Title
Constraints to Climate Change Mitigation and Adaptation

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Publication Date
2022

UNIVERSITY OF CALIFORNIA,
IRVINE

Constraints to Climate Change Mitigation and Adaptation

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Earth System Science

by

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Dissertation Committee:
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2022

DEDICATION

To humanity and the subsequent generations. I hope that we were able to act in time so that you may enjoy this wonderful and special place in the universe called Earth as so many have done before you.

To my mom, Guadalupe Navarro, thank you for all the sacrifices throughout the years and for teaching me to love the natural world. Without your love and support, I wouldn’t have made it this far.

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ACKNOWLEDGEMENTS

To the ones who know me personally, especially my spouse, mom, brothers, close friends, and the rest of family, I'd like to thank you for your love and support throughout this journey. Your patience has taught me so much about resiliency in the face of extreme challenges. Too many times I learnt too slow, too many times my knowledge beaten down by insecurity in my own abilities and fear of the unknown. Your patience and support really were something, and a great motivator in the most difficult times. At times when I felt like giving up, you reached out with love, patience, and tolerance, and pushed me to keep going and to believe in myself.

To the ones who fell during my PhD journey, I wish we could have had more time together and that we could laugh, love, and rejoice one last time. You will also have a special place in my heart and thank you for your love and support, even if your journeys were cut short. May each of you find peace wherever you may be. *May you all Rest in Peace - Tio Juan Pablo Navarro, Tia Maria Carmela Rhodes, Abuelo (Rigoberto Navarro), and my good friend Kendra Herrera.*

To my advisor, Steven J. Davis, I'd like to thank you for giving this first-generation college Mexican American student a chance that isn't afforded to most from my community, and it has been a sincere pleasure working with you. Looking back at the first time we met in your office, I was but a lost soul who knew very little about this journey. You've been an incredible support throughout these years, and I truly wouldn't have made it this far without your uplifting spirit. You have done more for me than I can ever return, and I would like to thank you for taking a chance on me.

To my committee, thank you for your support throughout the years and for your insight that helped propel my research forward. I'd also like to thank Steven Allison, for his continued support and the useful training I received through the Ridge 2 Reef program, particularly through his work on scientific communication and policy.

Lastly, I'd like to thank the entire ESS department. I've become close to many of you throughout these years and our daily conversations were an invaluable part of my PhD experience. During the hard times, your uplifting spirits motivated me to keep going and I hope that the ESS community continues to remain a family.

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ABSTRACT OF THE DISSERTATION

Constraints to Climate Change Mitigation and Adaptation
by
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Over the 20th century, critical advancements in energy generation and agriculture have revolutionized contemporary society, propelling many of the modern advancements enjoyed by humanity today. However, these developments have come at a considerable cost to the natural environment, resulting in, among others, global climate change, ecological decline, and wildlife extinction (IPCC, 2013, Masson-Delmotte et al., 2021, Tubiello et al., 2015). Recent international efforts to mitigate severe climate warming and minimize further environmental damage, aim for swift and significant reductions in annual anthropogenic CO_2 emissions worldwide the vast majority of which originate from fossil energy generation (89%), and agriculture driven land-use expansion (11%) (Le Quéré et al., 2018, Friedlingstein et al., 2021, Ramankutty et al., 2008). Thus, climate mitigation pathways that successfully limit future warming below 2°C require the swift transformation of modern agriculture and energy generating practices (Popp et al., 2017, Rogelj et al., 2018b, Audoly et al., 2018, Rogelj et al., 2018a, Rogelj et al., 2015c). However, fossil-burning infrastructure is generally long-lived (Seto et al., 2016, Davis and Socolow, 2014b, Davis et al., 2010, Shearer et al., 2017) and current climate change mitigation

scenarios do not track the magnitude and patterns of necessary power plant retirements (Fofrich et al., 2020). Here, we show fossil-fired power plants retiring up to three decades earlier than historically has been the case in scenarios consistent with international climate targets (i.e., keeping global warming well below 1.5 °C or 2°C), potentially jeopardizing trillions of dollars in power generating assets. If instead, power generators continue to operate as they have historically, we find the resulting emissions are incompatible with more ambitious climate mitigation targets without the equivalent removal of atmospheric CO_2.

We show China, India, the United States, and Western Europe hold the largest share of share of potential stranded assets, risking trillion dollars in stranded fossil-fired power generating assets if these generators are forced to retire prematurely. However, the monetary and social cost of unabated climate change will be much greater than those accrued by stranded fossil-fired generators. For instance, climate change is projected to reduce agricultural productivity in historically warm regions of the planet (Lobell et al., 2011b, Lobell et al., 2013, Schlenker and Roberts, 2009, Rosenzweig et al., 2014) and limit the availability of arable land over the remainder of this century. Therefore, we investigate potential shifts in the location of major grain crop (maize, rice, soybean, and wheat) cultivation under different scenarios of climate change and find that just 2^{o}C of warming risks roughly 19% of global crop production, rising to 35% in scenarios where global temperatures approach or exceed 3°C of warming. Although the agricultural impacts of climate change might be lessened through adaption, our findings emphasize the large extent to which a warming planet may disrupt global food production in the coming years.

Thus, unmitigated anthropogenic warming stems to jeopardize future food security and equity over the next century.

CHAPTER 1.

INTRODUCTION

In the coming decades, humanity will experience more than 1.5^{o}C in preindustrial climate warming if current anthropogenic emission rates are left unchecked (IPCC, 2013, Shukla, 2019b, Masson-Delmotte et al., 2021), resulting in severe and long-lasting repercussions around the world. Over the last century, the global climate system has become increasingly stressed due to marked increases in anthropogenic emissions, land-use conversion, and alterations to global biogeochemical cycles (i.e., nitrogen and phosphorus cycles). These shifts have been largely driven by technological breakthroughs in global energy and agricultural systems (i.e., the Industrial and Green Revolutions) (Le Quéré et al., 2018, Friedlingstein et al., 2021, IPCC, 2013, Masson-Delmotte et al., 2021), and while these advancements have largely been beneficial to humanity (e.g., reducing world hunger and decreasing global poverty), they have also tipped the balance in the Earth system, resulting in anthropogenic climate warming, flora and fauna species decline, and ecological degradation (IPCC, 2013, Masson-Delmotte et al., 2021, Wiens, 2016, Haddad et al., 2015). Nonetheless, as the global population and economic well-being continue to rise, society's demand for agriculture and energy will continue to grow thereby exacerbating existing pressures on natural resources. Thus, in the coming years, energy and agricultural systems must undergo radical transformations to minimize further environmental damages (e.g., climate warming and ecosystem decline) (Luderer, 2016, Rogelj et al., 2018b, Rogelj et al., 2018a).

Future anthropogenic climate warming poses a direct threat to contemporary society and ecosystems at large (IPCC, 2013, Le Quéré et al., 2018, Masson-Delmotte et al., 2021, Shukla, 2019a, Urban, 2015, Otto, 2018, Wiens, 2016). However, the most extreme consequences of climate change can be largely be avoided by further developing energy and agricultural production practices (Peters, 2016, Rogelj et al., 2018b, Rogelj et al., 2018a), deploying negative emission technologies (Azar et al., 2013, Minx et al., 2018, Muri, 2018), and implementing international climate mitigation policy (e.g., a global carbon tax) (Iyer et al., 2015, Warren et al., 2018, UNFCCC, 2015). While the cost and complexity of these measures have largely prevented their widespread adoption thus far, further delaying their implementation only serves to increases the cost and complications of these challenges over time. Moreover, increased planetary warming is also expected to exacerbate anthropogenic emission pressures by increasing global energy demand and reducing the viability of cultivation worldwide thereby increasing pressure on land-use conversion (Sailor, 2001, Isaac and van Vuuren, 2009). While some future warming is already locked into the earth system due to past emissions (Masson-Delmotte et al., 2021), the survival of many natural biological systems and the general wellbeing of humanity requires the swift stabilization of future climate warming below 2^{o}C. However, stabilizing rising global temperatures would require annual anthropogenic emissions to reach net zero in the coming decades (Luderer, 2016, Millar et al., 2017, Rogelj et al., 2015a, Rogelj et al., 2018b, Kriegler et al., 2018, Rogelj et al., 2018a, Matthews and Caldeira, 2008), and therefore, profound changes would need to occur to both the energy and agricultural sectors which are the two largest contributors to global greenhouse gas emissions (Le Quéré et al., 2018, Masson-Delmotte et al., 2021, Tubiello et al., 2015). However, these industries have coevolved with contemporary society and are integratedly woven providing critical services for humanity, making the immediate reduction of emissions from these sectors extremely challenging (Seto et al., 2016, Unruh, 2000, Unruh and Carillo-Hermosilla, 2006, Davis and Socolow, 2014a, Davis et al., 2010, Pfeiffer et al., 2018).

While many studies have been conducted on climate change, there is still a lot of uncertainty regarding the constraints of achieving climate change mitigation pathways and potential challenges to climate change adaptation measures. Thus, I present a detailed interdisciplinary assessment of global energy and agricultural systems in respect to climate change mitigation and adaptation and investigate the financial and social consequences of future climate warming and international climate mitigation policies. Here, I briefly introduce each topic and discuss how this research will help reduce the number of uncertainties and unknowns revolving around potential climate change mitigation policies and their impacts on agricultural and energy systems.

1.2 Energy systems

Chapter 2 focuses on the premature closure of fossil-fired power generators inherent in current climate mitigation forecasts. Models that stabilize temperatures below 2^{o}C require the immediate and marked reduction in fossil-fuel energy generation. Currently, fossil-fired power plants generate 66% of the world’s electricity and 42% of annual anthropogenic CO_2 emissions (Le Quéré et al., 2018, Friedlingstein et al., 2021), and the historical turnover of these power generating assets has been around 35-40 years (Davis et al., 2010, Davis and Socolow, 2014b, Shearer et al., 2017, Pfeiffer et al., 2016, Bertram et al., 2015a, Erickson et al., 2015, Seto et al., 2016, Unruh, 2000, Unruh and Carillo-Hermosilla, 2006). While retiring power plant infrastructure before the end of its historical operational life is possible it can be extremely costly (2016, Binsted et al., 2020, Johnson et al., 2015, Pfeiffer et al., 2016, Baron and Fischer, 2015), and at odds with international development goals if retired power generators are not replaced with low cost, reliable, and non-CO_2 emitting electricity generating sources (Modi, 2005). Additionally, future energy scenarios project an increasing demand for energy services around the globe. Nonetheless, continuing to meet this demand through the deployment of newly constructed fossil-fired power generators ultimately serves to delay necessary reductions in cumulative CO_2 emissions and inevitably locks in future CO_2 contributions for decades to come.

Previous studies have assessed locked-in carbon from long-lived CO_2 emitting infrastructure (Bertram et al., 2015a, Erickson et al., 2015, Seto et al., 2016, Unruh, 2000, Unruh and Carillo-Hermosilla, 2006, Davis et al., 2010, Davis and Socolow, 2014b). However, relatively little attention has been paid to future emissions that are imbedded in climate mitigation energy-emissions pathways, providing little insight into the implications of achieving international climate goals. Here, we evaluate the degree of which climate mitigation scenarios prematurely retire power generating infrastructure, and the resulting carbon emissions if instead these power generators operate as they have in the past. We accomplish this by examining the proportion of future electrical demand satisfied by fossil-fired electricity generation under different climate mitigation pathways. We begin by using unit level data of existing and historical power generators along with future projected energy derived by integrated assessment models for each of the more ambitious climate change projections (i.e., 1.5 & 2.0°C), and model future power plant deployments and subsequent carbon dioxide emissions under each scenario. We additionally quantify the necessary retirement schedules of fossil-fired power generators required to meet these climate mitigation targets.

1.3 Agricultural systems

In chapter 3 we explore the ramifications of climate change on future agricultural production. Climate change is projected to have notable impacts on global food production, influencing future agricultural yield and cropland extent (Ramankutty et al., 2002, Burke et al., 2009, Rosenzweig et al., 2014, Challinor et al., 2014, Tubiello et al., 2007, Lobell et al., 2011b). While a variety of crops are cultivated globally in various climates (Monfreda et al., 2008, Ramankutty et al., 2008, Ramankutty et al., 2002, Leff et al., 2004, Ramankutty and Foley, 1998), their yields are highly sensitive to specific and narrow climatic ranges. Future warming is projected to diminish agricultural yields in historically warmer regions, particularly when crops are exposed to higher temperatures early in their development (Schlenker and Roberts, 2009, Lobell et al., 2011a, Zhao et al., 2017, Tigchelaar et al., 2018, Fatima et al., 2020). However, in cooler areas of the planet, climate change may serve to benefit crop production by extending their growing season. Thus, climate warming will affect global agricultural production differently, benefiting crop cultivation in at higher latitudes while hindering agricultural production in tropical regions of the planet (Mendelsohn and Dinar, 1999, Rosenzweig et al., 2014, Butler et al., 2018, Wheeler and von Braun, 2013). In some cases, diminished yields from higher temperatures may be alleviated through improved farming practices and adapting future cultivars to hotter, drier, and in some cases wetter conditions (Howden et al., 2007, Mueller et al., 2017, Henry, 2020, Moore and Lobell, 2014). Nonetheless, future changes in growing season temperature and precipitation may ultimately force cropland migration or the complete abandonment of certain crop cultivation (Pugh et al., 2016).

Earth’s climate has been relatively stable for thousands of years (Marcott et al., 2013), resulting in the endemic evolution and domestication of certain crops (Gupta, 2004, Feynman and Ruzmaikin, 2007), and the differences in regional climate and cultural factors has led to diversity in agricultural practices and crop cultivation dates (Howden et al., 2007, Sacks et al., 2010). However, the magnitude and rate of current warming are unprecedented during any point of human civilization (Bova et al., 2021, IPCC, 2013, Burke et al., 2018). Preindustrial global temperatures have already increased by over 1^{o}C (IPCC, 2013, Masson-Delmotte et al., 2021), and are likely to increase an additional 1 - 4^{o}C by the end of the century (Zhou et al., 2021, IPCC, 2013, Masson-Delmotte et al., 2021). Thus, without proper steps to mitigate more severe climate change, the migration or abandonment of historical croplands might be necessary to alleviate the climate-induced burden on global food systems. The impacts of temperature on agricultural yield (Deryng et al., 2014, Lobell et al., 2011a, Schlenker and Roberts, 2009, Rosenzweig et al., 2014, Zhao et al., 2017, Fischer et al., 2005), and ecological climatic niche migration rates are well documented (Loarie et al., 2009, LoPresti et al., 2015, Diffenbaugh and Field, 2013, Brito-Morales et al., 2018, Carroll et al., 2015, Hof et al., 2011, Kosanic et al., 2019, Elsen et al., 2020, Dobrowski and Parks, 2016, Hamann et al., 2015). However, many global studies have relied on agriculture simulation models (Fischer et al., 2005, Zhao et al., 2017, Rosenzweig et al., 2014, Schleussner et al., 2018, Beltran-Peña et al., 2020), and the migration rates of climatological cultivation zones have not been fully explored. Therefore, we investigate the migration of cropland extent for 4 major crops (maize, rice, soybean, and wheat), and model changes to crop ranges under different scenarios of climate warming. Additionally, we explore the implications these changes will have on national food sovereignty, showing where future crop production may occur.

1.3 Stranded investments

In Chapter 4, we explore the financial ramifications of climate mitigation pathways on the power sector. Future climate warming is an existential threat to contemporary society (Masson-Delmotte et al., 2021), however meeting ambitious climate goals is not without financial and social costs. Here we explore the risk of fossil-fired power asset stranding under different carbon pricing targets using unit-level power plant data from around the world. Stranded assets can occur from an unanticipated devaluation of power generating infrastructure due to rapid changes in policy. Thus, an abrupt implementation of stringent climate policy could result in trillions of unrecoverable investments if it results in a sudden and unexpected change in the operational schedule of existing and newly financed fossil-fired power generators. We therefore explore the ramifications of various climate mitigation pathways on existing fossil-fired power infrastructure and show which corporate and state-owned enterprises are at most risk for stranded investments, and calculate the proportion of their fossil-fired investments that could be potentially stranded. Additionally, we uncover which companies hold the largest share of stranded electricity generating assets. Therefore, our study highlights the urgent need for the international implementation of climate-mitigation-energy policy and the financial risks if such a policy is not swiftly adopted.

CHAPTER 2.

EARLY RETIREMENT OF POWER PLANTS IN CLIMATE MITIGATION SCENARIOS

Adapted from:

R Fofrich., D Tong, K. Calvin, H Sytze de Boer, J Emmerling, O Fricko, S Fujimori, G Luderer, J Rogelj and SJ Davis. Early retirement of power plants in climate mitigation scenarios. *Environmental Research Letters* **15**, 094064 (2020)

2.1 Introduction

Among scenarios that succeed in stabilizing global mean temperatures at less than 2°C warmer than the preindustrial era, CO_2 emissions from the power sector decrease rapidly in the coming decades, in almost all cases reaching net-zero before mid-century (Davis et al., 2018, Rogelj et al., 2015b, Williams et al., 2012, Audoly et al., 2018, Luderer et al., 2018). Such rapid and complete decarbonization entails similarly rapid turnover of historically long-lived electricity-generating infrastructure. Coal- and gas-fired power plants have historically operated for 39 and 36 years (s.d.14 and 13 years), respectively (Davis et al., 2010). However, in Integrated Assessment Models (IAMs), the decision of when to retire a generator is primarily economic, e.g., based on marginal operating costs, revenues, and the levelized costs of new generating infrastructure (Taylor and Fuller, 1986, Davis and Socolow, 2014a, Seto et al., 2016). IAM mitigation scenarios reconcile these economics with swift decarbonization of the electricity sector by modeling both policy-driven increases in the operational costs of CO_2-emitting power plants and rapidly decreasing costs of non-emitting sources of electricity (Rogelj et al., 2015a, Rogelj et al., 2018a). In reality, lawmakers may follow a similar approach, incentivizing the early closure of plants or severely reducing their operating hours by imposing strict regulations that increase their operating costs relative to non-emitting competitors. Examples of specific policies include setting a price on carbon, disallowing major maintenance (e.g., New Source Review in the United States), or subsidizing non-emitting technologies (e.g., renewable production tax credits). However, economics aren't the sole determinant of power plant retirements, as there are numerous examples of fossil power plants now operating at a loss (Wamsted, Gray, 2018, Gimon Eric, 2019). This suggests that more direct regulations such as an outright ban of a given fossil technology or mandating the early closure of certain power plants may be necessary. Nonetheless, given the initial capital costs of fossil fuel electricity generating capacity are typically \$200-5000 per kW and installed fossil capacity worldwide is today ~4000 GW (Seto et al., 2016, Baron and Fischer, 2015, Tong et al., 2019b), the premature retirement of power generating infrastructure could result in the loss of trillions of dollars of capital investment and future returns, and perhaps even jeopardize the stability of financial systems if not adequately managed and anticipated (Battiston et al., 2017, Sen and von Schickfus, 2020, Binsted et al., 2020, Iyer et al., 2015). Moreover, losses from early retirement of fossil electricity generating assets may ultimately be borne by the rate- and tax-paying populace. For these reasons, the socioeconomic and political repercussions that arise from very early retirement of coal- and gas-fired power plants may be challenging to overcome.

