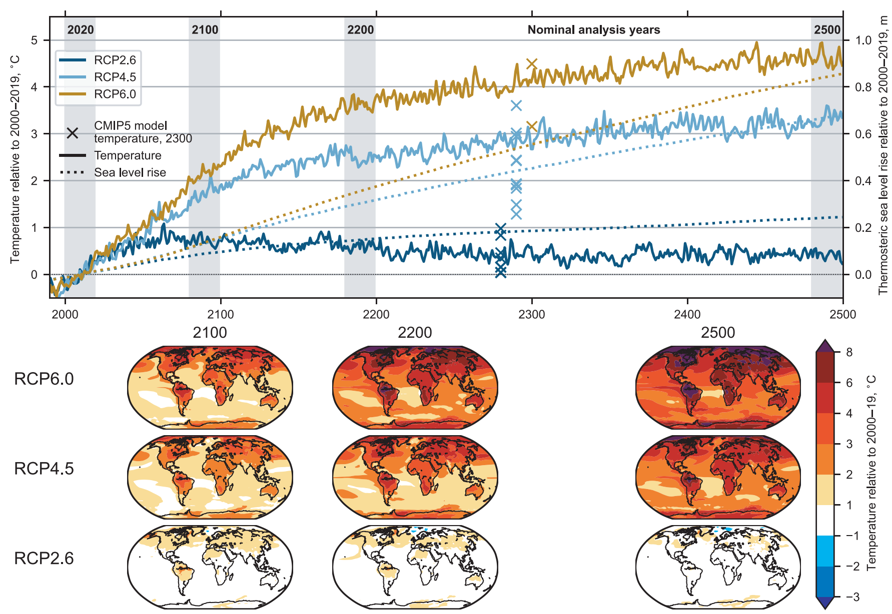


FIGURE 1 Top panel: Global mean near-surface air temperature (solid lines) and thermosteric sea-level rise (dotted lines) anomalies relative to the 2000–2019 mean for the RCP6.0, RCP4.5 and RCP2.6 scenarios. Shaded regions highlight the time horizons of interest and their nominal reference years: 2020 (mean of 2000–19, representative of present-day climate); 2100 (2080–99); 2200 (2180–99); and 2500 (2480–2499). Crosses represent warming projections from CMIP5 models for 2280–2299 relative to 2000–19. Bottom panel: Spatial anomalies relative to 2000–2019 mean for the 2100, 2200, and 2500 climates under the three RCPs

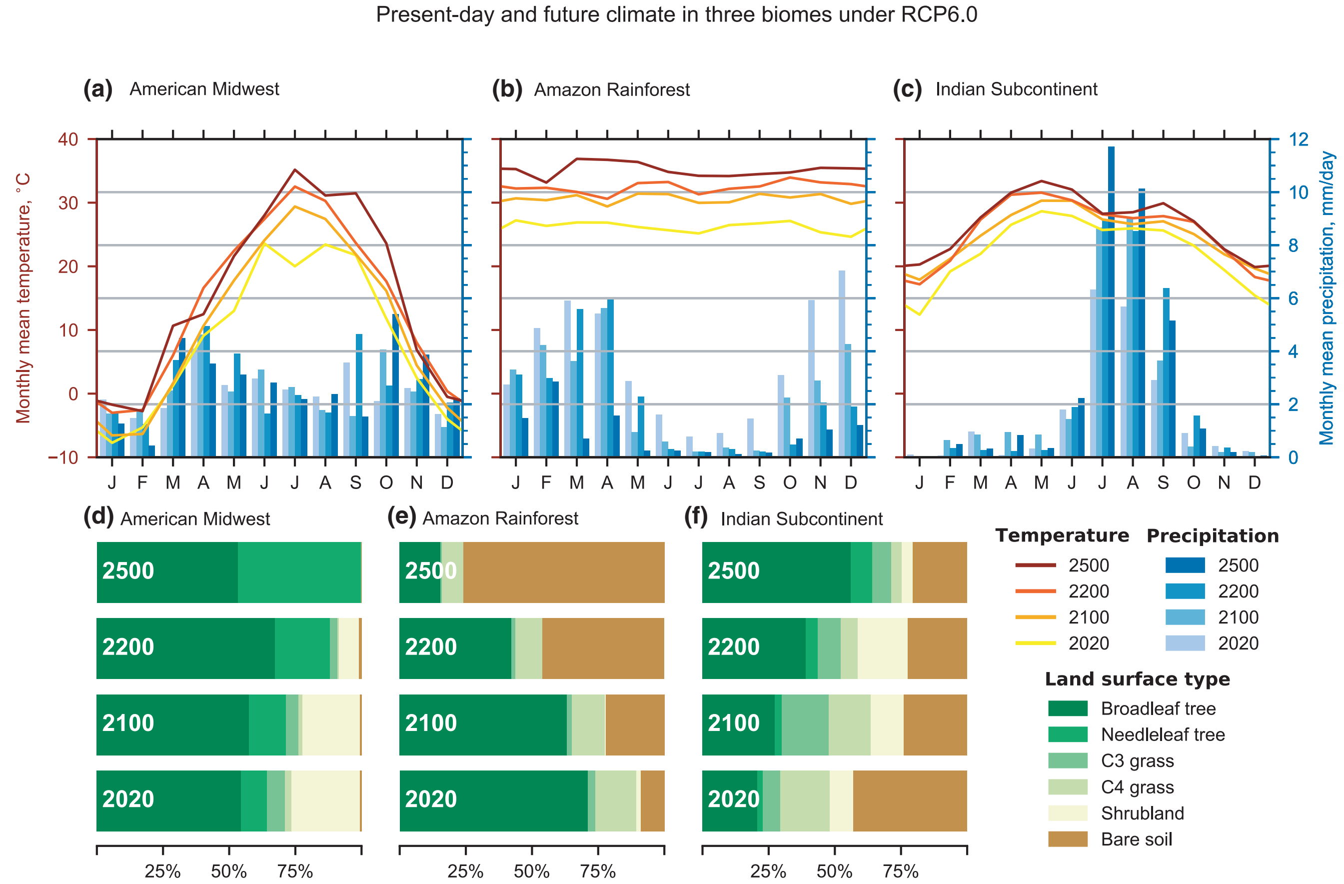


FIGURE 2 Climatic indices for the three case study regions under the RCP6.0 scenario in HadCM3. Monthly mean temperatures (°C; left axis) and precipitation (mm/day; right axis) in the (a) American Midwest, (b) Amazon, and (c) Indian subcontinent. Land cover fractions, from the TRIFFID dynamic vegetation model in (d) American Midwest, (e) Amazon, and (f) Indian subcontinent

modelling past 2100 is currently not focused on projecting aspects of ecosystem services of importance to human well-being, such as useable land not inundated by sea-level rise (Clark et al., 2016), habitable temperatures (Schwingshackl et al., 2021), agricultural change (Müller et al., 2021), and availability of freshwater (John et al., 2021).

In short, although 50 years have passed since the initial climate projections (Forster, 2017), our time horizon for coupled climate projections remains primarily at 2100 (though see, e.g. Goodwin et al., 2018; Palmer et al., 2020; Zickfeld et al., 2013). We therefore argue that climate and social projections beyond 2100 need to become more routine (Pearson, 2020; van Renssen, 2019). To make our case, we present climate projections modelled to 2500 under three emission scenarios representing strong, moderate, and weak global climate policy (RCP2.6, RCP4.5, and RCP6.0). We explore crop viability and heat stress after 2100 to highlight the necessity of socio-economic planning on timescales beyond the next 80 years and propose a social-governance approach to account for longer-term climate dynamics. Our modelling exercises provide an initial framework and baseline for the assessment of longer-term anthropogenic effects on climate and Earth systems and highlight the need for further work in this area.

2 | CLIMATE PROJECTIONS AND VEGETATION BEYOND 2100

Results of our preliminary climate projections (SI Methods) drawn from the HadCM3 atmosphere–ocean coupled climate model (Gordon et al., 2000) combined with the TRIFFID dynamic land surface model (Cox, 2001) clearly demonstrate the need for quantification of climate change effects past 2100. Global mean temperature, for example, continues to increase after 2100 under all but the low-emission RCP2.6 scenario. Under the moderate–high RCP6.0 emissions scenario (a realistic scenario with low mitigation; Hausfather & Peters, 2020), global mean warming is 2.2°C above present-day levels by 2100 (Figure 1, Figure S1) but continues to rise to 3.6°C in 2200 and 4.6°C in 2500. Warming is unequally distributed, with greater warming over the land surface and in polar regions (Figure 1).