Several previous studies have estimated the CO_2 that will be emitted by existing and proposed energy infrastructure if it is operated for historical average lifetimes (Davis and Socolow, 2014a, Davis et al., 2010, Tong et al., Tong et al., 2019b). Others have used IAMs in various ways: using scenarios as a guide to future fossil capacity (Pfeiffer et al., 2016), adding plant lifetime as an exogenous constraint within a model (Cui et al., 2019), or evaluating the infrastructural inertia of emissions in a designed multi-model experiment (Bertram et al., 2015b). However, prior work has generally focused on differences in emissions related to the lifetime, operation, or commissioning of generating infrastructure. Here, we also take the opposite perspective: what do the rapid emissions reductions in mitigation scenarios imply for the lifetime, operation, and commissioning of generating infrastructure? Specifically, how severely must the lifetime or operation of power plants be abbreviated or curtailed, respectively, in order to achieve the emissions decreases (i.e. mitigation rates) in different scenarios and regions? Although the answers to these questions can be explicitly calculated by some IAMs, modeling approaches between IAM vary, retirements are endogenous to the models, and retirement rates aren't reported—or even tracked—by all modeling groups.

2.2 Results

Here, using detailed data of currently existing power plants worldwide (Platts, 2018) in addition to electricity and emissions outputs from six major integrated assessment models, we analyze coal- and natural gas-fired power plant utilization rates and lifetimes embedded in 171 recent scenarios, spanning three levels of emissions mitigation (1.9, 2.6, and 4.5 W/m^2 of radiative forcing; i.e., trajectories likely to avoid 1.5°C, 2°C, and 3ºC of mean warming this century), and five different socioeconomic trajectories (SSPs) (Bauer et al., 2017). We explicitly excluded oil-fired power generators from our analysis since they compose less than 5% of global electricity generating capacity (Agency, 2019). Further details of our analytic approach are in the *Methods* and *Appendix A* though Figure 2.1 summarizes how our analyses were conducted schematically. In this figure we only show the simplest approach to facilitate the readers understanding of our methodology. Here we assume a uniform operating lifetime (e.g., 40 years in Fig. 2.1a) and capacity factor (e.g., 70% in Fig. 2.1a). In addition, we evaluate whether and when fossil fuel- and region-specific electricity demand in each IAM scenario (black curves) will require new capacity to be commissioned (colored squares) if existing capacity (gray squares) is not able to meet the projected fossil electricity need. As fossil electricity demand declines within the IAMs in the future, we quantify the extent to which there would be excess generating capacity given the assumed lifetime and capacity factor of operating power plants (black-hatched squares). By further assuming a carbon emissions factor (CO_2 per unit electricity generated) in line with historical estimates, we can in turn quantify the potential emissions associated with such excess capacity. Assumed lifetime, capacity factor, and carbon emission factors are varied in repeated analyses (e.g., Figs. 2.1b and 2.1c). We analyze model projections using fixed lifetimes and capacity factors to project all plausible values of future emissions. Additionally, we vary power plant operating conditions in each subsequent annual time step as a sensitivity test for our results. However, this added flexibility to the initial operational conditions of power generating infrastructure had very little impact on our overall results. For context, Table 2.1 compares operating conditions and constraints on infrastructure retirements within each of the six IAMs.

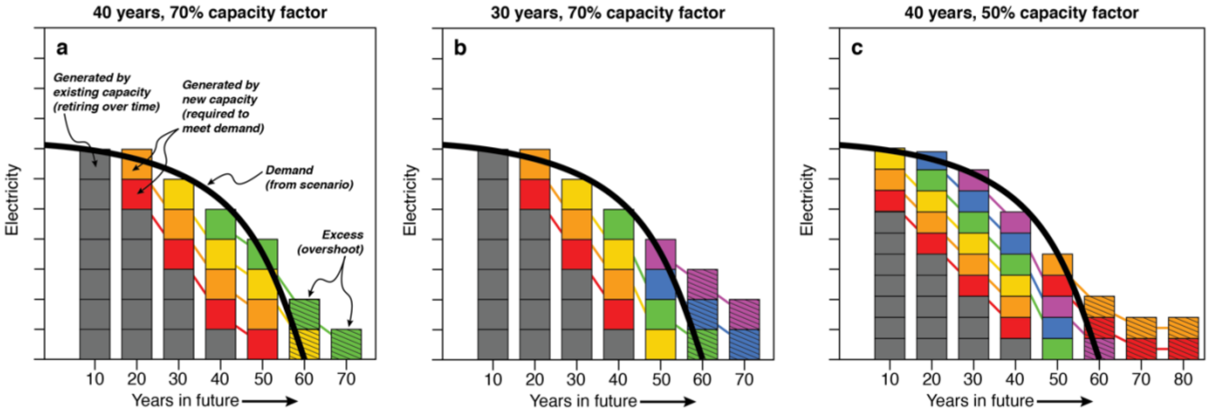

Figure 2.1 | Schematic of modelling approach. Figure shows a hypothetical scenario to illustrate our methodological approach and isn't representative of any specific integrated assessment model or shared socioeconomic pathway. Here we see, given a future electricity demand from coal- and gas-fired power plants in an integrated assessment model scenario (black curves), it may be necessary to build additional generating capacity (colored squares), whose operation may eventually exceed demand with corresponding "overshoot" of emissions (hatched squares). Nonetheless, this schematic represents the model in its simplest form and does not capture the full extent of model ensembles.

In Figure 2.2, the black curves show the annual CO_2 emissions from coal- and gas-fired electricity generation, as projected by the integrated assessment models, for all SSPs under different levels of future warming used in this study (i.e., radiative forcing of 1.9, 2.6, and 4.5 W/m^2). In comparison, colored curves show our calculated emissions if power plant lifetimes are assumed to be 10, 20, 30, 40, 50, or 60 years (purple, blue, green, yellow, orange, and red, respectively). Here we also assume historical mean capacity and carbon emissions factors, see Tables A.1-6, however we vary power plant operational conditions in subsequent calculations to test impacts on our results. In all cases, bold curves represent the median of all global integrated assessment model scenarios (n=171).

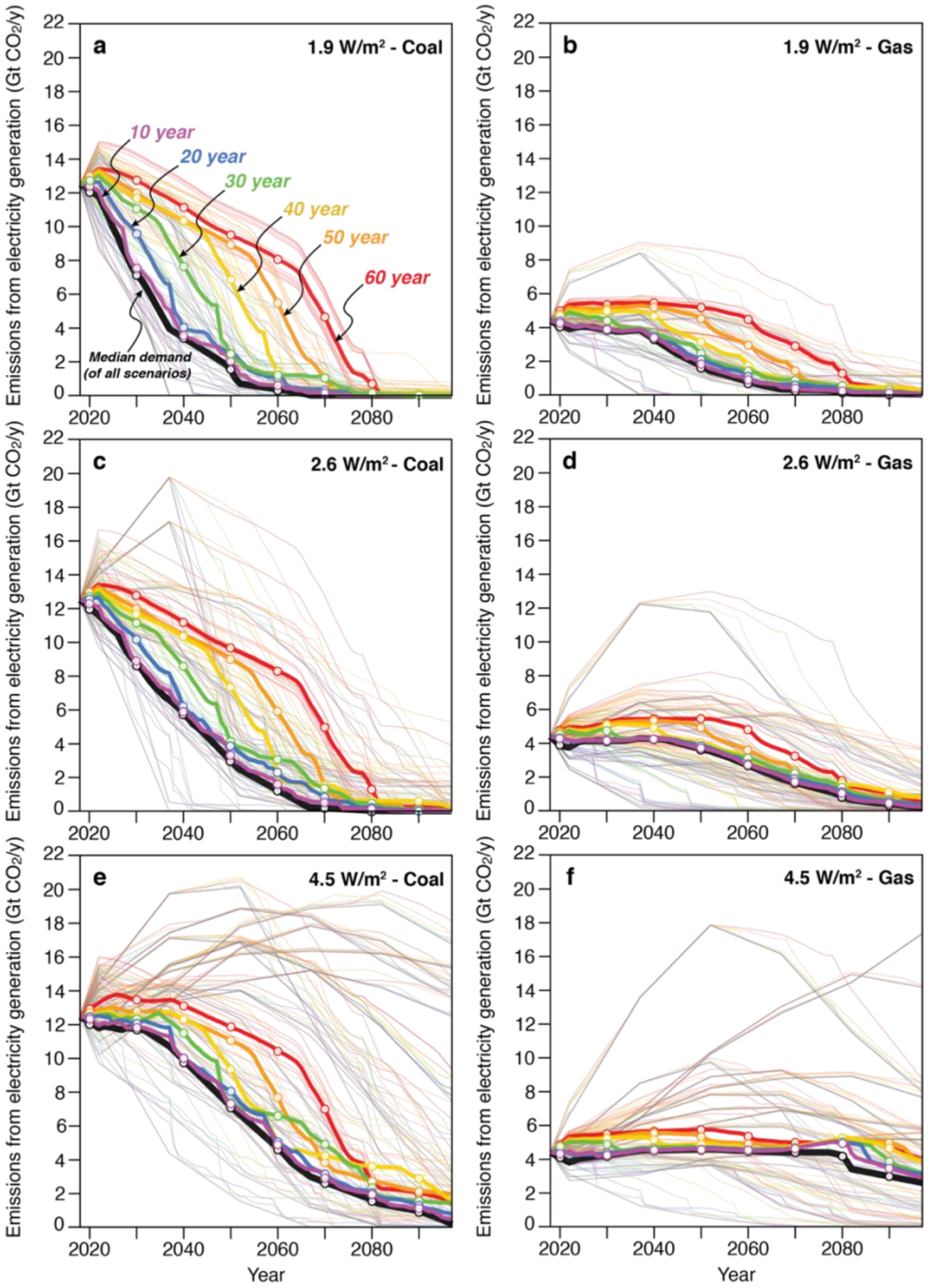

Figure 2.2 | Inertia in power sector emissions. Future emissions from coal- and gas-fired power plants in the 1.9, 2.6, and 4.5 W/m^2 radiative forcing scenarios (black curves) often decrease more rapidly than emissions from power plants which at region-specific mean capacity factors and power plant lifetimes ranging from 10 years to 60 years (colored curves). The thin lines show each IAM-SSP combination, and the bold lines show the median value of all IAM-SSP projections. Given the age structure of now-existing energy infrastructure, ambitious mitigation pathways such as 1.9 and 2.6 W/m^2 imply very short power plant lifetimes, particularly for coal-fired units.

We see the median IAM emissions (black curves) generally decrease more quickly than the emissions we estimate if plants were to operate for more than 30 years (green curves), especially in the case of coal-fired plants and under the more ambitious (lower warming) scenarios (Fig. 2.2). For example, Fig. 2.2a shows that median emissions, assuming coal-fired generator lifetimes greater than 30 years, do not decline as rapidly as the median IAM projections (bold black curve) for the 1.9 W/m^2 scenario. The differences between the black IAM curves and our calculated curves reflects the magnitude of such excess emissions, which consistently increase as longer lifetimes are considered. However, the scenarios from different IAMs and SSPs can result in considerably different cumulative emissions, with greater model spread under higher warming scenarios (from left to right in Figs. 2.3a-c). For instance, in the lower warming (i.e., likely to avoid 1.5 and 2 ^{o}C) scenarios, cumulative emissions averaged across models and assumed lifetimes are greatest for SSP2 (“middle-of-the-road”; blue), followed by SSP5 (“fossil-fueled development”; pink) and least for SSP1 (“sustainability”; green) and SSP4 (“inequality”; pale orange). See *Methods* or ref (Riahi et al., 2017b) for further discussion on how the SSPs differ. Averaging across models, for a given lifetime, cumulative emissions vary by 27%, 30%, and 36% across SSPs in the different warming scenarios, respectively. In comparison, the average variation in cumulative emissions among models for a given SSP and lifetime are 31%, 45%, and 48% in the different warming scenarios, respectively.

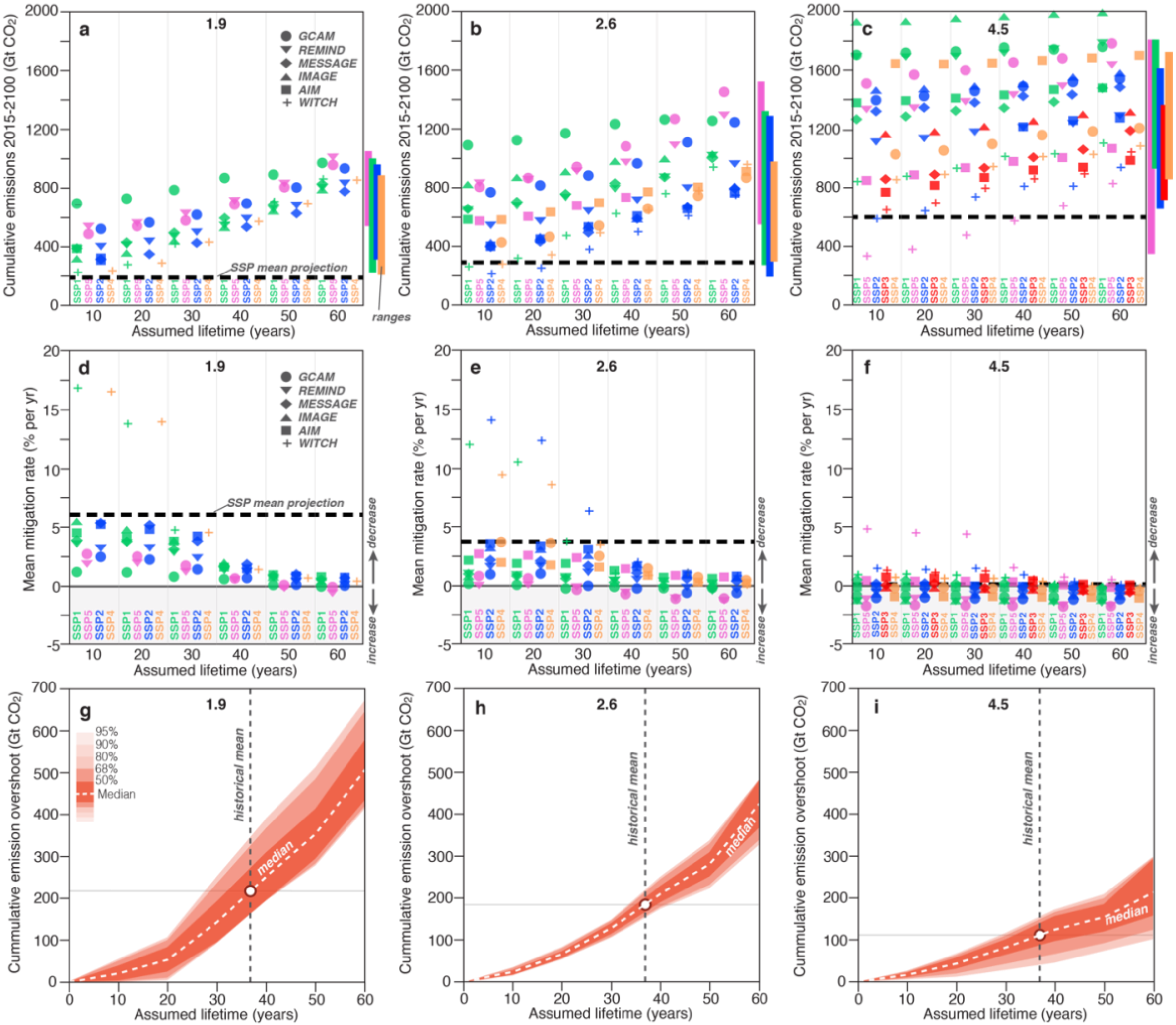

Figure 2.3 | Annual mean emission mitigation rates, cumulative emissions and emission overshoot in energy-emission scenarios. Cumulative CO_2 emissions from coal- and gas-fired power plants in the 1.9, 2.6, and 4.5 W/m^2 radiative forcing trajectories over the 21st century (**a-c**). Cumulative emissions increase as power plants lifetimes are prolonged and as climate mitigation goals wane. Annual emission reductions from coal and gas electrical generators decline with an increase in assumed power plant lifetime and with increased inertia from electricity production (**d-f**). Differences between SSP emissions projections and emissions under different lifetime assumptions (**g-i**). Dashed vertical line indicates the historical mean lifetime whereas the white dashed line is the cumulative emission mean across all IAM-SSPs for each of the forcing scenarios.

The longer the assumed lifetime of power plants, the lower mean mitigation rates (defined here as the annual percent reduction in CO_2 emissions from 2017-2050) will be, Figures 2.3d-f. Since mean mitigation rates are inversely related to future warming, this relationship illustrates the temporal constraints imposed by infrastructural inertia. For example, in the scenarios likely to bring back warming to below 1.5°C by 2100 (SSPx-1.9 scenarios from ref. (Rogelj et al., 2018a)), integrated assessment model outputs average 6% per year reductions in emissions from coal- and gas-fired power plants (dotted gray line), but mean mitigation rates when assuming plant lifetimes of 30 or more years decrease to <3% per year (Fig. 2.3d). Similarly, model outputs average 3.7% per year reductions in scenarios likely to avoid 2°C (SSPx-2.6, dotted gray line), but mean mitigation rates when assuming plant lifetimes of 30 or more years decrease to <2% per year (Fig. 2.3e). Thus, allowing fossil-fired power infrastructure to operate for more than 30 years from initial commissioning is incompatible with the rapid mitigation rates achieved in the IAMs.

Since climate change is proportional to society's cumulative emissions, we were interested in quantifying the amount of emissions over the IAMs (hereby 'cumulative overshoot') when power generators are operated for different periods of time. We find the cumulative overshoot increase along with assumed lifetimes but are also substantially greater in the lower warming scenarios (Figure 2.3g-i). For instance, if we assume power generators will follow historical operating norms, a lifetime of 37 years and mean capacity factor (dashed lines), the cumulative overshoot rises from a median 112 Gt CO_2 in 4.5 W/m^2 scenarios, to 188 Gt CO_2 in 2.6 W/m^2 scenarios, to 220 Gt CO_2 in 1.9 W/m^2 scenarios. Given that total cumulative emissions averages just 182.5 Gt CO_2 in 1.9 W/m^2 scenarios, an additional 220 Gt CO_2 represents an overshoot of 220.5% and is roughly equivalent to the entire fossil electricity CO_2

budget in the 2.6 W/m^2 scenario. We find the similarity between the 1.9 and 2.6 W/m^2 scenarios largely result from the age distribution of the existing power fleet. In both cases, the IAM scenarios result in immediate reductions to global CO_2 emissions but do not consider the power infrastructure lifetimes of operating plants. Using our methods, but following the 2.6 W/m^2 scenario requires modest deployment of new fossil capacity resulting in a similar overshoot. Nonetheless, these findings indicate the extent to which the low cumulative emissions in ambitious mitigation scenarios are the result of early retirement of coal- and gas-fired power plants. In addition, the similarity of the IAM electricity pathways while achieving different levels of radiative forcing indicate that a substantial reduction of annual CO_2 emissions from other industries is required to reach the 1.9 W/m^2 pathway.