Our projections compare well to previous assessments of warming past 2100. RCP projections are within the range of those from available CMIP5 models to 2300 (crosses in Figure 1). The recent IPCC Sixth Assessment Report, drawing evidence mostly from the MAGICC7 reduced complexity climate model, assessed likely year-2300 warming to be 1.3–3.6°C above 2000–2019 under SSP2-4.5 (a similar scenario to RCP4.5) and 0.0–1.2°C above 2000–19 under

SSP1-2.6 (a similar scenario to RCP2.6), which easily encompass our projections (Lee et al., 2021). Note that IPCC Sixth Assessment Report projections are taken from Table 4.9 in Lee et al. (2021), which are relative to 1850–1900, and 1.0°C is subtracted from these values to represent warming from 1850–1900 to 2000–2019 (Gulev et al., 2021).

The higher emission scenarios (RCP4.5 and 6.0) result in major restructuring of the world's biomes by 2500. For example, HadCM3 projects a severe dieback of Amazon rainforest under RCP6.0 and RCP4.5 by 2500 (Figure 2), congruent with previous research using the same model under a high-emission scenario (Huntingford et al., 2008). Conversely, the low-emission scenario (RCP2.6) reaches peak warming this century (Figure 1) with stabilization of global mean temperature only 0.5°C above the 2000–2019 mean and limited long-term shifts in global vegetation (Figure S2). Sea level, however, continues to rise long after warming has stabilized (Palmer et al., 2018, 2020), even in the RCP2.6 scenario, due to slow continued mixing of heat into the deep ocean (Oppenheimer et al., 2019) (Figure 1; Table 1). The long-term impacts of 21st-century emissions are therefore likely to be felt for centuries to come, continuing even after greenhouse gas concentrations have reached equilibrium (2150 for RCP4.5 and RCP6.0).

TABLE 1 Calculated contribution to sea-level rise (meters) from deep ocean heat mixing in 2100, 2200, and 2500 under three RCP scenarios

RCP	2100	2200	2500
2.6	0.09 m	0.15 m	0.24 m
4.5	0.15 m	0.32 m	0.68 m
6.0	0.16 m	0.37 m	0.86 m

3 | HEAT STRESS AND HUMAN WELL-BEING BEYOND 2100

Heat stress can be fatal to humans when wet-bulb temperatures exceed 35°C for 6 or more hours (Buzan & Huber, 2020; Sherwood & Huber, 2010). Physiologically fit humans can tolerate higher dry-air temperatures, but such temperatures can still lead to high mortalities (Diniz et al., 2020; Varghese et al., 2020). These conditions also cause damage to critical infrastructure on which humans rely, such as electricity (Burillo et al., 2019), transportation (Villalba Sanchis et al., 2020), and agriculture (Anderson et al., 2020; Mehrabi, 2020). Although several measures (Schwingshackl et al., 2021) of regional heat stress projections exist (Im et al., 2017; Li et al., 2020; Pal & Eltahir, 2016), few studies project global patterns (Buzan & Huber, 2020; Mora et al., 2017; Schwingshackl et al., 2021), and none do so beyond 2100.

We estimate changes in heat stress to 2500 using the Universal Thermal Climate Index (UTCI) (Błażejczyk et al., 2013; Jendritzky et al., 2012). UTCI is a measure of heat stress encompassing both

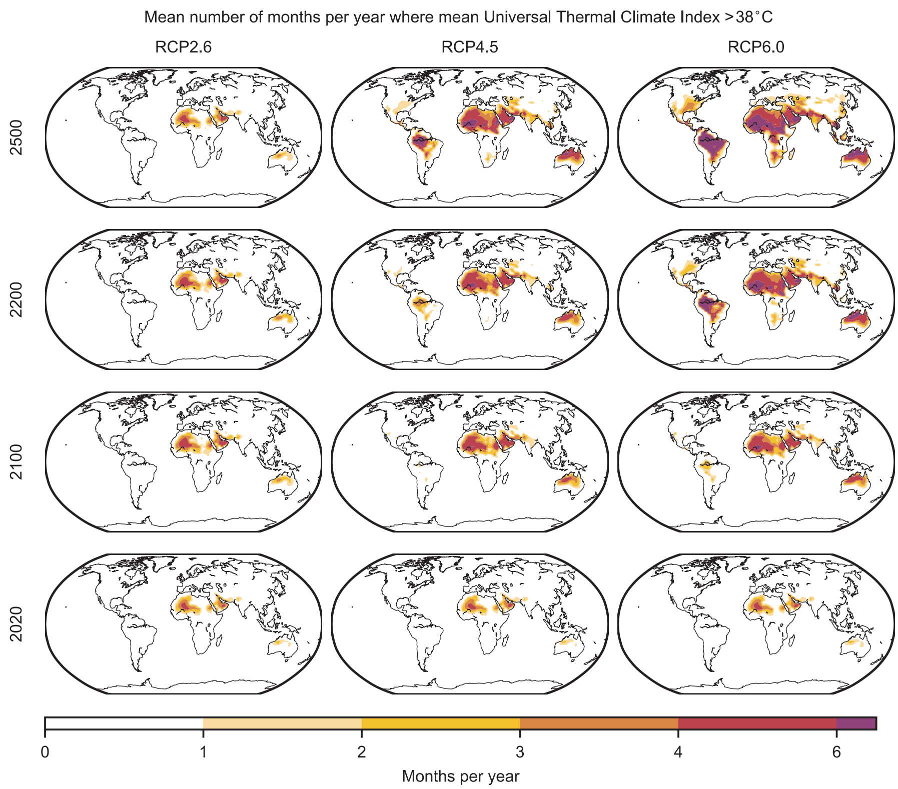


FIGURE 3 Mean number of months per year where UTCI, a measure of heat stress, exceeds 'very strong' levels (38°C on the UTCI scale) in present (2020) and future climates in three RCP scenarios

fatal and physiologically stressful temperatures on a °C scale that reports the effects of climatic conditions on human physiological comfort, taking ambient temperature, humidity, solar and thermal radiation, and wind speed into account.

Our measure of UTCI provides an estimate of heat stress levels that are representative of daily near-maximal values (SI Methods; Figure S3). The regions that currently experience periods of very strong heat stress today tend to be deserts, but also include the Indian subcontinent and south-eastern USA during parts of the year (Figure 3). Larger proportions of the Earth are projected to experience strong heat stress in the future under RCP4.5 and RCP6.0 scenarios, with affected areas spreading into more temperate zones, such as the Mediterranean, by the end of the century.

By 2500 under RCP6.0, the proportion of the year exhibiting very strong heat stress is greater than 50% in much of Africa, the Amazon, the Arabian Peninsula, Southeast Asia, the Maritime Continent, and northern Australia. By contrast, today these regions experience this level of heat stress between 0% (Maritime Continent) and 25% (Arabian Peninsula) of the year. Many of these regions are only slightly less affected in RCP4.5 in this timeframe. In contrast, heat stress projections do not become substantially worse beyond 2100 in RCP2.6, showing the long-term advantages of climate mitigation (Figure 3).

4 | AGRICULTURAL CHALLENGES AFTER 2100

The effects of climate on agriculture are a major research area covering crop adaptation, migration, and food production (Anderson et al., 2020; Mehrabi, 2020; Stringer et al., 2020). Climate-driven crop migration and yield reductions have been observed already (Moore, 2020; Sloat et al., 2020; Zhang et al., 2017) and projected for the future (Ceglar et al., 2019; King et al., 2018), but are not typically examined beyond 2100 (Tigchelaar et al., 2018). Using our climate projections and the Crop Ecological Requirements Database (Ecocrop) of FAO (Food and Agriculture Organization (FAO), 2016), we model how climate change beyond 2100 may affect the global extent and location of suitable land for the growth of 10 major food crops (Food and Agriculture Organization, 2016): cassava, maize, potato, rice, sorghum, soybean, sweet potato, taro, wheat, and yam (SI Methods). Our investigations consider only precipitation and temperature on crop viability and provide a skeleton framework for integrating more sophisticated crop growth measures under projections of longer-term climate conditions (e.g. through an ensemble modelling approach, see https://www.isimip.org). We did not, for example, consider how technological and crop innovations and altered land use norms may change viability patterns, nor did we consider factors such as soil depth, soil texture, soil organic matter,