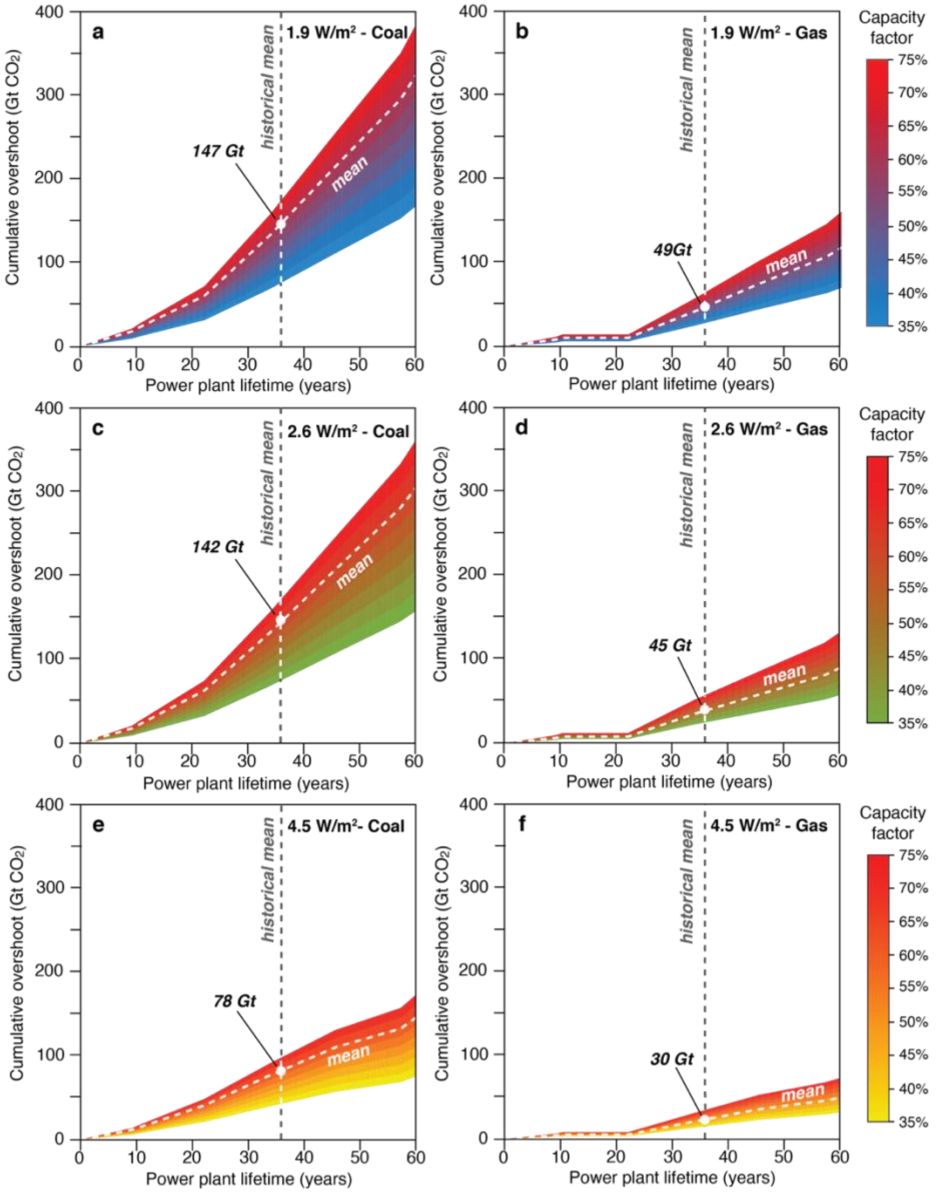

Figure 2.4 | Excess CO_2 emissions from coal and gas-fired power plants. Differences between mean IAM emissions projections and mean estimated CO_2 emissions under different capacity factor and lifetime assumptions. The panel rows represent the three different levels of radiative forcing (1.9, 2.6, and 4.5 W/m^2) while the panel columns show the difference between coal- and gas-fired power plants. Color shading indicate a range of capacity factors ranging from 35-75%. Dashed vertical line represents the historical mean power generator lifetime of 37 years whereas the white dashed line moving along the x-axis represents the historical mean capacity factor.

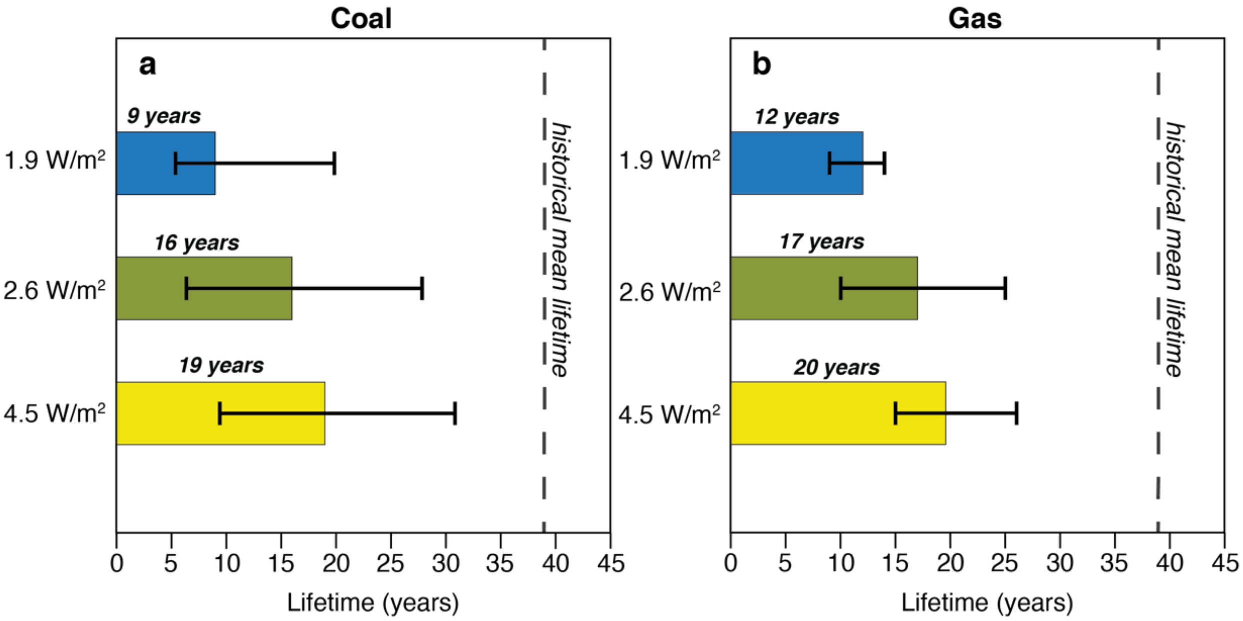

Figure 2.5 | Maximum power plant lifetime under different electricity-emission scenarios. Under ambitious climate change scenarios, fossil powered electricity generating infrastructure retire much earlier than they have historically. Here we present the maximum obtainable lifetime under different electricity demand scenarios for three levels of radiative forcing (radiative forcing 1.9, 2.6, and 4.5 W/m^2). Error bars show the full range of power retirements under different capacity factor assumptions.

In turn, Figure 2.6 shows how key regions contribute to the cumulative overshoot in lower warming scenarios (averaging across the values for 1.9 and 2.6 W/m^2 shown in Figs. 2.3g and 2.3h). In comparison to the other regions shown, overshoots increase most dramatically in China when longer lifetimes of power plants are assumed. This is consistent with previous unit-level inventories of emissions which have shown that half of now-existing coal-fired generating capacity is in China, and mostly <15 years old (Tong et al., 2018). Fig. 2.6 reveals the extent to which model scenarios anticipate the retirement of these Chinese plants before they reach 20 years of age. Similarly, early retirements are required to avoid substantial overshoots in other regions, but the magnitude of overshoot when an historical lifetime of 37 years is assumed are roughly 53%, 26% and 87% less in India, the U.S. and Western Europe than in China, respectively.

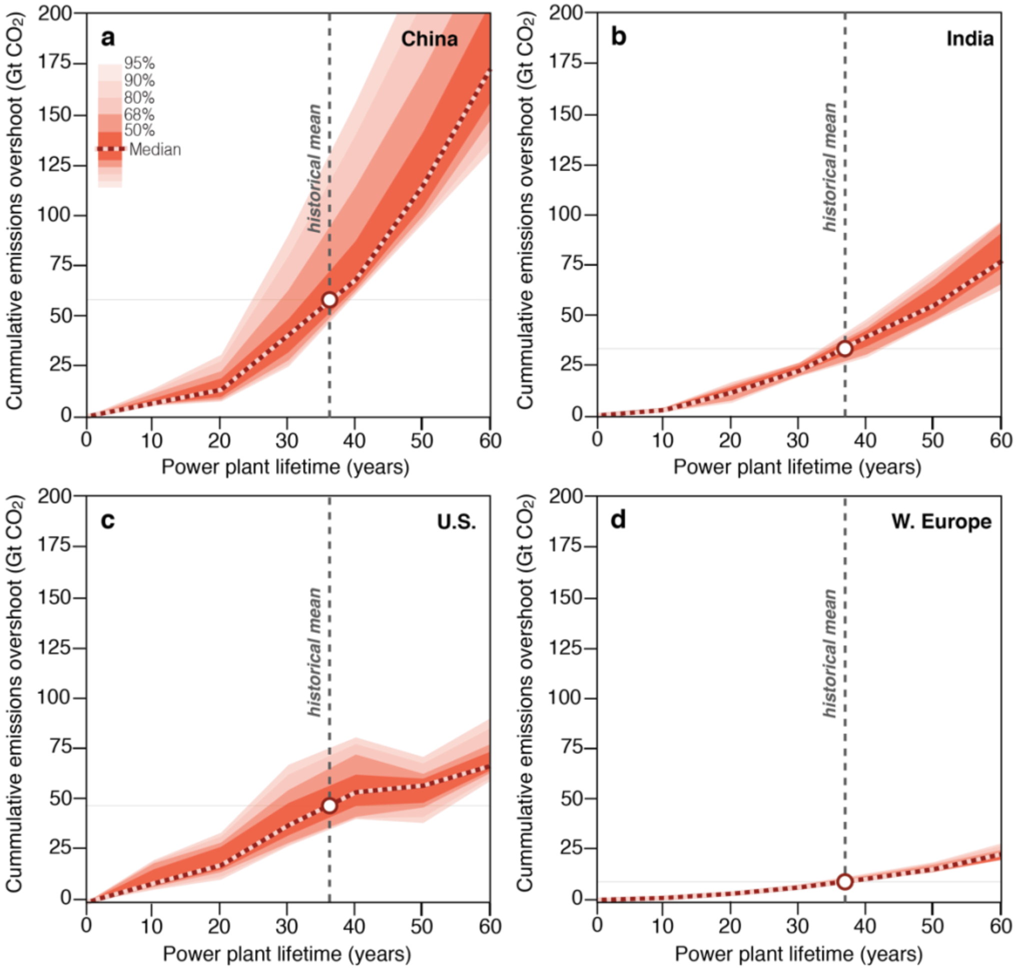

Figure 2.6 | Regional emission overshoot in power sector emissions. The magnitude of cumulative future emissions from coal- and gas-fired power plants in excess radiative forcing projections ("overshoot") is sensitive to assumed power plant and climate mitigation pathways. Here we see the overshoot from coal and gas emissions from a median 1.9 and 2.6 forcing pathway for the top four CO_2 emitting regions. Color intensity indicates the 50th – 95th percentile cumulative emissions for all of the IAM-SSPs.

Figure 2.7 acts as sensitivity test to our projected emissions from allowing additional flexibility in initial power plant operational conditions. For example, varying assumptions of plant lifetime and capacity factor by 25% has a similar effect on estimated cumulative emissions, regardless of radiative forcing or SSP (Fig. 2.7). However, both lifetime and capacity factor become less important in higher warming scenarios, and the assumed carbon intensity of electricity becomes a dominant factor (Fig. 2.7).

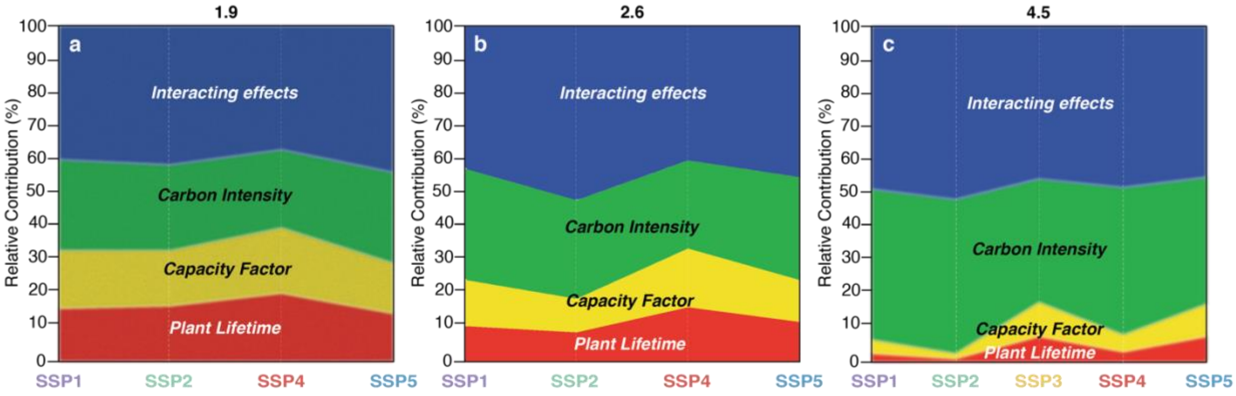

Figure 2.7 | Relative contributions to overall emissions. Relative contributions to future cumulative emissions from power infrastructure lifetime, capacity factors, and carbon intensity to each energy-emission scenario. We see the relative contributions from the power plant's capacity factor and lifetime decrease as climate mitigation policy goals decrease. In contrast, the relative contribution of a plant's carbon intensity increases with these same goals.

2.3 Discussion

Our results suggest that climate scenarios which are stabilize global temperatures in the range of 1.5 to 2°C or below, retire coal- and gas-fired plants decades before their technical or historical lifetimes have been reached. Although it is generally understood that CO_2 emitting infrastructure will need to be swiftly decommissioned in order to mitigate the most extreme consequences of climate change, the extent to which climate mitigation scenarios rely on the premature retirement of existing plants and the curtailment of future construction isn't widely known. Since IAMs conduct power plant retirements endogenously, the rates and processes that dictate these retirements seem obscure to many who wish to interpret IAM results (2015). In addition, the IAM projections typically begin in 2005 and without incorporating information about the current installed fossil capacity or age distribution of fossil fuel-fired plants. Thus, climate mitigation scenarios may underestimate the inertia of emitting infrastructure. As a result of the IAM structure, the operating power capacity and projected mitigation rates in their scenarios can quickly diverge from the realities of the existing fossil fleet and can vary greatly between IAMs and SSPs.

The mitigation rates observed within IAMs are unprecedented and thus represent a potential challenge to society, particularly with the continued deployment of coal-fired power plants around the globe (Shearer et al., 2017). If coal-fired power generators are not retired early (or their capacity factors drastically reduced), then mitigation rates will fall behind IAM scenarios (Figs. 2.3d and 2.3e) and cumulative emissions will rise sharply (Figs. 2.3a, 2.3b, 2.3g, and 2.3h), thus undermining the ability to achieve lower-warming targets without additional compensatory decreases in emissions from other sources. Although negative emissions are represented within the integrated assessment models, our results highlight that longer power plant lifetimes would require an even larger negative emissions than the prodigious quantities already present in some of the more ambitious mitigation scenarios (which are in some cases many Gt CO_2 per year) (Smith et al., 2016). Moreover, the need for shortened infrastructure lifetimes is particularly critical in China, where coal-fired generating capacity is both young and large (Tong et al., 2019b).

Given the established relationship of cumulative carbon budgets and climate warming (Matthews et al., 2009, Allen et al., 2009, Rogelj et al., 2019, Meinshausen et al., 2009), prior studies have estimated and compared "committed" emissions over the expected lifetime of emitting infrastructure (Davis et al., 2010, Davis and Socolow, 2014a, Raupach et al., 2014, Tong et al., 2019a). Many climate mitigation scenarios thus optimize operating and retirement schedules of fossil-fueled infrastructure to lower their cumulative carbon emissions (hence attaining lower carbon budgets and establishing lower warming trajectories) by prioritizing economic conditions where costs of the power sector are equal to revenues from electrical generation rather than reflecting the inertia of the power fleet which is already in existence today. In actuality, decommissioning trillions of dollars' worth of privately-owned capital after only 25% of its anticipated life has elapsed will present enormous political and economic challenges. Indeed, it is these challenges, collectively, that represent the infrastructural inertia (i.e., carbon lock-in)(Seto et al., 2016, Raupach et al., 2014, Tong et al., 2019a).

While the IAMs serve as a powerful tool, allowing users to gain insight regarding a particular sector, the mechanisms behind endogenous calculations are often seen as black boxes by the broader scientific community leading some to question their methods as inscrutable (2015). Thus, by using a standardized method to quantify the implicit lifetimes of power plants within these climate mitigation scenarios, our analysis provides a transparent process while demonstrating the extent to which lower warming scenarios may be contingent upon the early retirement of power sector infrastructure. In many cases, deliberately planned retirement of coal- and gas-fired power plants are necessary in mitigation scenarios which project limited growth in demand for fossil-fuel electricity. If instead, the deployment of fossil fuel power capacity is continued in the upcoming years, stabilizing global mean temperatures at less than 2°C relative to the preindustrial will require even shorter retirement ages than those achieved within climate mitigation scenarios. Nonetheless, our results suggest that these targets can only be achieved through a strategic manipulation of installed coal- and gas-fired power capacity, generator lifetimes, and capacity factors (e.g., retiring certain plants prematurely or severely curtailing their usage while extending the lifetime of others until renewable electricity generating technology is deployed locally at scale). Thus, if current power sector trends continue, this may necessitate economically costly options – e.g., stranding fossil electrical assets, retrofitting existing plants with CCS, or offsetting increased emissions through mass deployment of carbon dioxide removal technologies (Luderer et al., 2018, Kriegler et al., 2018), which ultimately may come at a higher expense than early retirement. While the value of such generating capital and the total cost to society are represented and depreciated within these scenarios, the distribution of these costs is not. Therefore, lost revenues and profitability for plant owners and local governments, or job losses for workers might prove prohibitively high.

It should be noted that some of our projections of future emissions reported here do not allow lifetimes and capacity factors to vary over time, across regions, or between different generating assets which is in contrast to the flexibility allowed in power plant operational conditions both in the integrated assessment models and the real world. Thus, insofar as capacity factors and lifetimes may in reality decrease over the lifetime, operation, and retirements may be strategically scheduled, and plants might be mothballed and re-operated. Thus, the overshoot we project should be interpreted to reflect the capacity-weighted average lifetime and may be overestimated. However, we find it crucial to demonstrate the incapability of continued investments in fossil fuel power infrastructure with more ambitious climate mitigation scenarios rather than focus on any one single lifetime trajectory. That is, because it is newly commissioned power plants that create the greatest inertia and scenario overshoot. While in some cases inertia and emissions could be avoided by extending the life of existing and due-to-retire plants, such that new plants will not have to be built (and the older plants can be more readily retired to rapidly decrease emissions), achieving such flexibility in reality would depend upon clear foresight of both regional electricity demand and global climate-energy policies, as well as rational economic behavior on the part of utilities and power plant owners whom historically have not been transparent in their decisions (Gerrard, 2018, Jewell et al., 2019). Nonetheless, decarbonizing the global power sector is currently technically and economically feasible given proven technology but is contingent on the increased investment and construction of low-carbon technology and infrastructure as well as passing legislation regulating carbon emitting technologies (Haley, 2019). While costly, the co-benefits to society often outweigh the overall financial burdens that result from a swift retirement of polluting plants (Rauner et al., 2020). Thus, policy makers should immediately begin to phase out fossil-fired power plants by supporting low-carbon energy infrastructure while simultaneously implementing legislation that’s unfavorable for continued fossil fuel use. However, in reality, governments have been observed taking the opposite approach, choosing instead to prop up economically unstable power plants through subsidies and/or by passing industry favorable regulations in order to minimize the socioeconomic consequences of plant closures and ultimately prolonging the infrastructural inertia of these plants (Jewell et al., 2019).

2.4 Conclusion

Thus, in conclusion, power sector capital that is amassed over decades will also take decades to retire unless its value is sacrificed, and lower-warming scenarios often demand such sacrifice. Which policy mechanisms force early retirements may ultimately determine who will bear the economic losses. In jurisdictions with strict climate policies, proactively limiting the time period that new coal- and gas-fired plants will be allowed to operate might forestall investments that would otherwise either contribute to emissions overshoot or else be forced to retire early at great expense. In the future, operating lifetimes and economic implications of CO_2 emitting-infrastructure should be considered when formulating future energy investments that are consistent with existing climate policies so that investors may determine the compatibility of their planned energy infrastructure investments with different scenarios of climate change and fully understand the risks of their monetary investments (Gerrard, 2018, Sen and von Schickfus, 2020).

2.5 Methods

2.5.1 Existing and historical infrastructure.

We use the Global Power Plant Emissions Database (GPED) to analyze historical coal and gas power plants that are currently operating. We quantify the annual electrical generation, installed nameplate capacity, yearly averaged emission intensities, and annual mean capacity factor of all existing and past power plants. For currently operating generators, we identify current installed capacity in each region and the year each was commissioned, and project the expected year of retirement based on an assumed lifetime.

2.5.2 Power infrastructure commissioned in future.

Regional scenarios of future electricity projections were produced for each of the Shared Socioeconomic Pathways (SSPs) by the Asia-pacific Integrated Model/Computable General Equilibrium (AIM/CGE), Global Change Assessment Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), the Model of Energy Supply Strategy Alternatives and their General Environmental impacts - Global Biosphere Management (MESSAGE-GLOBIOM), Regional Model of Investments and Development - Model of Agricultural Production and its Impact on the Environment (REMIND-MAGPIE), and World Induced Technical Change Hybrid - Global Biosphere Management (WITCH-GLOBIOM) integrated assessment models (IAMs). Each IAM uses different number of regions to represent global society and classifies these regions based on their socioeconomics, geopolitics, and stage in economic development of the nations represented. A full list of IAM regions and associated historical mean capacity factors and carbon intensities is provided within *Appendix A*, *Tables A.1-6*. We quantify existing power generating infrastructure, electricity demand, and generator operating conditions using the same regional classifications as represented in each IAM. We then project the need for new electricity generating capacity by estimating the difference between IAM projections and existing electrical capacity in each world region and SSP-model-radiative forcing trajectories.

Repeated analyses vary the assumed lifetimes of coal- and gas-fired power plants 10-60 years and capacity factors from 35-75%, applicable to both existing generators and any infrastructure commissioned in the future. In our standardized approach, power generators are phased out once their expected operational lifetime has elapsed. New power generators are only built if the annual power supply dips below annual power demand, which can occur when existing power infrastructure is retired or if there is a sustained increase in power demand projected by the IAMs. Newly constructed generators are assumed to have the same operating conditions as the corresponding model run. Nonetheless, we calculate the 1.9 and 2.6 W/m^2 radiative forcing scenarios required very little deployment of new coal-fired power plants, instead most of the overshoot observed in our results come from existing power infrastructure with the exemptions of a few regions globally.

2.5.3 Emissions.

We convert our estimates of electricity generation to carbon dioxide emissions using IAM electricity projections, our energy calculations under different lifetime assumptions, and IAM regional mean historical carbon intensities ranging from 387-1381.4 gCO_2/kWh. Here we analyze 18,810 of individual IAM regional coal and gas electricity scenarios and categorically applied the corresponding carbon intensity. A detailed list of IAM regional mean carbon intensities can be found in the *Appendix A, Tables A.1-6*. Additionally, we use a linear regression approach and looked at the annual emission reductions 2017 to 2050, to determine the annual emission mitigation rates of each IAM-SSP included in this study. For each radiative forcing pathway, cumulative emissions overshoot was determined by taking the difference between the cumulative emission projection and the cumulative emissions trajectories under the various power plant lifetime assumptions used for this study. In each RF, cumulative emissions are calculated by model, SSP, and lifetime assumption individually then separated by their statistical distribution thus identifying the probability of the emissions trajectory.

2.5.4 Regional Analysis.

We analyze regional emissions under each of the IAMs included in this study using the mean IAM regional capacity factors and carbon emissions intensities. In each case, we calculate the cumulative emission overshoot for both coal-fired and natural gas electricity generation individually by RF, IAM, and SSP. We separate the cumulative emission overshoot by their statistical distribution to quantify the likelihood of this emission projection and plot the median cumulative carbon dioxide emissions in each case. Additionally, we identify the magnitude of CO_2 emission overshoot for each region based on historical median power plant lifetimes of 37 years. Regional calculations are based on IAM regional classifications and are aggregated to quantify global energy and emissions. In each case, we analyze global emissions overshoot for each of the radiative forcing trajectories included in this study. Here we calculated the overshoot and again vary the historical capacity factors by 35-75% and vary the power plant lifetimes from 10-60 years. Using the GPED database, we estimate the historical capacity factors to be ~65% and ~55% for coal and gas power plants, respectively.

2.5.5 Overview of Modeling Framework

We draw upon 171 electricity model trajectories across 5 SSPs produced by six integrated assessment teams under three different radiative forcing trajectories throughout the 21st century. Given regional definitions of the models varies between 11 and 32 world regions, and using the original model region definitions, we obtain a total of 18,810 regional trajectories to project future energy demand from coal-fired and natural gas power. Future demand is compared with existing power supply to assess whether additional power plants deployments are necessary during each year of our timeseries. Historical power data is obtained using the Global Power plant Emissions Database (GPED) which includes key unit level details on power plant fuel, emissions, carbon intensity, nameplate capacity, capacity factor, date of deployment, and operating status (Riahi et al., 2017a). We sort historical generator data accordingly by IAM region, power plant fuel, and the operating status of the power generators. Power plants are decommissioned based on the original deployment date along with the assumed lifetime of the power plant. Thus, if a power plant was built in 1988 and the assumed lifetime was 30 years then this power plant would be decommissioned immediately within our model. However, if the same power plant had an assumed lifetime of 60 years then we would allow the power generator to operate for another 30 years based on historical operational conditions of the plant. If and when the maximum available power supply drops below the current power demand, then our model dictates new power plant deployments to compensate for the difference between electrical supply and demand. We accomplish this using the following equation:

$$EP_{i:i+j-1,j,k,l,m} = HP_{i,j,k,l,m} + \left(PD_{i,j,k,l,m} - EP_{i,j,k,l,m} \right) CF_{i,j}$$

Where EP is the electricity generated, HP is the historic power supply, CF is the historical regional averaged capacity factor, and PD is the power demand. Here we use the subscripts i, j, k, l, and m to describe the year, operating lifetime, IAM, radiative forcing, and power plant fuel type, respectively. Power generators are only deployed if and when power supply falls below the power supply threshold, otherwise power supply is kept steady in cases of oversupply (i.e. where power output is in excess of power demand). Assumed power plant lifetime is varied between 10-60 years in each subsequent model run. Power produced by electrical generators is converted to CO_2 emissions using regionally averaged historical plant carbon intensity (CI) and capacity factors. Cumulative CO_2 emissions were calculated by aggregating annual CO_2 emissions for each model, fuel type, radiative forcing, and power plant lifetime:

$$CO_{2\,total} = \sum_{i=1}^{n} \left[\left(EP_{i,j,k,r}\; CI_{k,r} \right)_{Coal} + \left(EP_{i,j,k,r}\; CI_{k,r} \right)_{Gas} \right]$$

Similarly, annual CO_2 mitigations rates were obtained by calculating the mean annual rate at which CO_2 emissions decreased through time:

$$Retirement\ Rate = \sum_{i=1}^{n} \frac{CO_{2\,i,j,k} - CO_{2\,i-1,j,k}}{CO_{2\,i-1,j,k}} * n^{-1}$$

For each IAM - SSP included within this study we calculate the CO_2 emission overshoot by taking the difference between the cumulative emission projections and our estimates under the varied lifetime assumptions (10 – 60 years). We take a similar approach when analyzing regional and global emission overshoot where each model and SSPs magnitude of overshoot is analyzed individually and organized in accordance to their statistical distribution.

Lastly, we test the power generators capacity factor, lifetime, and emission intensity's relative contribution to future anthropogenic CO_2 emissions by setting the average emissions generated in each case using the historical mean IAM CO_2 estimates and individually test each of the SSPs and radiative forcing goals. We constrain the lower bound by setting all the parameters to their mean values and simultaneously increasing each of them by 25% to set the upper bound. By increasing the individual variables median assessment by 25% and keeping all other factors at their historical rates we can assess the relative contribution to future emissions in each case. SSP3 was omitted from the more ambitious climate forcing tests since it was not replicable by any IAM for the 1.9 and 2.6 forcing scenarios.

2.5.6 Existing Power Plants - Global Power Plant Emissions Database

The recently developed GPED contains data on 126,906 individual power generators from 231 countries (Riahi et al., 2017a). Key unit level information relative to this study contained in the database include power plant nameplate generating capacity, deployment year, intake fuel, annual operating hours, energy output, annual CO_2 emissions, and country where the plant is located. GPED was developed using data from World Electric Power Plants Database (WEPP), Emissions & Generation Resource Integrated Database (eGRID), China coal-fired Power plant Emissions Database (CPED), and ICPD. Data and a detailed overview of GPED is available at http://www.meicmodel.org/dataset-gped.html.

	Lifetime (years)	***Capacity factor (maximum / minimum)***	***Depreciation of capital rate (average percent per year)***	***Carbon intensity (range across technologies, regions, years, and SSPs)***
Coal				
AIM/CGE	35	60%	4%	Different across regions
GCAM	60	80 to 85% depending on type of plant		643 to 1233 gCO2 per kWh, depending on technology, region, year
IMAGE	40	Depending on relative operational costs (~85% till 0%)	Capacity gets retired after 40 +/- 5 years of operation	Different per region, year, technology
MESSAGE-GLOBIOM	30	67%-85%	5%	724-1302 gCO2 per kWh
REMIND-MAGPIE	40	75-80%	Non-linear	Different per region, year, technology; regional fleet averages of 738-1140 g/kWh in 2015
WITCH-GLOBIOM	40	85%	2.8%	699 to 1390 gCO2/kWh, depending on technology, region, year
Gas				
AIM/CGE	30	70%	4%	Different across regions
GCAM	60 for existing gas plants, 45 for new plants	80 to 85% depending on type of plant		274 to 720 gCO2 per kWh, depending on technology, region, year
IMAGE	40	Depending on relative operational costs (~90% till 0%)	Capacity gets retired after 40 +/- 5 years of operation or via early retirement in case of relatively high operational costs	Different per region, year, technology
MESSAGE-GLOBIOM	30	58-85%	5%	260-850 gCO2/kWh
REMIND-MAGPIE	35	55-65%	Non-linear	Different per region, year, technology; regional fleet averages of 328-547 g/kWh in 2015
WITCH-GLOBIOM	25	70%	4.4%	354 to 1000 gCO2/kWh, depending on technology, region, year

Table 2.1 | Integrated Assessment Model Assumptions. Regional averaged values for each of the integrated assessment models used within this study. However, as the IAMs continue to evolve so do the underlying parameters. Thus, values represented in this table may change over time as newer versions of IAMs are released.

CHAPTER 3.

Crop Migration in Response to Future Climate Change

Adapted from:

R Fofrich., L. Sloat, N. Diffenbaugh, F. Moore, N. Mueller, S. Davis. Crop migration in response to future climate change. *In review*

3.1 Introduction

Maize, wheat, rice, and soybean (henceforth “crops”) are each cultivated in a wide range of climates across the globe (Monfreda et al., 2008, Ramankutty et al., 2008, Ramankutty et al., 2002, Leff et al., 2004, Ramankutty and Foley, 1998), but their yields are particularly sensitive to high temperatures during their growing season (Schlenker and Roberts, 2009, Lobell et al., 2011a, Zhao et al., 2017, Tigchelaar et al., 2018, Fatima et al., 2020). As a result, climate change—which has already affected agricultural yields (Ramankutty et al., 2002, Burke et al., 2009, Rosenzweig et al., 2014, Challinor et al., 2014, Tubiello et al., 2007, Lobell et al., 2011b)—is expected to further reduce agricultural productivity in warmer regions while benefitting in historically cooler regions (Rosenzweig et al., 2014). In turn, agronomists are pursuing adaptive cultivars and practices that could counter the negative impacts of climate change on crop yields in warmer regions (Howden et al., 2007, Mueller et al., 2017, Henry, 2020, Moore and Lobell, 2014). However, the potential for such *in situ* adaptations to offset climate impacts on a global scale is not clear and will depend upon both the efficacy of adaptation efforts as well as the magnitude of future climatic changes (e.g., it may be possible to adapt cultivation to 2ºC but not 4ºC), especially in heat and drought extremes (Pugh et al., 2016, Vogel et al., 2019, Toreti et al., 2019, Diffenbaugh et al., 2012). To the extent that adaptations are not protective against the climatic changes, agriculture may move to cooler areas to avoid damages (Diffenbaugh et al., 2012, Sloat et al., 2020). Such shifts in the ranges of natural species and ecosystems have been projected and observed (Loarie et al., 2009, LoPresti et al., 2015, Diffenbaugh and Field, 2013, Brito-Morales et al., 2018, Carroll et al., 2015, Hof et al., 2011, Kosanic et al., 2019, Elsen et al., 2020, Dobrowski and Parks, 2016, Hamann et al., 2015), and recent research shows that major crops have already migrated in a manner that avoids extreme high temperatures (Sloat et al., 2020, Wang and Hijmans, 2019, Li et al., 2015). Nonetheless, the extent to which farmers engage in such shifts in the future will ultimately depend on the availability and quality of arable land as well as social and economic factors such as potential revenues vs costs to transport crops to market. Yet the various models that have most often been used to assess agricultural production under scenarios of future climate change have focused on potential changes in productivity in currently cultivated areas and have often been regionally focused in scale, with much less attention to when, how fast, and to where croplands might shift in the future and the inequity that such shifts may incur, particularly in a global context (Fischer et al., 2005, Zhao et al., 2017, Rosenzweig et al., 2014, Schleussner et al., 2018, Beltran-Peña et al., 2020, Franke et al., 2020, Müller et al., 2019, Lobell et al., 2013, Lobell et al., 2012).

Here, we assess potential shifts in the agroecological zones of four major rainfed grain crops in response to changes in growing season temperatures and precipitation projected under different levels of climate change, and further analyze the differential effects on national and regional food production. Details of our approach are provided in the *Methods*. In summary, we first evaluate the ranges of growing season temperatures and precipitation of historical rainfed crop cultivation sites (1993-2007) using climate data from the Climate Prediction Center (ESRL, 2020b, ESRL, 2020a) and crop areas from the EarthStat (Ray et al., 2012) database. We then analyze changes in temperature and precipitation over the currently cultivated areas under increases in radiative forcing of 2.6, 4.5, and 7.0 W m^{-2} as reflected in bias-corrected, multi-model means (and individual model projections) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). Where crops are projected to experience average growing season temperatures or total growing season precipitation that are at or beyond the extremes of their historical ranges (see Figs. 3.5 and 3.6), we identify the nearest area where conditions will be within the historical ranges and analyze the magnitude and rate of disruptions in national and regional food production if the crops were displaced accordingly (assuming crop yields and thus the total area of cultivated land remain the same). Our results are thus not a prediction of shifts in agricultural composition and displacement but rather reflect potential shifts in cropping areas if other adaptations (e.g., more heat-tolerant cultivars, temporal modifications to growing seasons timings, and changes in the types of crops grown) are either ineffective or cost prohibitive.