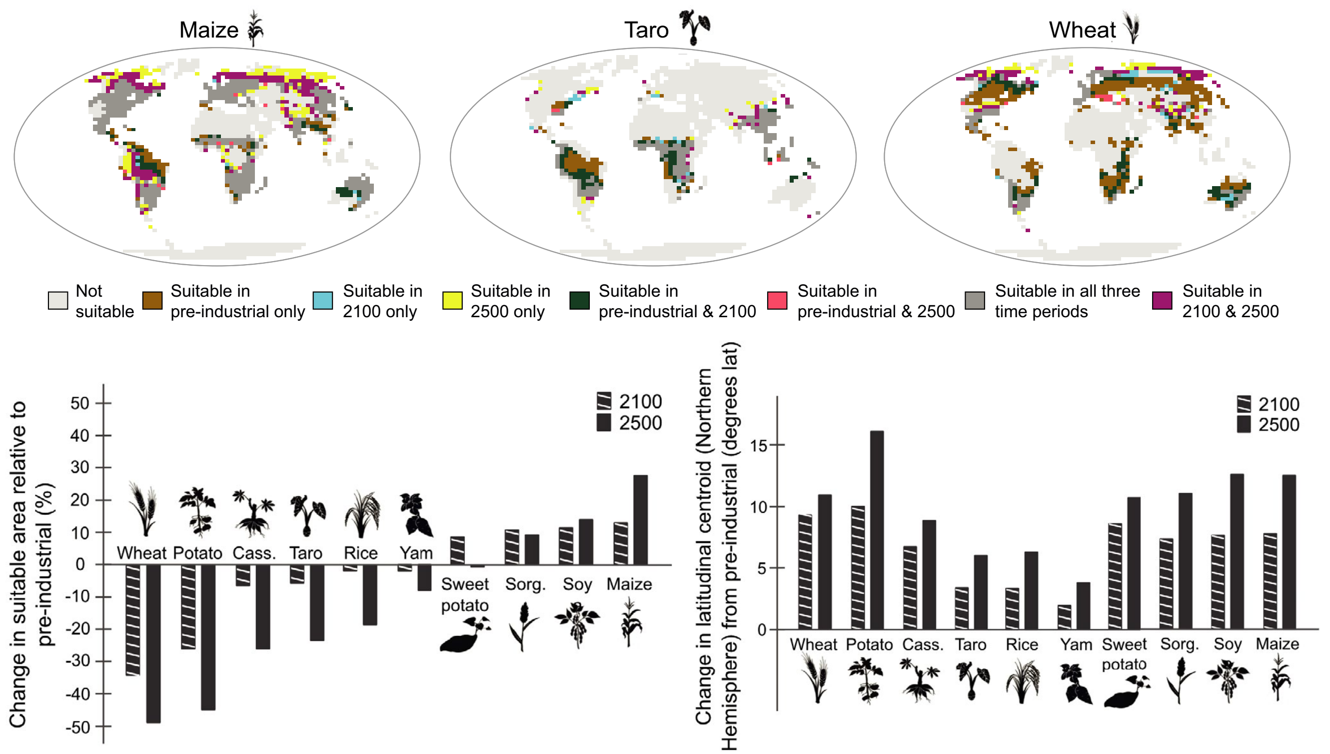


FIGURE 4 Projections for crop suitability to 2100 and 2500 under the moderate–high RCP6.0 emission scenario. Modelling was based on temperature and precipitation requirements derived from the FAO (Food and Agriculture Organization (FAO), 2016), with crop growth length calibrated to the maps (Monfreda et al., 2008) (see SI Methods). (a) Suitable regions for select crops projected to 2100 and 2500. (b) Projected changes in the area suitable for crop growth globally relative to the pre-Industrial (1851–1899). (c) Projected changes in latitude at which crops can be grown in the Northern Hemisphere relative to the pre-Industrial (1851–1899). Analyses relied on the latitudinal centroid of suitable crop regions. Cass. = Cassava and Sorg. = Sorghum

soil pH, nutrient availability, biotic symbionts, animal agriculture, pollinators, pests, and diseases – all of which are sure to improve model projections. Climate change impacts on agriculture are also projected without consideration to changes in hydrology that will occur with climate change; crop viability will be affected by to irrigation systems and by sea water intrusion in coastal regions.

Our analyses suggest declines in suitable growth regions and shifts in where crops can be grown globally with climate change (Figure 4). By 2100 under RCP6.0, we project declines in land area suitable for crop growth of 2.3% (±6.1%) for staple tropical crops (cassava, rice, sweet potato, sorghum, taro, and yam) and 10.9% (±24.2%) for stable temperate crops (potato, soybean, wheat, and maize), averaged across crop growth-length calibrations (Figure 4; Table S1, see also Figures S4-S12 for additional RCP scenarios). By 2500, declines in suitable regions for crop growth are projected to reach 14.9% (±16.5%) and 18.3% (±35.4%) for tropical and temperate crops, respectively (Figure 4; Table S2). These changes represent an additional six-fold decline in temperate crops and a near doubling of decline for tropical crops between 2100 and 2500. By contrast, if climate mitigation is assumed under RCP2.6, a decline of only 2.9% (±13.5%) is projected by 2500 for temperate crops, and an increase of 2.9% (±3.8%) is projected for tropical crops.

Declines in suitable regions for crop growth are the dominant pattern projected under future emission scenarios, but considerable variation is found in crop-specific responses (see the high standard deviations above and Figure 4). Wheat, potato, and cassava are projected to lose the greatest area for crop growth by 2500 (Figure 4; Table S2) under RCP6.0 across crop-growth calibrations. Conversely, soybean and maize are the only crops consistently projected to maintain or gain suitable area under RCP6.0 by 2500 across crop-growth calibrations (Figure 4; Table S2).

Significant changes are also projected in the locations for staple crop growth. Suitable regions are projected to shift poleward for both hemispheres, although greater shifts are projected in the Northern Hemisphere (Figure 4; Dataset S1).

These latitudinal shifts and reductions in suitable area for crop growth in the centuries after 2100 are not accounted for in existing models forecasting food production for future generations. The impacts of these potential changes may be further compounded by changes in human population. At present, population projections suggest that humans may number anywhere between 7 and 16 billion by the year 2100 (Crist et al., 2017; Kc & Lutz, 2017), putting additional strain on models that suggest increasingly scarce food resources and highlighting the urgency of addressing population and food security questions (Aguiar et al., 2020; Bodirsky et al., 2015; Mehrabi et al., 2018; Mosby et al., 2020).

5 | REGIONAL CASE STUDIES

The changes we have projected are likely to have profound effects on natural vegetation and on human society by altering the distribution of tolerable environments and by changing the feasibility of agriculture. To explore the potential effects of these changes on human well-being, we highlight site-specific projections for three regions (Figure S13) of global importance under RCP6.0: the North American 'breadbasket', the Amazon Basin carbon sink, and the densely populated Indian subcontinent. We use our results to inform artistic interpretations of these regions to highlight the profound changes they may face under a plausible medium- to high-emission scenario (RCP6.0) (Hausfather & Peters, 2020) after 2100 (Box 1). For results from additional RCP scenarios, see Figures S14 and S15.

5.1 | North American Midwest

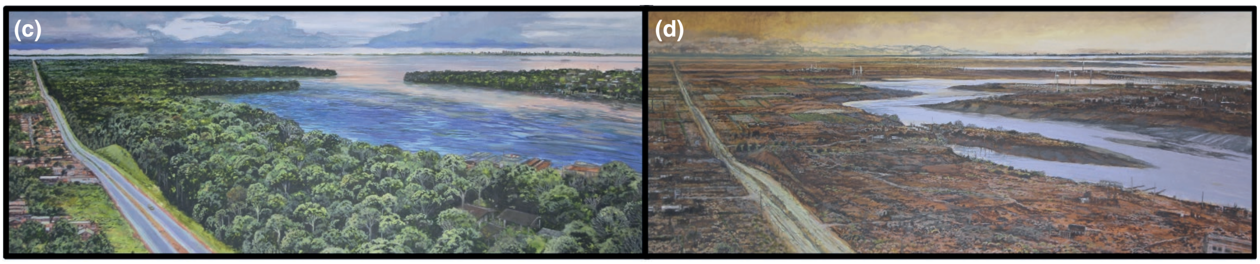
The interior plains of the American 'Midwest' are a global breadbasket. Today, the Midwest is characterized by cold winters and warm summers (Angel et al., 2018). Under RCP6.0, mean summer temperatures increase from 28°C today to 33°C by 2100 and 36°C by 2500 (Figure 2). Heat stress (measured with UTCI) increases in line with ambient temperature: 34.8°C in the warmest month today to 39.8°C in 2100, 42.9°C in 2200, and 44.9°C in 2500. With a definition of 'very strong heat stress' at UTCI >38°C (Błażejczyk et al., 2013), such a seasonal climate approaches levels that are physically stressful for humans and many other species.

5.2 | Amazon Basin

The Amazon Basin is home to one-third of Earth's known species (Heckenberger et al., 2007) and currently serves as a carbon sink for roughly 7% of anthropogenic CO_2 emissions (Brienen et al., 2015; Friedlingstein et al., 2019) (Figure S13). The region is also culturally and linguistically diverse, home to more than 350 indigenous languages (Aikhenvald, 2015). Our modelling suggests that rising temperatures and disrupted rainfall patterns will render the Amazon Basin unsuitable for tropical rainforests by 2500 (Figure 2, Box 1), with consequences for the global carbon cycle, biodiversity, and cultural diversity. Initial declines in forest cover in the model lead to a positive feedback of reduced transpiration, further reduced rainfall, and further forest retreat. The HadCM3 climate model exhibits this feedback more than most climate models, especially in the Amazon Basin (Poulter et al., 2010; Sitch et al., 2008), but still has a plausible sensitivity (Cowling et al., 2004). The HadCM3 model projects a limited retreat of the Amazon rainforest by 2100, but in the following centuries, forest dieback feedback enhances forest loss, and high temperatures and low precipitation (Figure S16) conspire to produce a barren environment in most of the Amazon Basin (Boulton et al., 2017). Amazonian forest cover declines from 71% in the present day to 63% in 2100, 42% in 2200, and 15% in 2500. The newer HadGEM2-ES model also shows Amazon dieback (though less severe), with freely evolving vegetation when run to 2300 CE under a high-emission scenario (Drijfhout et al., 2015).