3.2 Results

Figure 3.1 shows shifts in cultivation sites by the end of the century (i.e., mean of the period 2070-2100) due to projected changes in growing season temperatures only (i.e., if irrigation and drainage improvements mitigate changes in precipitation). Brown shading on the maps indicates outmigration from current crop areas where temperatures will exceed historical thresholds under the different levels of warming, and green shading shows expansion of croplands in the nearest areas where temperatures are suitable (Fig. 3.1). For reference, gray shading indicates currently cultivated areas where temperatures remain within the crops’ historical envelopes (Fig. 3.1). The crop migration depicted is generally poleward or into higher elevations, with the magnitude of affected areas and the distances of displacement both increasing in proportion to the level of future warming. Map insets highlight those regions with the largest shifts in cultivated areas under a high level of warming (i.e., exceeding 3.0°C), with

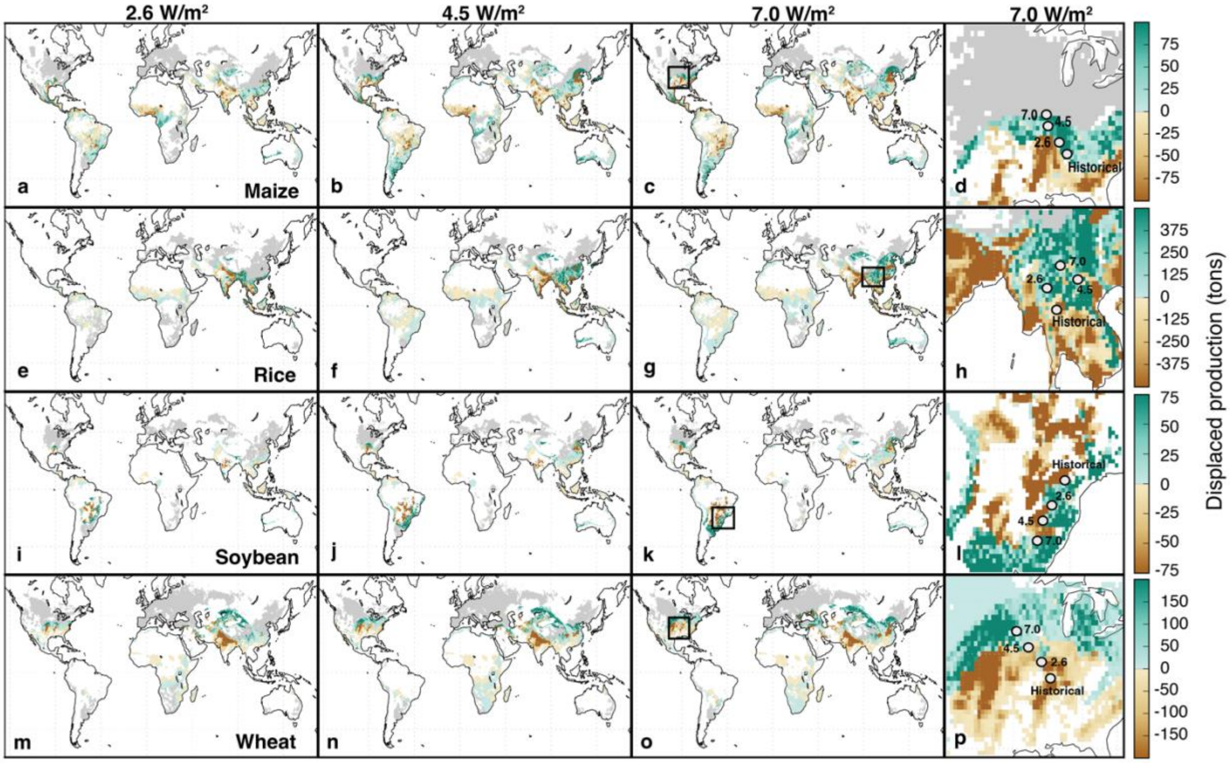

Figure 3.1 | Potential crop migration due to changes in growing season temperature. Brown and green shading indicate areas of outmigration and new cultivation, respectively, with darker colors showing the magnitude of production affected in tons. Gray shading shows currently cultivated areas where temperatures remain within crops’ historical range. Newly cultivated areas are the nearest suitable areas from where crops are displaced. Inset maps at right show 10° x 10° regions where migration is greatest under the highest warming scenario (i.e., 7.0 W/m^2), with circles denoting the production-weighted centroid historically and under each level of warming.

white circles showing the spatially-averaged centers of crop production historically and under different levels of warming (Figs. 3.1d, 3.1h, 3.1l, and 3.1p) At higher levels of warming, production retreats substantially from the southern U.S., northern South America, West Africa, the Indian subcontinent, and the Indonesian archipelago (Fig. 3.1). Conversely, agricultural areas expand prodigiously in many higher latitude and higher elevation regions, including the U.S. corn belt, Argentina, central Africa, central Asia, interior China, and southern Australia. Key displacements include Brazilian soybean, South and Southeast Asian rice, and North American wheat.

Figure 3.2 summarizes the shares of each major crop that may be displaced, globally (left) and in the most-affected regions (right), under different levels of warming, including whether the migration is within the same country, between countries, or between continents. Depending on warming level, 7-14% of global maize, 33-66% of rice, 10-20% of soybean, and 17-30% of wheat production is projected to experience mean growing season temperatures outside of their historical range by the end of the century (yellow and orange bars in Figs. 3.2a-3.2d). If both mean growing season temperature and total precipitation are considered, the shares of these crops' production projected to experience conditions outside of their historical envelope is considerably larger: 27-34% of maize, 53-76% of rice, 24-28% of soybeans, and 29-43% of wheat (blue bars in Figs. 3.2a-3.2d). These results suggest that irrigation and water management could substantially reduce climatic disruptions to crop production (particularly for maize, soybeans, and wheat) if water is available and irrigation/drainage systems are feasible. Meanwhile, with increases in radiative forcing of 4.5 W/m^2, as much as 46% of North American maize production, 63% of Asian rice, 82% of South American soybeans, and 53% of North American wheat might be displaced (Figs. 3.2e-3.2h). Although a large majority of such displacements occur within a country’s national borders (e.g., the U.S. in the case of North American maize and wheat), more than two-thirds of the possible displacements of Asian rice or South American soy would be international.

Poorer countries bear the brunt of agricultural losses due to future warming (Figs. 3.3 and 3.7). We find tropical countries (which often have a lower per capita GDP) tend to lose production while more affluent nations at higher latitudes gain production. An exception to this is countries at lower latitudes with higher-elevation cultivatable land that can serve as a site for future cropland expansion. However, many of higher-elevation regions identified may be poorly suited for cropland expansion due to poor soil quality, steep gradients, and inaccessibility. Outmigration from poorer countries is especially disproportionate for rice and maize but such inequities exist for all crops and increase with the level of warming (Fig. 3.7).

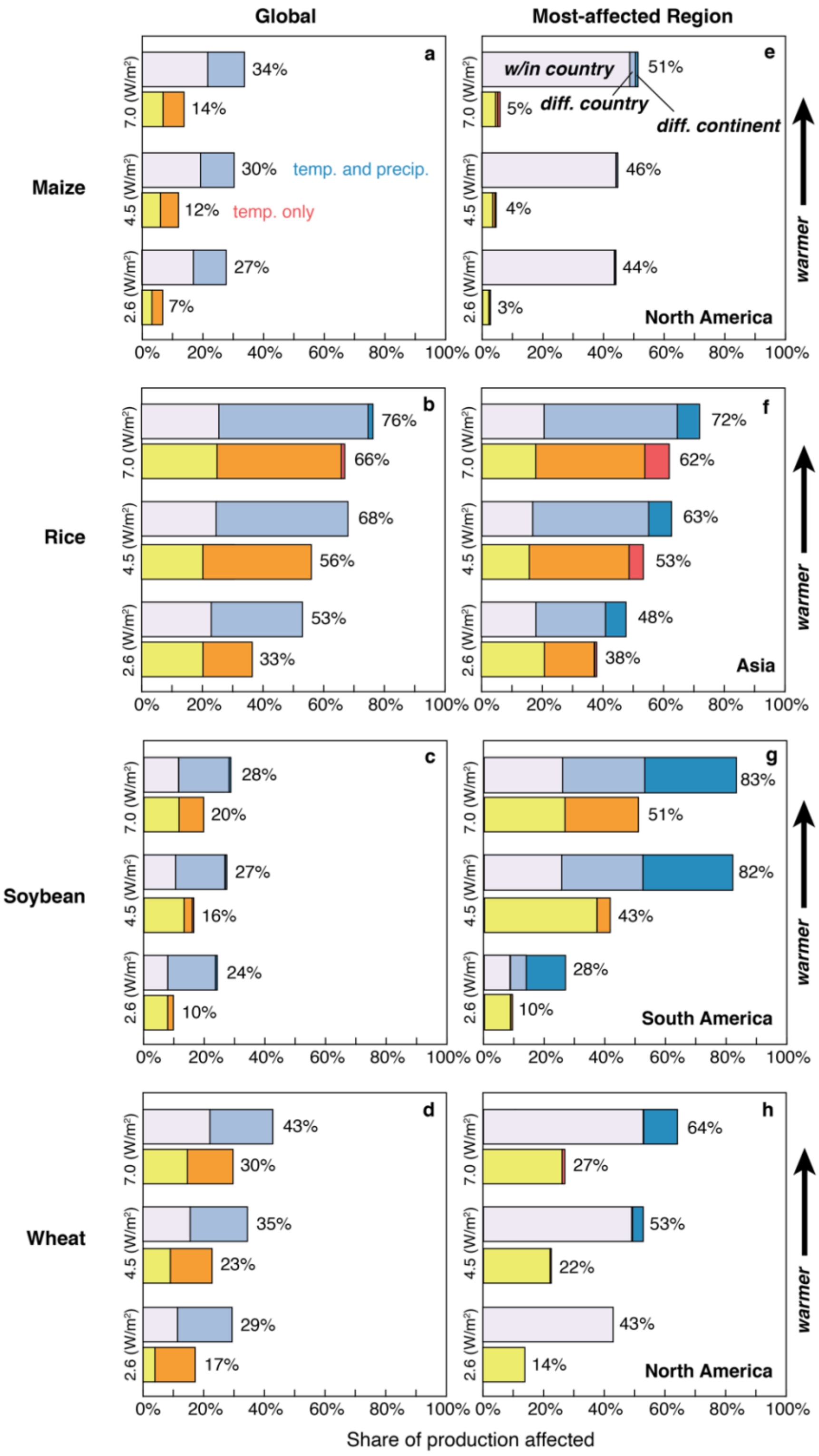

Figure 3.2| Shares of global and regional crop production displaced. Bars in each panel indicate the share of global (a-d) or regional (e-h) crop production outside of their climate envelope. Bar colors correspond to whether crop migration occurs within a country (yellow, light purple), to another country (orange, light blue), or to another continent (red, dark blue) in temperature only and precipitation included scenarios, respectively.

Another indicator of potential disruption in the agricultural sector is the rate of changes in crops' climate space. For example, in regions where temperatures increase rapidly throughout the century, crops might relocate to areas that in time also become unsuitable for cultivation. Figure 3.8 shows the large increases in warming rates over current croplands under different levels of warming compared to what those same areas have experienced during the historical period (1993-2007). By combining the rates of projected changes in climate with the minimum distances crops would need to migrate to reach suitable climate space, we also estimate differences in the velocities of migrating crops (in distance per unit time). Figure 3.9 maps these velocities for each major crop and warming level, highlighting that the greatest velocities (>10 km per decade for maize, rice and soybeans) are concentrated in flat, low-lying, and low-latitude regions, especially in west Africa, the Indian subcontinent and southeast Asia.

To understand the climatological barriers to future crop cultivation, Figure 3.4 maps the relative drivers of potential migration of each crop under low levels of warming (i.e., 2.6 W/m^2). At temperate latitudes of the Northern Hemisphere (e.g., North America, the Middle East, and Asia), crops are displaced by changes in temperature (red and orange shading), but in similar latitudes of the Southern Hemisphere (e.g., southern Brazil, Argentina, and south central Africa), changes in precipitation are more often the cause (Fig. 3.4, blue shading). Meanwhile, in the tropics of South America, West Africa, and Indonesia, changes in both temperature and precipitation contribute to crop migration (Fig. 3.4, green shading).

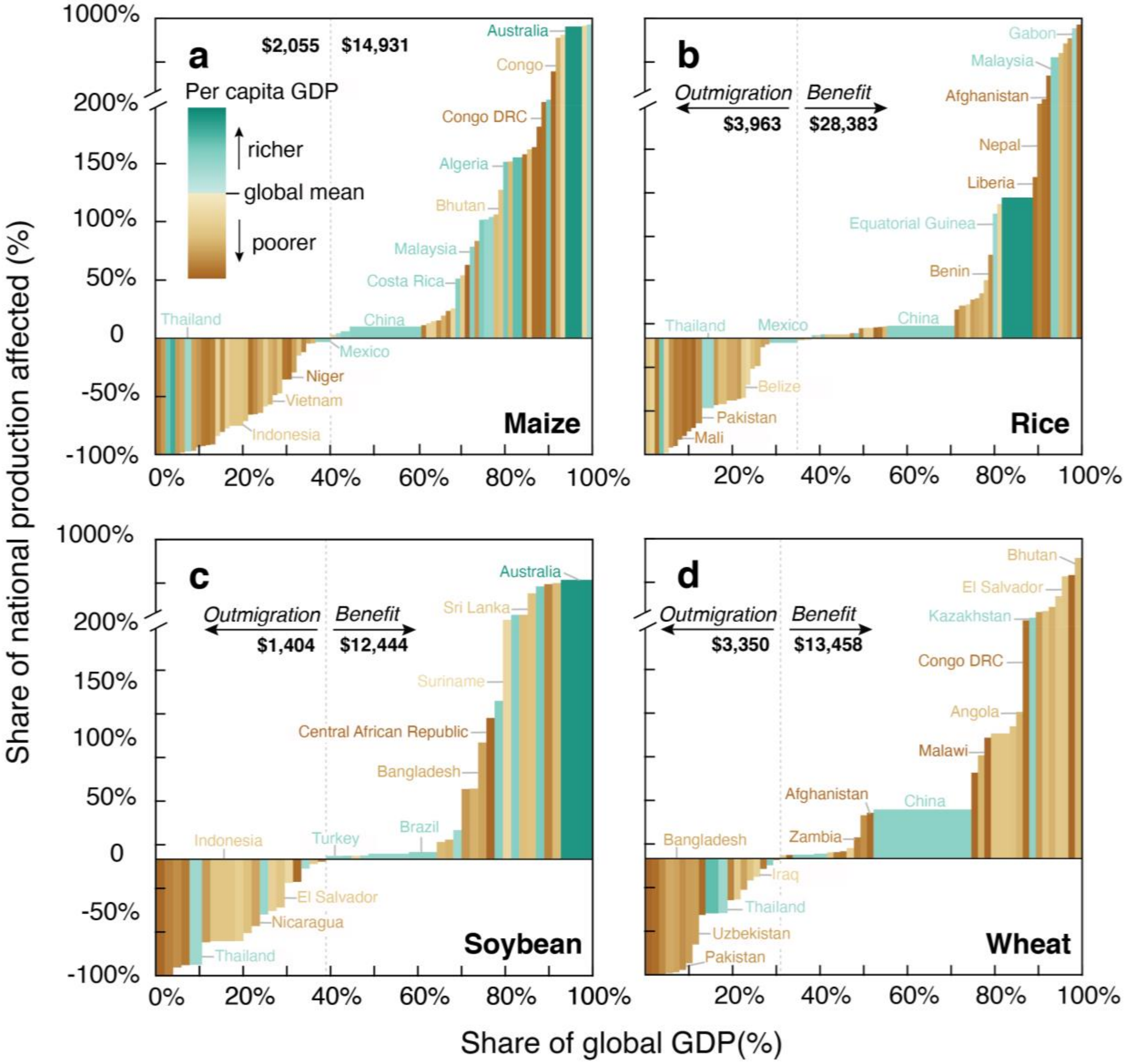

Figure 3.3 | Inequality of cropland migration under a 2.6 W/m^2 scenario. Bar heights show the share of affected production within each country where cropland migration occurs, bar width represents the share of global GDP, and the orientation shows the proportion of production lost (negative values) or gained (positive values). Bar colors highlight the per capita GDP of a given country, with brown colors showing less affluent countries and green colors representing more affluent countries. In addition, the average GDP per capita (weighted by share of global GDP) is shown for countries losing and gaining production.

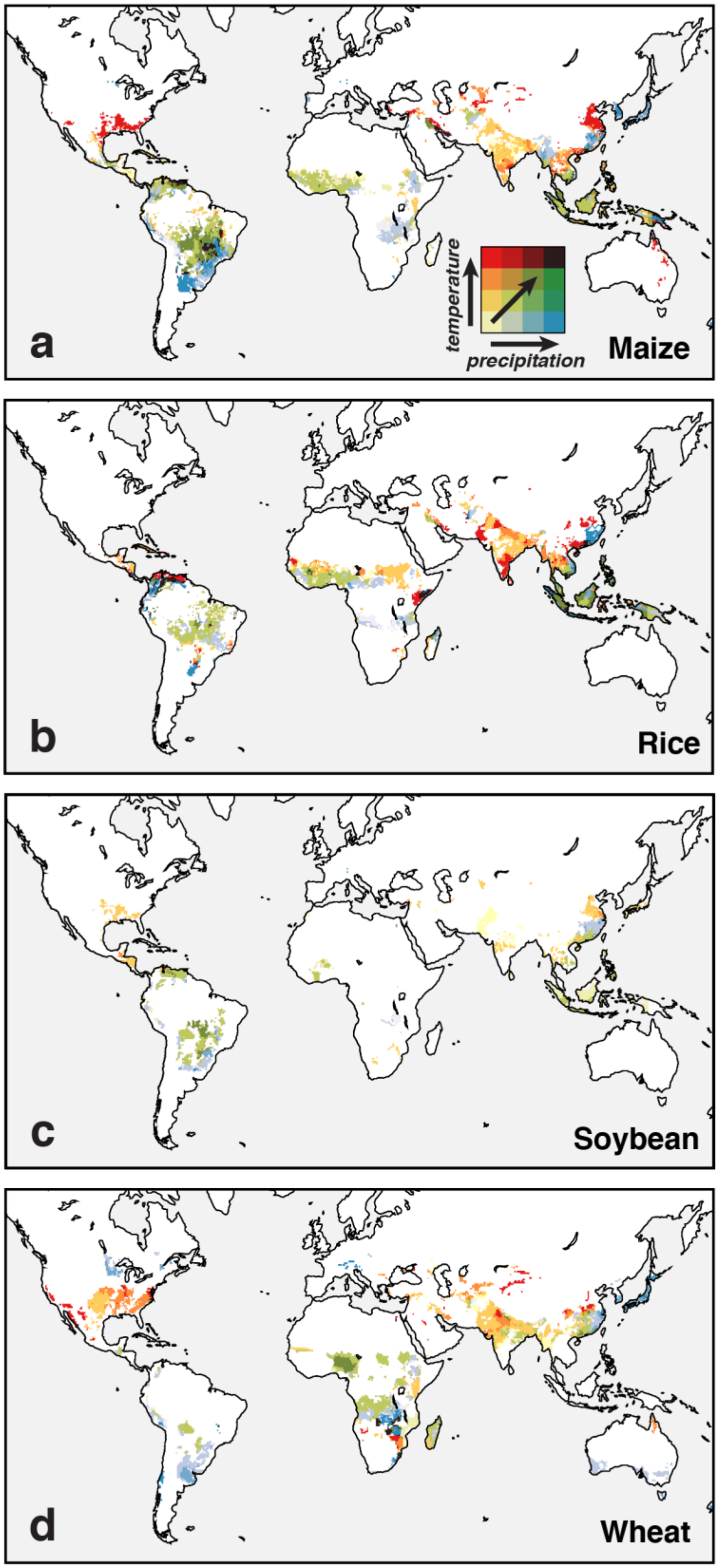

Figure 3.4 | Climate drivers of cropland migration. Color intensity shows affected yield in each region under a 4.5 W/m^2 climate scenario with darker colors representing areas of higher yield and lighter colors illustrating regions with lower yield. Warm colors indicate regions where changes in the mean growing season temperature would surpass climate thresholds while cool temperatures reveal regions where changes in the growing season precipitation are the dominating factor. Climatic thresholds are reported in Table S1.

3.3 Discussion and conclusion

Across the globe, crops are notably grown in vastly different climates but regions with higher levels of production have a smaller temperature and precipitation range (Fig. 3.5) and are thus more sensitive to future warming. Even under the most ambitious climate scenarios, each crop’s climatic range shifts poleward or to higher elevation. Maize, rice, soybean, and wheat currently supply over two-thirds of humanity’s calorific intake, and prior studies have shown their yields diminish by 3-7% for every degree of warming above their climatic threshold (Zhao et al., 2017, Tigchelaar et al., 2018, Porfirio et al., 2018). Thus, in the absence of more resilient cultivars or other adaptation measures, global grain output will likely decline considerably if crop production does not migrate and keep pace with future warming. And it is not only crops that may need to shift: supporting infrastructure, agricultural expertise, sociocultural demand, and capital investments will also need to relocate and evolve, and indeed these accompanying elements are likely to be more challenging than changing crops—particularly in less affluent countries where there is a lack of institutional support. Thus, the redistribution of global croplands may be quite disruptive to agricultural economies and will likely exacerbate existing global issues such as economic inequality and regional food insecurity (Mendelsohn and Dinar, 1999, Wheeler and von Braun, 2013, Rosenzweig and Parry, 1994) (Fig. 3.3). For example, given that many of the disproportionately-affected poorer countries are also heavily reliant on agriculture for both food and income (Fig. 3.10), loss of croplands and food production could in turn drive economic destabilization and outmigration of people (i.e., environmental refugees) (McMichael, 2014, Myers, 2002, Barbieri et al., 2010).

Our analysis is subject to several important caveats and limitations. For one, our results are sensitive to the climatological limits assumed for each crop, and our results do not incorporate potential future adaptations to additional warming. Instead, they represent upcoming geographic shifts necessary for future crop cultivation to remain static in climatic space during their historical growing season. We therefore test the sensitivity of our results to different temperature and precipitation ranges, changes in climate extremes, and soil property thresholds, and while the magnitude of migration differs, we observe similar patterns of displacement and new cultivation regions across all cases (Figs. B.1-B.7). We also do not assess the effects of CO_2 fertilization, irrigation expansion, or changes in crop water demand on crop productivity or future cultivation, nor do we model economic or nutritional pressures on crop selection and abandonment. In addition, we do not directly model crop yield, instead we assume future crop cultivation will reflect their historical values. In some cases, future cropland losses could be lessened by expanding irrigation (Rosa et al., 2020b, Elliott et al., 2014), using more resilient cultivars, shifting planting dates, and improving farming practices. However, capital costs, lack of economic and institutional capacity (Rosa et al., 2020a), and climatic-geophysical constraints could prove prohibitive (Elliott et al., 2014), and climate change is expected to limit the intensification potential of current croplands (Pugh et al., 2016) despite deploying additional irrigation (Zaveri and B. Lobell, 2019). Even if adaptation technologies are available, climate change will alter the comparative advantage of growing regions, meaning shifts in crop areas are likely. While future research will almost certainly apply ever more detailed models to examine potential climatic impacts on agriculture, our analyses reveal the possibility of profound disruptions in current cultivation patterns even under relatively modest levels of warming. Hence, our findings underscore that land management, spatial planning, and investments in infrastructure and more resilient cultivars will be increasingly critical as farmers and policymakers seek to maintain agricultural productivity, food security and conserve unmanaged landscapes.

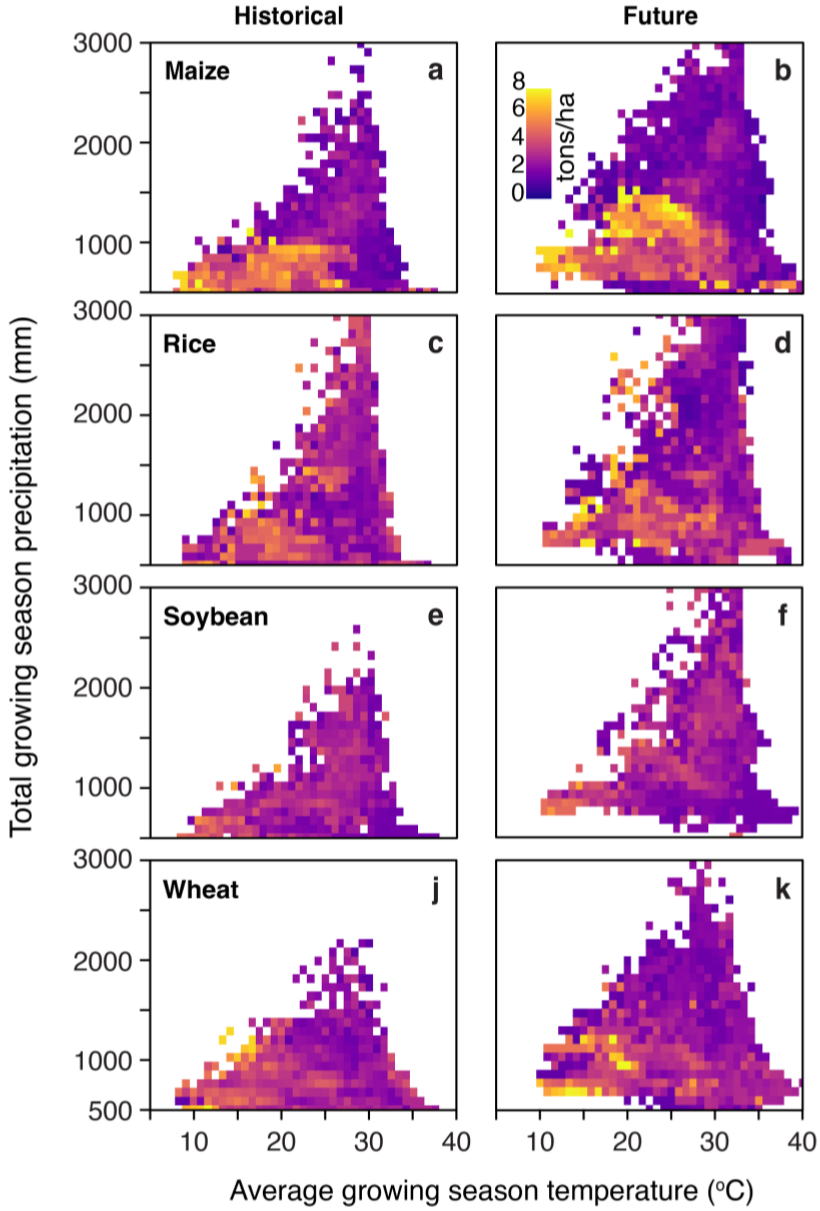

Figure 3.5 | Changes in the climate space of current croplands. Colored points in each plot show the average precipitation and temperature during growing seasons (climate space) of each crop in each grid cell (0.5º x 0.5º) in which the crop is currently cultivated, shaded according to the average yield (tons per hectare) in that location. Gray points show the projected changes in the climate space at the end of the century (mean 2070-2100) under moderate levels of warming (4.5 W/m^2 increase in radiative forcing). Yield data reflects the local mix of rainfed and irrigated croplands.

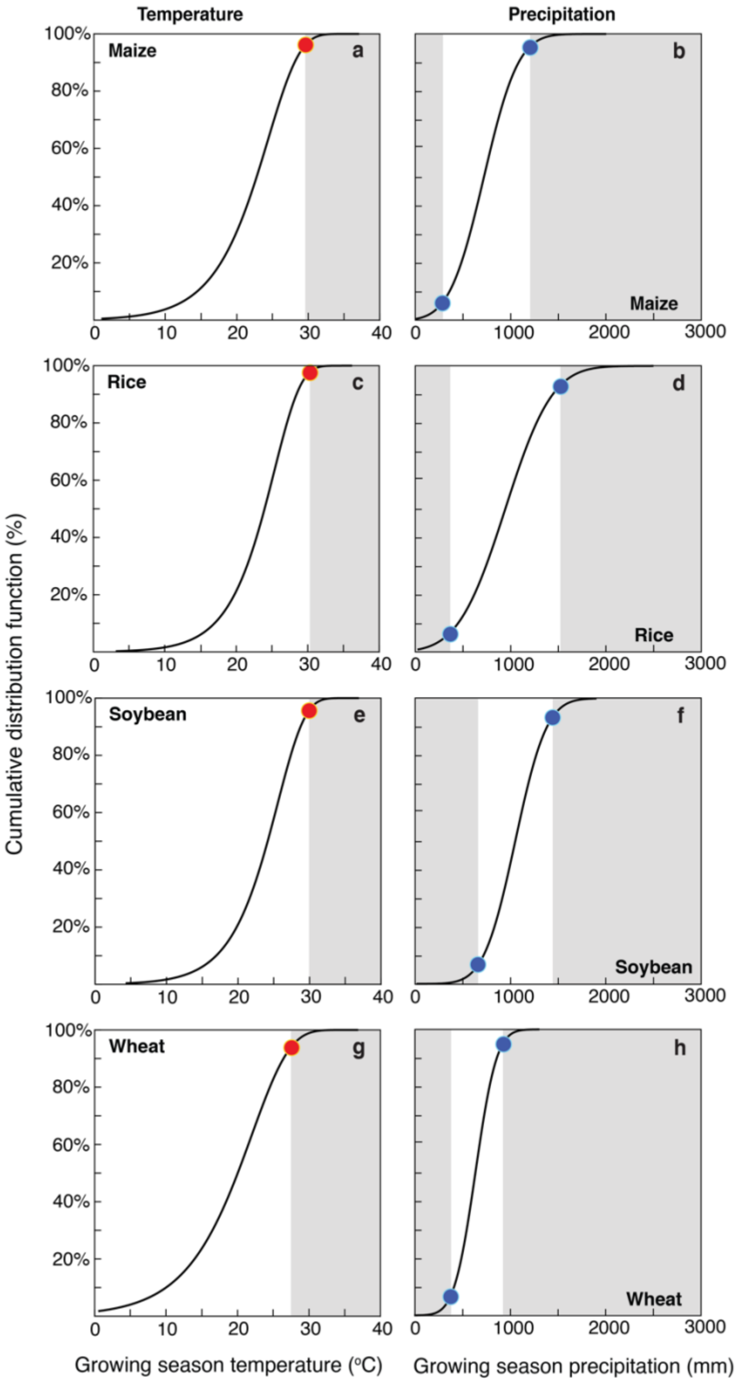

Figure 3.6 | Cumulative distributions of major crop production by temperature and precipitation. Distributions of mean cropping season climate conditions experienced by each major crop during the period 1993-2007. Red and blue circles indicate inflection points in growing season temperature and precipitation of each crop, respectively. These inflection points are the limits of climate space used to identify crops that may need to migrate to avoid damage under climate change.

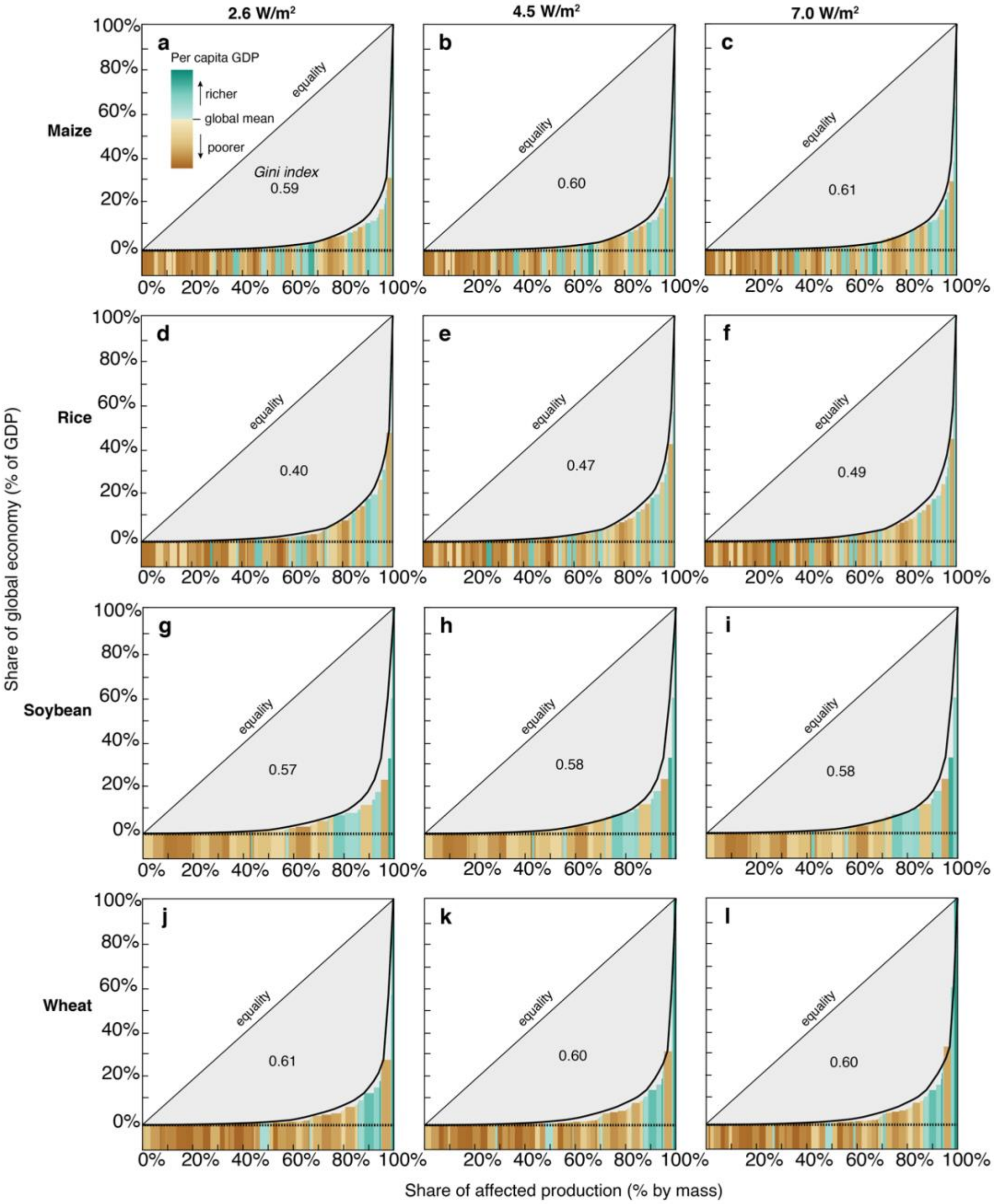

Figure 3.7 | Inequality of displaced production. Bars represent countries whose crops may be displaced under different levels of warming, sorted from lowest to highest GDP and colored according to per capita GDP. The Gini-Coefficient (area under the line of perfect equality) indicates the level of inequality with 0 symbolizing perfect equality and 1 indicating absolute inequality. In all cases, we observe a disproportionate share of affected agricultural production is located in poorer countries, with inequality increasing along with warming in most crops.

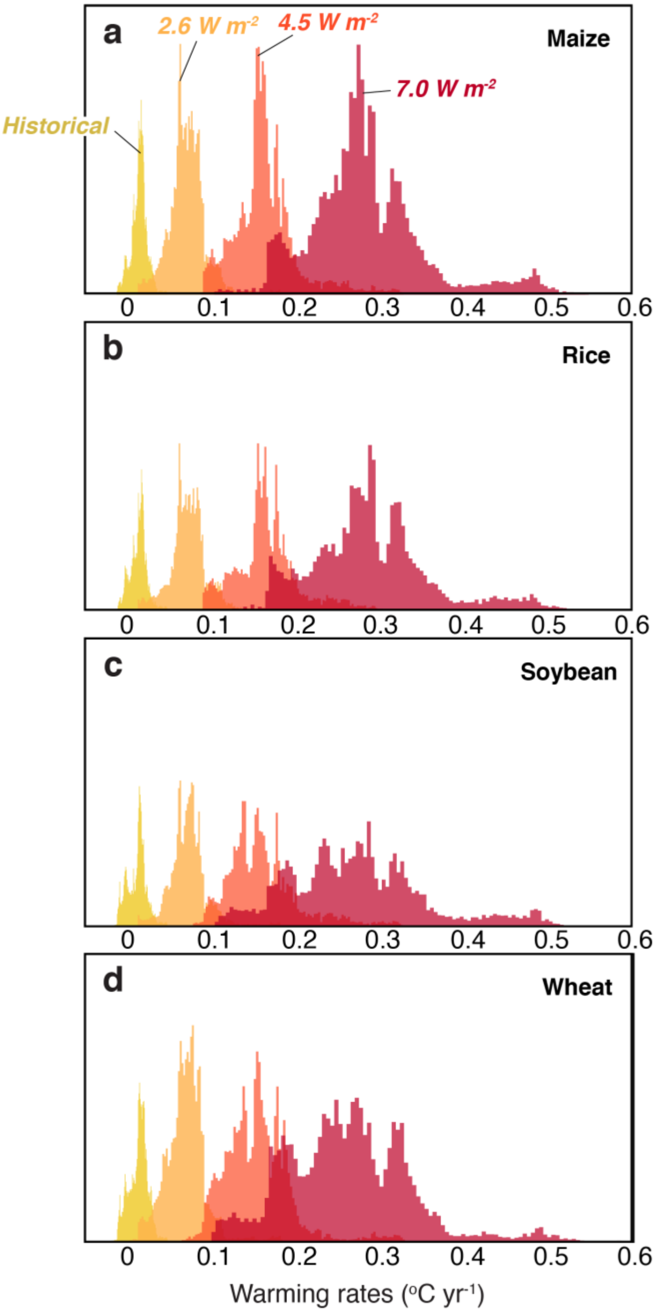

Fig. 3.8 | Projected warming rates of current global croplands. Histograms of annual average warming rates in currently cultivated areas of each major crop as experienced between 1993-2007 (yellow) and as projected in bias-corrected, multi-model means of CMIP6 with increases in radiative forcing of 2.6 W/m^2, 4.5 W/m^2, and 7.0 W/m^2.