BOX 1 Artistic comparison of potential changes in regional landscapes and human activity between 2020 and 2500 under RCP6.0. Three image pairs illustrate the potential scope of regional changes under RCP6.0 (Figure 2). Although technology in 2500 is essentially unknowable, we limited technological advancement for the purposes of making comparisons between 2020 and 2500.

US Midwest Breadbasket (a) 2020 and (b) 2500 under RCP6.0 scenario. A characterization of the 'breadbasket' area of the US Midwest today and in 2500. In 2500, monocultured cereals may be replaced by a subtropical agroforestry of fictional plants (based on oil palms and arid zone succulents). Potential future water capture and irrigation devices can be glimpsed among the crops to offset the effects of extreme summer heat.



Amazon (c) 2020 and (d) 2500 under RCP6.0 scenario. A characterization of the Amazon today and in 2500. In 2500, forest cover may be largely gone, with reduced surface water levels. Human presence and infrastructure may be minimal, degraded or absent, given high temperatures and water stress.

Indian subcontinent (e) 2020 and (f) 2500 under RCP6.0 scenario. A characterization of India in the present day and in 2500. We illustrate a conservative view of potential human adaptations based on similar technology today and from science fiction (Elson, 2016; Smith, 2008). Extreme heat may require protective personal clothing for outdoor activity – in this hypothetical case, a sealed helmet and a suit conducting water and coolants around the body. Outdoor agriculture in 2500 may be managed by automated drone-machinery.

5.3 | Indian subcontinent

The Indian subcontinent is one of the most populous regions on Earth (Figure S13). The region already experiences extreme climatic conditions, with thousands of heat-stress-related deaths recorded between 2013 and 2015 alone (Mazdiyasni et al., 2017). Our modelling suggests that mean summer monthly temperatures could increase 2°C by 2100 and 4°C by 2500, suggesting the Indian subcontinent will experience even higher heat stress than that projected for 2100 (Im et al., 2017) (Figure 2; Box 1). The dynamic land vegetation model projects tropical forest expansion across the Indian subcontinent towards 2500. Monsoon rainfall is projected to increase substantially into the future, reaching double the rate of precipitation today by 2500 under RCP6.0. Conversely, year-2500 climate and heat stress projections are similar to today under the RCP2.6 mitigation scenario, showing the effect of early reduction in greenhouse gas emissions.

6 | SUGGESTIONS FOR GOVERNANCE FOR LONG TIMESCALES

Human activity has already caused warming of ~1°C above average global pre-industrial levels (IPCC, 2018). Global mean temperatures will continue to increase until the point at which CO_2 emissions reach net zero (Allen et al., 2009; Matthews et al., 2009; Rogelj et al., 2019). Return to a pre-industrial climate is not possible without either removal of excess greenhouse gases added to the atmosphere or a sustained geoengineering programme (Carton et al., 2020). Such efforts appear unlikely given failures of governance around negative emissions technologies (Carton et al., 2020; McLaren & Markusson, 2020; Stevenson, 2021). As such, we argue that a longer-term, post-2100 perspective is critical for assessing the scope of climate change on Earth systems and on human well-being (van der Geest & Warner, 2020).

Our climate, heat stress, and agricultural projections parallel work that suggests climate increasingly drives global and regional human dispersal (Burke et al., 2021; Chen & Caldeira, 2020), especially from the heat-stressed tropics where habitability and crop suitability may be reduced. The scale of change we project over the coming centuries, especially under RCPs 4.5 and 6.0, will therefore necessitate more cooperative and collaborative approaches to global mobility to accommodate substantial human movement from less habitable regions (Adger et al., 2020). Meeting this challenge will require a major evolution in international relations away from national security and competition toward cooperation and integration (Beardsworth, 2020).