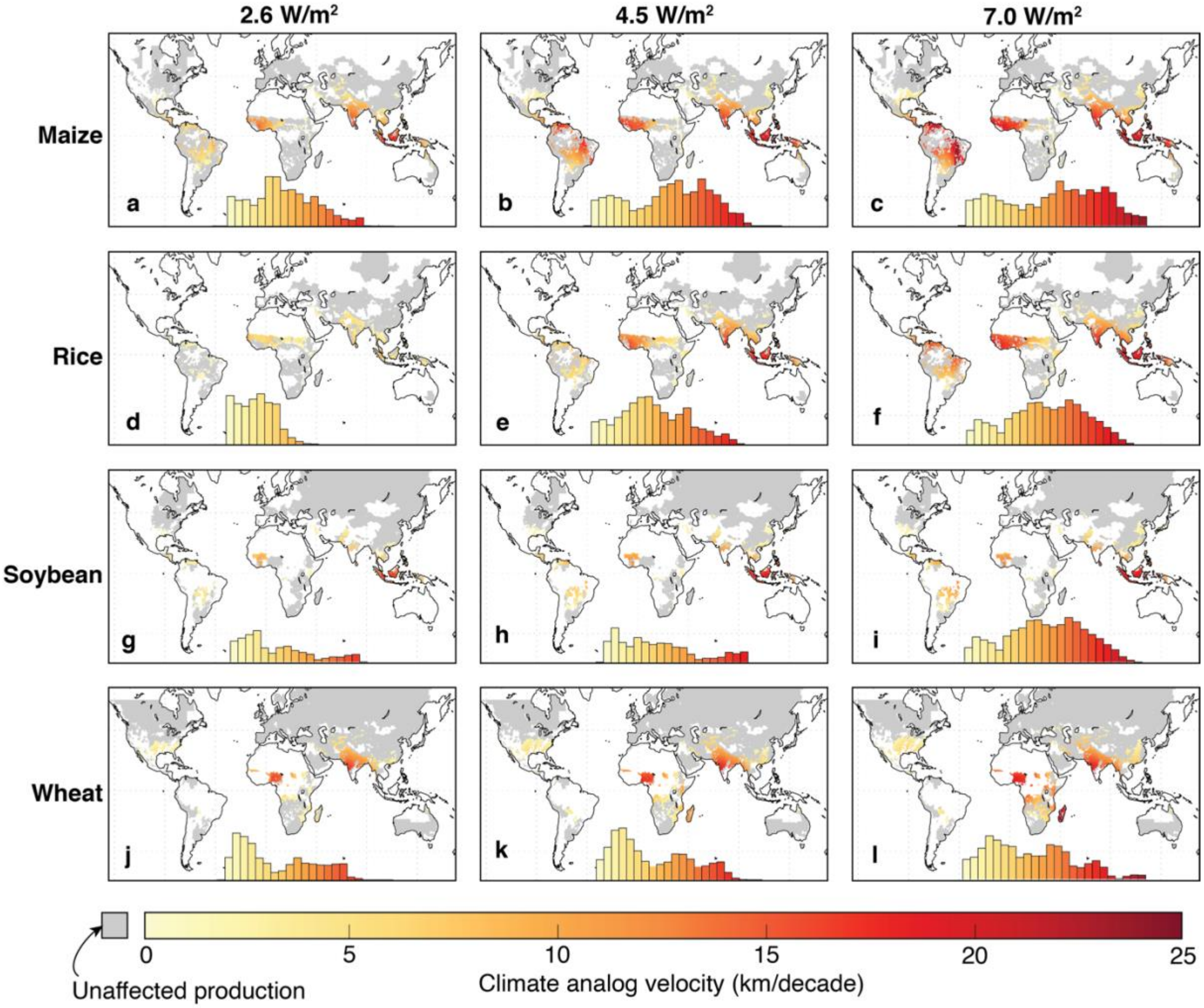

Fig. 3.9 | Projected climate velocity of migrating global croplands. Shading on maps shows the temperature velocity (i.e., the annual rate of retreat needed to remain static in temperature space) of croplands that may need to migrate in response to warming. Velocities are notably greater at low latitudes, especially for maize and wheat, and increase with the level of warming. Gray shading indicates croplands that remain within the bounds of the crops' historical temperature space.

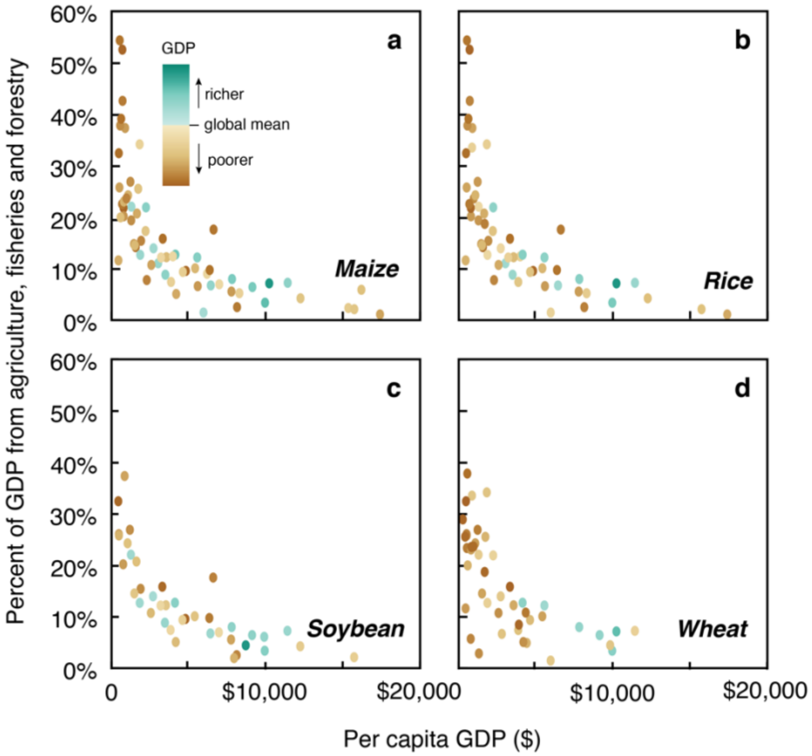

Fig. 3.10 | Percent of GDP from food production in crop disrupted nations. Average per capita GDP compared to the percentage of GDP that stems from agriculture, fisheries, and forestry in nations whose cultivation is disrupted under a 2.6 W/m^2 scenario. Bar colors highlight the national GDP of each point, with brown colors showing nations whose GDP falls below the global average and green colors representing nations with higher-than-average GDP.

3.4 Methods

In order to quantify the historical climatological ranges of each crop we obtain harvested area and yield data for rainfed maize, rice, soybean, and wheat from EarthStat (Ray et al., 2012). Global crop data have a 10 x 10 km resolution at the equator and cover a 15-year time-period (1993-2007) while historical and future resolution are projected in a much courser resolution. We therefore rescale gridded crop data to a 0.5 x 0.5-degree resolution to harmonize across crop and climate datasets. Historical monthly temperature and precipitation data are obtained for the same years through the Climate Prediction Center (CPC) (ESRL, 2020b, ESRL, 2020a). Climate data provided by the CPC are collected through the Global Historical Climatology Network (version 2) and the Climate Anomaly Monitoring Systems, and are interpolated in between collection sites to capture past changes of the climate system across the globe (Fan and van den Dool, 2008). However, CPC data are available in monthly intervals and therefore we linearly interpolate the CPC data to produce daily climate values. We combine CPC data with crop-specific planting and harvested dates obtained through the Sacks et al. database (Sacks et al., 2010). Both climatic and non-climatic factors influence cropping dates (e.g., technological advances, socioeconomic, and cultural factors) and therefore these dates can be difficult to predict and model(Sacks et al., 2010). Thus, for modeling simplicity, we assume static planting and harvesting dates in future simulations in current harvested areas. Historical temperature is averaged over the growing season (defined as the time from crop sowing to harvest), while the total precipitation is summed over the same time frame.

We use the crop data (obtained through EarthStat) to remove temperature and precipitation values that reside outside of the historical cultivated regions of each crop and independently quantify the global temperature, precipitation, and soil cumulative distribution functions (CDF) for each crop to define their historical climatic thresholds and select the highest and lowest inflection points as the upper and lower bounds. Temperature or precipitation values above or below these thresholds are assumed to be out of the crop's climatological bounds in cropland migration simulations. In subsequent model runs, we alternate the climatological bounds by setting the limits to the 90th and 95th percentiles which allows us to test the sensitivity of our results to different bounds and report these results in the supplementary figures. Additionally, we test the effects of growing season climatic extremes on crop migration to compare against changes in mean growing season climate values.

We calculate future temperature and precipitation using climate change projections from the Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring et al., 2016, O'Neill et al., 2016). We select the ssp126, ssp245, and ssp370 CMIP6 ScenarioMIP simulations to analyze the impacts that different climate pathways will have on future crop production. ScenarioMIP ensembles use societal development trajectories, or Shared Socioeconomic Pathways (SSPs), to qualitatively describe different alternative narratives of global development in relation to climate change adaptation and mitigation (e.g., population and economic growth, research and development, and multinational cooperation), coupled with RCP-based climate projections (O'Neill et al., 2016), and are produced by various Global Climate Models (GCMs). However, GCMs have different spatial resolutions, and projected warming can differ across GCMs due to structural differences between the models and the “irreducible uncertainty” of variability internal to the climate system. Therefore, we re-grid the ScenarioMIP data to a 30-minute resolution, harmonizing the data and take the average across model ensembles to create future climate pathways. We further our analysis by comparing our results using the mean GCM projections to those acquired when each GCM is run individually (Figure B.4-B.7). While ScenarioMIP is vital in understanding future climate impacts, future projections often contain systematic errors due to simplified natural processes or incomplete knowledge of the earth system (Ramirez-Villegas et al., 2013). Thus, we remove CMIP temperature and precipitation biases using the delta(Hawkins et al., 2013) and change factor (Tabor and Williams, 2010) bias correction methods.

As a means of modeling future spatial shifts to the agroecological zones of major crops we test whether each historical cultivation site is within a crop's climatic range under future climate scenarios. If the harvested location in future climate simulations resides outside of the crop's climatological bounds, we assume that production will migrate to the closest region with a suitable climate. Therefore, we estimate the distance to each location with a suitable future climate using a 3x3 neighborhood search and select the minimum Euclidean distance between the two points.

$$Minimum\ Euclidean\ Distance\ (MED) = \min\left(\sqrt{(lat_{t2} - lat_{t1})^2 + (lon_{t2} - lon_{t1})^2}\right.$$

We assume harvested area and yield will be conserved in future simulations and only allow future suitable grid points to be occupied once by the migrating historical production. We alternate the starting grid point of the nearest distant search and average these results so that our findings are not affected by the initial search direction of our model. Each crop is assessed independently of one another, and we do not restrict croplands from migrating to regions where cultivation does or does not currently exist.

To assess the spatiotemporal rate of change in agroecological zones we quantify the velocity of climate change (Carroll et al., 2015, Hamann et al., 2015, Loarie et al., 2009, LoPresti et al., 2015) (km yr^{-1}) for each crop. The velocity of climate change has been used to quantify the vulnerability of ecosystems as a response to climate change and represents the minimum exposure of a species to unsuitable climates. The climate analog velocity is calculated as the minimum distance (km) between suitable future and historical climates and the subsequent climate scenario timeframe (years).

$$Climate\ analog\ velocity = \frac{MED}{time}$$

The spatial migration of agroecological zones do not occur uniformly around the globe, resulting in discrepancies in future production and equity between tropical regions and those at higher latitudes. Thus, to assess regional differences in affected production we convert grid area from degrees to hectares and then quantify the production in each grid point multiplied by each location's harvested area (grid cell fraction) while adjusting for grid cell size (L) based on latitudinal differences.

$$Total\ production\ (tons) = Yield * Harvested\ Area * \sqrt{\mathrm{L}^2 \cos(°lat\,\frac{\pi}{180})} * 100$$

We use country-specific polygons obtained through the Union of International Associations to calculate production at the country level and at the continental scale. We take the difference between production lost and production gained within a country and continent to determine whether cropland migration occurred within or outside national borders. We order production by the absolute difference between country-level losses and code these values by the average GDP per capita within each country. We omit countries whose impacted production represents less than 1% of their total production from the graph to visualize the results and report the average GDP per capita of affected countries weighted by their share of global GDP.

Since both temperature and precipitation can impact future crop viability we project the effects of climate change on crops, mapping historical crop yields in regions where temperature and/or precipitation surpass established thresholds. We overlay the out-of-bound climate variable maps to create bivariate choropleth maps (Figure 3.4) and display regions that reside outside a crop's climatic space.

To assess differences in historical and future climate space we plot the average growing season temperatures, and total precipitation over the growing season in each grid point from historical cultivation and future simulations. We plot the temperature, precipitation, and yield frequency using 1^{o}C bins, 10 mm bins, and 10-ton/ha bins, respectively. We further quantify gained cultivation and outmigration locations in relation to the current climate space occupied by crop areas.

	UPPER INFLECTION		90 PERCENTILES		95 PERCENTILES	
	Temp (^oC)	*Precip(mm)*	*Temp (^oC)*	*Precip(mm)*	*Temp (^oC)*	*Precip(mm)*
MAIZE	27.1	804.5	27.7	892.4	28.7	1054.5
RICE	28.1	1043.5	27.9	1162.6	28.9	1394.3
SOYBEAN	26.7	844.4	27.4	1017.2	28.3	1204.4
WHEAT	24.7	552.6	26.2	641.3	27.8	794.6

Table 3.1 | Maximum temperature and precipitation bounds. Upper temperature and precipitation bounds used in the study.

	LOWER INFLECTION		10 PERCENTILES		5 PERCENTILES	
	Temp (^oC)	*Precip(mm)*	*Temp (^oC)*	*Precip(mm)*	*Temp (^oC)*	*Precip(mm)*
MAIZE	16.9	161.4	15.5	99.1	13.3	44.3
RICE	18.6	158.6	17.3	95.3	14.0	39.6
SOYBEAN	16.9	164.8	16.0	145.8	14.0	98.6
WHEAT	13.8	85.1	13.2	91.0	10.3	49.3

Table 3.2 | Minimum temperature and precipitation bounds. Lower temperature and precipitation bounds used in the study.

CHAPTER 4.

Distribution and Ownership of Power Plants Stranded by Current Climate Targets

Adapted from:

R Fofrich., L. Libermann, D. Tong, Q. Zhang, F. Moore, and S. Davis. Distribution and ownership of power plants stranded by current climate targets. *In prep*

4.1 Introduction

Climate change has the potential to substantially affect future international economic growth and restructure large segments of the global economy. For instance, climate mitigation pathways directly impact projected economic returns by influencing future business profits, investments, and corporate closures (Krueger et al., 2020), and while the implementation of climate mitigation policy can be costly (Köberle et al., 2021, Riahi et al., 2021), further delaying climate action or surpassing international climate change mitigation targets (i.e., <1.5 & <2.0ºC) will ultimately have broader and more profound economic repercussions (Sanderson and O'Neill, 2020, 2021a). Nonetheless, mitigating the most extreme effects of climate change requires a swift and broad transition away from CO_2 emitting power generating infrastructure (Masson-Delmotte et al., 2021, Rogelj et al., 2015a, Rogelj et al., 2018b) most of which have amassed over decades and have historically operated for 36-40 years (Davis and Socolow, 2014b, Davis et al., 2010). Yet unplanned and abrupt changes to the operational schedules of power generators inherently increases financial risk and the sudden marked closure of fossil generating capacity could potentially jeopardize trillions of dollars of power generating infrastructure around the globe (Mercure et al., 2018). Nonetheless, to meet climate mitigation targets, some governments may be forced to adopt more aggressive mitigation strategies (e.g., implementing higher carbon price or forcing power plant closure), and to the extent that future climate policy requires the underutilization or closure of fossil power generators, locked in financial obligations may not be well covered by prior predictions of future revenue.

Transition risks to corporate firms generally increases in companies that have continuously invested and deployed new CO_2 emitting power infrastructure, ultimately increasing the likelihood of unrecoverable anticipated projected returns, i.e., stranded assets. Thus, to minimize stranded asset exposure, and a disruption in services, power generating companies should prepare for the reduced profitability of their current fossil power generating infrastructure and ultimately plan for the retirement their fossil-power generating fleet. Financial risks to the power sector in climate mitigation pathways are well studied and are categorized by future losses whereby economic losses due to a change in regulatory policy (i.e., transition risks) are distinguished from projected losses due to changes in climate (i.e., physical risk) (Gambhir et al., 2022). While prior research have investigated the physical and transition risk of different climate mitigation pathways (Baron and Fischer, 2015, Gambhir et al., 2022, Battiston et al., 2021, Battiston et al., 2017, Drouet et al., 2021, Bos and Gupta, 2019), surprisingly, no study to date has identified and named the corporate owners of stranded power plants, providing little to no insight on the ramifications and exposure of these companies to changes in existing climate policy. Here, we build on prior research and aim to fill several critical gaps in the existing literature, focusing on the power sector transition risks to corporate enterprises. Details of our approach are provided in the *Methods*. In summary, we apply a discounted cash flow (DCF) model to individual power generators in order to quantify their net present value (NPV) and calculate the proportion of NPV at risk of stranding under different climate mitigation targets. Second, we compute annual global stranded fossil-fired electricity generating assets under the 1.5ºC and 2 ºC temperature targets and categorize potential financial losses by region, fuel, and corporate holdings. Third, we identify and allocate stranded assets to their parent companies and reveal the corporate entities which will have the highest share of stranded fossil-fired power generating assets. Lastly, we identify national and regional disproportionalities in fossil-fired stranded assets, generating capacity, power plant operational conditions, and power generator annual CO_2 emissions while categorizing these assets by fuel type and corporate holding. Thus, our results provide insight into which power generating entities are most exposed to stranded assets and transition risks under future climate mitigation policy.