Our projections for crop viability also portend declines in ecosystem services after 2100. Even before 2100, projections of climate change suggest low-income (often tropical) countries are vulnerable to reduced crop suitability, and high-income countries face challenges with inward migration and converting climatically suitable land to agriculture (Chaplin-Kramer et al., 2019; Poeplau et al., 2019; Zabel et al., 2014). Such shifts also bring risks of soil carbon release, incursion into biodiversity hotspots, and threats to water security (Hannah et al., 2020; Poeplau et al., 2019). Over the long term, proposed strategies for food security, even those considered transformative such as meatless diets and urban farming (Fraser & Campbell, 2019; Stringer et al., 2020), may be insufficient if present agricultural areas fall out of production and technological advancements or landscape management (e.g. agroecology) prove unworkable at scale. The structure and function of the global food system will require reimagining, potentially via changes to property rights, use, and ownership (Healy et al., 2020) that mirror changes in productive climates, landscapes, populations, and technologies (Aguiar et al., 2020; Stringer et al., 2020).

The scope of projected future changes examined here will likely require long-term and adaptive integration of diverse cultural, knowledge, and governance structures that are global in scope and approach (Caniglia et al., 2020; Fazey et al., 2020). For example, new knowledge-action synthesis efforts (Marien, 2007; Pedde et al., 2020) could inform governance institutions. These centres could be new organizations, such as long-range foresight groups (Burrows et al., 2018) or 'Ministries for the Future' (Robinson, 2020), that are independent of or tied to existing governance institutions (e.g. United Nations) and networks of local governments (e.g. 100 Resilient Cities; Papin, 2019).

These cross-cultural, trans-national organizations must evolve to keep ahead of observed and anticipated human migration, food production, disasters, and other climate and ecological challenges (Cleaver & Whaley, 2018; Schultz et al., 2015). Practically, this can mean using a rolling-baseline, Russian-doll approach to scenarios and decision-making, embedding subjectively short-term (0–50 years) local or regional assessments and actions inside medium (50–100 years) and longer-term global perspectives (>100 years) based on observed and modelled impacts and thresholds (O'Neill et al., 2020). The medium- and long-term approaches aim to anticipate, develop, and implement structures and technologies for Earth system governance that permits fair access to and allocation of resources to the global population under different impact trajectories (Biermann & Kim, 2020; Kalfagianni & Meisch, 2020). This nested anticipatory approach (Boyd et al., 2015; Muiderman et al., 2020) to adaptive governance would accommodate rapid events, such as floods and droughts, within slower-moving changes to temperature, sea-level, crops, and biodiversity. Projections of climate and Earth system changes beyond 2100 inform these longer-term approaches, helping to ensure changes to ecosystems and their resources are adequately managed to sustain human survival (Bennett, 2017; Burke et al., 2021).

7 | CONCLUSIONS

The year 2100 is one human lifespan away, and the window to readily curb emissions in line with the Paris Agreement is rapidly closing (Leach et al., 2018). Our projections past 2100 indicate that without rapid and significant reductions in greenhouse gas emissions, large areas of the Earth will change in ways that reduce their capacity to support large-scale human occupation. The long-term effects of 21st century warming will be felt for centuries to come, even if emissions are limited in the future (Figure 1). Efforts at mitigation (Kyoto; Paris Agreement; UNFCCC, 2015) may have slowed the growth of greenhouse gases in the atmosphere, but commitments still fall massively short of the 1.5–2.0°C goal (Roelfsema et al., 2020). Even if commitments are met, projections still show that we must contend with heat waves and other extreme events of unparalleled intensity and frequency (Dosio et al., 2018; Schleussner et al., 2016). We therefore need to understand and model these changes beyond the next 80 years. These longer-term projections are critical to preparing the way for a peaceful and habitable Earth in the coming decades and centuries.

Our projections and associated approaches to adaptation governance represent an initial attempt and have considerable uncertainty given their extended time horizon. These efforts are meant to highlight the need for more sophisticated climate and Earth system modelling beyond 2100, including a focus on aspects of ecosystem goods and services not considered here. Our work thus provides a framework and baseline for the assessment of longer-term anthropogenic effects on climate and Earth systems, and highlights the critical need for further work in this area.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHORS' CONTRIBUTIONS

The research was designed by C.L., E.E.S., T.A, A.P.B., A.B., A.M.D., D.J.H., R.M., L.C.S., P.O. Climate and vegetation modelling was conducted by D.J.H. and C.S. Crop modelling and analysis was conducted by E.E.S. and T.A. C.S. conducted the heat stress modelling. C.L., A.B., J.M., L.C.S., R.M., and P.O. assessed the human implications of modelling results. J.M. contributed the artistic visualizations. C.L., E.E.S. and T.A. wrote the initial draft of the paper, and all authors contributed to revisions.

DATA AVAILABILITY STATEMENT

All climate model outputs and associated code will be made available upon acceptance in open-access archives.

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