4.2 Results

Figure 4.1 shows the annual net present value (NPV) of fossil-fired power generators around the globe. The NPV of global power plants represents the current value of future cash flows derived from a difference in projected operational and maintenance cost, and generated revenues over the plants expected lifetime. Therefore, we observe a decline in future global power plant NPV irrespective of carbon pricing due to a combination of projected future cash flow discounted at their present value and the anticipated retirement schedules of existing plants. Nonetheless, we observe the inclusion of carbon pricing accelerating the decline in global fossil-fired power generator NPV thereby fast-tracking fossil-fired power plant retirement (Figure 4.1). We find the implementation a 1.5ºC carbon price (solid black line)

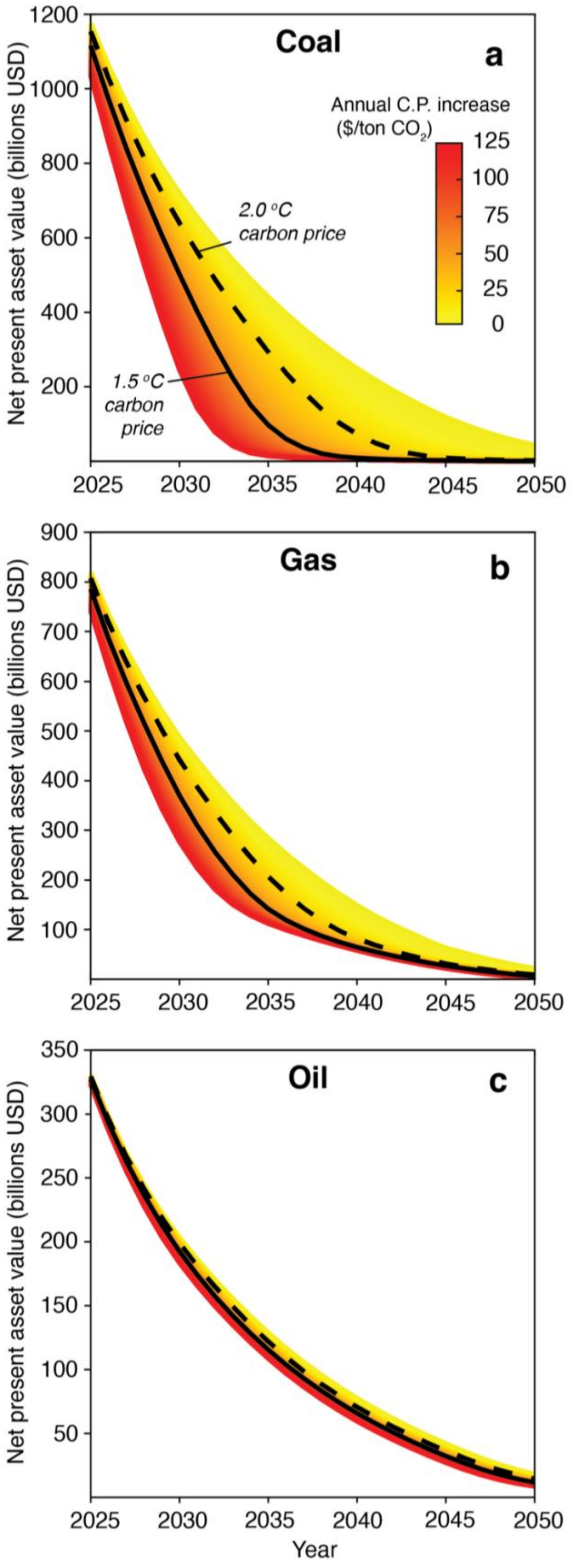

Figure 4.1 | Global fossil-fired power generator net present value decline. Colors represent differences in carbon pricing ranging from 0 to 10,000 USD in 2100. Black lines represent carbon pricing needed to achieve a 1.5 ºC (solid) and 2.0ºC (dashed) temperature targets.

resulting in the rapid decline of global fossil-fired power plant NPV over the next decade, retiring almost all coal- and gas-fired power generators by 2040 and 2050, respectively. By comparison, a 2ºC (dashed black line) carbon price would result in a slower decline in power generator NPV, reaching near zero by 2045, 2050, and 2055 for coal-, gas-, and oil-fired power plants, respectively.

We define stranded power plant assets as the difference in profits before and after the integration of a global carbon price and find the international adoption a 1.5ºC carbon tax (i.e., $4,234/ton in 2100) would result in roughly $13 trillion dollars in stranded fossil-fired power generating assets over the next 40 years. Nonetheless, we observe a decline in stranded assets over time if no additional fossil-fired power

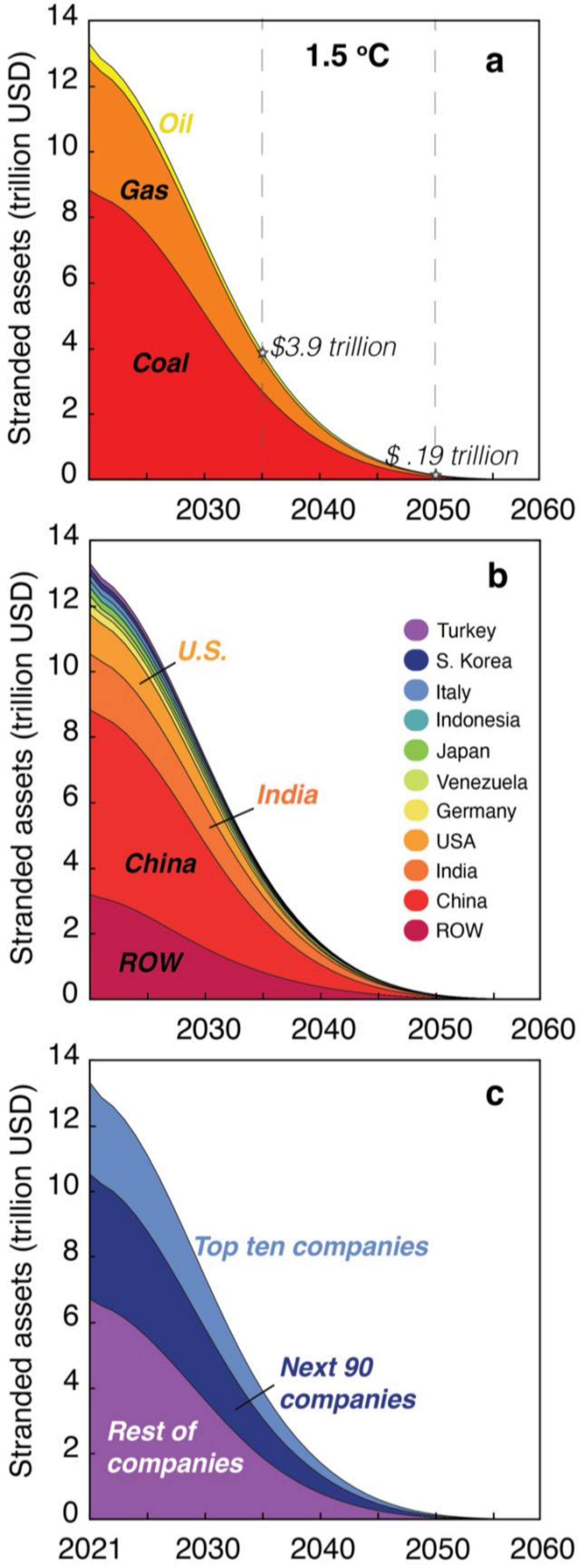

Figure 4.2 | Power plant annual stranded assets. Yearly fossil-fired power generation stranded assets are shown for a 1.5°C (left panels) & 2.0°C (right panels) and categorized by fuel (4.2a & 4.2b), country (4.2c and 4.2d), and top 100 companies (4.2e & 4.2f).

generators are commissioned and deployed. Thus, corporate holders can effectively decrease their financial liabilities by divesting from future fossil-fired power investments while strategically targeting older and more polluting power infrastructure for retirement. We observe the largest share of stranded assets occurring in coal-power generators followed by gas and oil, respectively, and while the value of stranded assets is dependent on future climate mitigation efforts, we find the proportion and patterns of stranded assets between the 1.5- and 2-degree scenarios to be very similar with the greatest difference in stranded asset value occurring before 2035 (Appendix figure C.1). We also find China, India, and the United States (Figure 4.2b) holding the vast majority of global stranded assets, more than the rest of the nations in the world combined. Similarly, we find roughly half of global stranded assets can be attributed to one hundred companies and about a fifth to just ten corporate entities (Figure 4.2c & Appendix figure C.3) irrespective of future climate mitigation pathway.

Figure 4.3 shows the top corporate and state-owned enterprises by stranded asset value, shaded by the percent of the present value stranded in the United States, China, India, and the European Union+ (EU plus the United Kingdom) under a 1.5 ^{o}C climate mitigation pathway. We show the largest share of stranded assets in companies with a large ownership of coal-fired power generation in China and India followed by European and American corporations with a large fraction of natural gas-fired capacity. We find between 67-75% of the present value of fossil-fired generating assets at risk for stranding under a 1.5^{o}C carbon price in state-owned companies with a large fraction of coal and gas-fired power plants in China where the average power plant age is less than 15 years. Similarly, we find roughly half of the present value of coal-fired fossil generating assets at risk for stranding under the same climate mitigation pathway in the top ten companies in India. Of the companies with the largest share of stranded assets in the European Union and the United States, we find the largest portion of stranded assets occurring in publicly traded companies with a large fraction of gas-fired power plants. On average, we find the share of these assets at risk for stranding is around 38-43% in U.S. corporations and 41-67% in European companies. Overall, we show a lower share in the total value and proportion of stranded assets in companies with oil-fired gas generators across all nations largely due to the age of these plants and the overall installed electricity generating capacity.

Table 4.1 shows the financial stranding exposure and average power holding operational conditions for the top global corporate entities by future stranded asset value (Table 4.1). We find the largest portion of stranded power generating assets occurring in four regions of the

Figure 4.3 | Corporate stranded assets by fuel in top companies. We show the stranded asset value in four global regions organized by fuel type and shade each company by their fossil-fired power generating infrastructure that is at risk for stranding.

world – China, India, the United States, and the European Union. Among the companies with the largest share of stranded assets are five Chinese state-owned entities which collectively produce 70% of global annual electricity related CO_2 emissions. Collectively these five state-owned companies hold 14,674 individual generators and a total of 3,830 GW in electricity generating capacity with an average age of 12-14 years, the vast majority of which is coal-fired power generation. Of the top ten companies by stranded asset value, only five are publicly traded while vast majority are national or provincial state-owned enterprises. With the exception of NTPC Limited, coal fired-power generators are a primary source of government owned stranded assets, constituting over 80% of all state-owned power generating infrastructure (Table 4.1). We find the top ten non-state-owned actors to be China Resource Power, RWE AG, the Adani Group, Engie S.A., Enel S.p.A., SDIC Power Holdings Co., Iberdrola SA, Duke Energy, Vedanta Resources, and the Tata Group, collectively owning nearly $3 trillion dollars in stranded fossil-fired power generating assets over the next 40 years. Collectively, we find the top twenty-four companies holding over $5 trillion dollars over the lifetime of their fossil-fired power holdings and are responsible for emitting 8.3 Gt of CO_2 per year.

Company	Ticker	Stranded assets (Billion USD)	Capacity (GW)	Generators	Age (yrs)	Gt CO_2/yr	Fuel
Nat. Energy Invest.*	🇨🇳	**814**	775.9	2427	12	2581.8	
Huaneng Group*	🇨🇳 HNP	596	117.2	415	13	556.1	
Huadian Corp.*	🇨🇳 HPIFF	577	1117.4	4173	14	**3672.6**	
Datang Corp.*	🇨🇳	572	**1801.9**	**7625**	14	413.9	
NTPC Limited*	🇮🇳 NTPC	380	3.9	33	21	12.7	
State Power Invest.*	🇨🇳	323	17.2	34	12	53.0	
China Resources Power	🇨🇳 CRPJY	220	101.8	103	**6**	150.2	
RWE AG	🇩🇪 RWEOY	167	24.2	104	23	69.5	
Guangdong Energy**	🇨🇳	165	14.6	36	10	47.7	
Adani Group	🇮🇳 ADANI	124	12.9	23	8	40.7	
Engie SA	🇫🇷 ENGIY	115	30.2	364	15	84.8	
Enel S.p.A.	🇮🇹 ENLAY	115	57.2	133	53	32.2	
North United Power*	🇨🇳	96	18.3	55	12	65.1	
SDIC Power	🇨🇳 SDIC	92	18.3	36	8	58.6	
Iberdrola SA	🇪🇸 IBDRY	80	10.8	90	14	27.7	
Duke Energy	🇺🇸 DUK	77	22.3	219	23	116.4	
Vedanta Resources	🇮🇳 VED	76	8.3	43	9	24.9	
Tata Group	🇮🇳 TATA	73	7.8	68	12	8.8	
Maharashtra State Power**	🇮🇳 MSEB	72	10.4	35	18	38.2	
Vistra Corp	🇺🇸 VST	69	21.9	101	28	58.1	
Damodar Valley*	🇮🇳 DVC	67	7.6	24	14	30.6	
Southern Company	🇺🇸 SO	66	33.6	145	34	104.0	
NextEra Energy, Inc	🇺🇸 NEE	65	20.4	134	23	36.1	
EDF Group	🇫🇷 ECIFY	62	20.9	336	27	38.3	

Table 4.1 | Corporate stranded assets. Corporate holders of stranded assets are ordered by stranded asset value along with the capacity weighted average age of their fossil-fired power generating fleet. National (*) and provincial (**) state-owned companies are distinguished with asterisks while publicly traded companies are shown by national stock exchange. Fuel composition shows the proportion of coal- (red), gas -(orange), and oil- (yellow) fired power generators held by each corporate entity.

4.3 Discussion and Conclusion

Limiting future temperature increases to 1.5ºC above preindustrial levels requires future financial flows to be consistent with low emission electricity generating pathways (Masson-Delmotte et al., 2021, 2021a, UNFCCC, 2015, Rogelj et al., 2015a, Rogelj et al., 2018a). Delayed climate policy and constantly changing political dynamics make transition risks difficult to predict, sometimes resulting in sudden shifts to existing policy and a unexpected revaluation of a company's assets (Riedl, 2021). Therefore, many energy sector investors are becoming increasingly concerned with the climate risk implications of their financial holdings and are seeking to minimize regulatory risk through a combination of strategies such as demanding higher compensation for higher climate risk exposure of more polluting financial assets (Bolton and Kacperczyk, 2021). Several fossil-energy companies have responded to shareholder pressures by publicly disclosing financial climate risk while others have pivoted away from traditional revenue sources and have increased monetary investments in public relations to alleviate their investor and customer environmental concerns. Nonetheless, there is growing anxiety amongst investors who suspect companies have failed to fully characterize their climate risk exposure (Goldstein et al., 2019), and while physical climate risks are more profound with more severe warming (e.g., risks to infrastructure from more frequent and intense of extreme weather events), climate transition risks increase when companies fail to anticipate the implementation of more restrictive climate mitigation policy.

Under the most ambitious climate mitigation scenarios (i.e., limiting climate warming to <1.5ºC) we find stranded assets increase in companies whose power holdings have capacity weighted average operational life of less than 20 years. While more ambitious climate mitigation pathways increase transition risk, 70% of global annual power sector emissions could be avoided by strategically stranding \$2.9 trillion dollars in mostly coal-fired generating assets held by China's big five energy generating companies - National Energy Investment Group, China Huaneng Group corporation, China Datang Corporation, China Huadian Corporation, and China Power Investment Corporation. However, these companies are directly owned by China's central government, State Asset Supervision and Administration Commission (SASAC), and have been at the forefront of China's energy growth in recent decades cumulatively holding 1406 and 28 GW of installed coal and gas-fired capacity representing 39% of China's electricity generating capacity. Although stranded assets are highest amongst China's state-owned companies, much of the world's commerce is produced within China's national borders and China's economic domestic growth has far reaching implications on the global economy. Thus, financial insolvency in these companies can be risky not only for China's central government but can have meaningful and widespread consequences on the broader global economy. By comparison, in western economies, corporate power generating entities and public utilities have largely lowered annual CO_2 emissions by heavily investing in natural gas-fired power generation. However, the substitution of aging coal-fired power generators with newer gas-fired power infrastructure has not substantially lowered future cumulative power sector emissions (Shearer et al., 2020) but has instead increased the transition risk of U.S. and European power sector corporate firms.

While this study provides some insight into future climate financial risks of certain companies, it is subject to several caveats and limitations. First, the stranded asset valuations reported here are directly dependent on projected growth and the implementation of global carbon pricing. Therefore, the monetary value of stranded assets may not reflect what is priced into financial markets and the results reported here should not be used to forecast expected corporate growth or revenue returns. Nonetheless, our results consistently show the same companies holding the greatest proportion of stranded assets irrespective of adopted carbon prices suggesting these companies are most at risk for asset stranding under all climate mitigation pathways. Second, future stranded assets are also contingent on the timing of climate policy implementation and the overall monetary risk to a given company subsides as the fossil-fired power fleet that company continues to age. Thus, the magnitude of stranded assets held by each corporate entity is subject to change overtime. Lastly, our results are based solely on our calculated power plant revenues and costs, and are based on historical electricity generation returns. However, projected revenue and input costs are subject to change and future operational conditions, maintenance and fuel costs are unknown and cannot be modeled. In some cases, future stranded assets can be lessened through the strategic retirement of older and more polluting fossil-fired electricity generators, and through the discontinuation of upcoming planned and commissioned coal- and gas-fired power plants. Nevertheless, our results suggest a large fraction of the fossil-fired generating assets of these companies will be stranded under current climate mitigation targets but the monetary value of these stranded assets pale in comparison to the natural, social, and economic consequences if climate mitigation pathways are not met. Thus, to meet crucial climate mitigation targets while minimizing economic losses, electricity generating companies should begin to strategically retire carbon intensive power generators and cease to invest in future fossil-fired electricity generating technologies.

4.4 Methods

We successfully identify the corporate and state owners of 98% of individual of fossil electricity generating capacity in the World Electric Power Plant (WEPP) database and calculate their financial risks under different climate policies. To quantify future profits, we project the expected future discounted cash flow of each power plant (i) individually over the anticipated operational life of the plant and assign these profits to their respective parent company.

$$Generator\ profits_{it} = G_{it}EP_{it} - G_{it}FP_f\vartheta_i - m_{it} - rK_{it}$$

Generator profits are defined as the revenue from electricity generation over period t minus the cost of production calculated as annual electricity generation (G) multiplied by the wholesale price of electricity (EP) and subtracting generating costs — i.e., annual electricity generation (G) multiplied by fuel price (FP) and a unit fuel to electricity conversion term (ϑ), minus the operations and maintenance costs (m), and the expected rate of return (r) on the undepreciated capital (K) to investors. We assume a fixed depreciation rate of 3%, consistent with global historical returns in equities and bonds, and vary this rate in subsequent runs as a sensitivity test of our finds. However, projected power plant profits and subsequent power plant monetary valuation is directly influenced by the anticipated rate of return. Thus, we vary the assumed rate in subsequent trials and report these results. As an individual power plants ages, the operational and maintenance costs typically increase such that these costs are not well covered by the generated revenues resulting in their closure which has historically occurred around 40 years (Davis et al., 2010, Davis and Socolow, 2014b, Shearer et al., 2017, Tong et al., 2019a, Cui et al., 2019). Therefore, we allow for an increase in operational costs as a function of age, indexed by t, ensuring existing power infrastructure retire in line with their historical norms.

To quantify the impacts of climate mitigation policy of fossil-fired power plant profits we first calculate the net present value of these generating assets (i) based on the discounted cash flows of expected revenue. In addition, we test the effects of carbon pricing on future profits by calculating the NPV with and without the inclusion of a carbon tax. Once power generating infrastructure becomes unprofitable we allow firms to simply retire these plants and do not explore the ramifications of the financial liabilities this may cause.

$$NPV_i = \sum_{t=0}^{\infty} \frac{\text{Generator profits}}{(1+r)^t}$$

To prevent power generating assets from instantaneously retiring we incrementally increase the carbon price on annual basis consistent with prior research (Riahi et al., 2017a). We test the sensitivity of carbon pricing on our results by varying these inputs from 0 to $10,000 USD per ton in the year 2100 and report the implications to the net present value of global fossil-fired power generators on an annual basis. We further extract and overlay the carbon pricing required to meet future climate pathways (e.g., 1.5 and 2^{o}C) to illustrate how these targets impact the future retirements of fossil-fired power generating assets.

We translate future climate trajectories (e.g., 1.5 and 2^{o}C) into stranded assets by incorporating global and regionally specific carbon price paths used by integrated assessment models for climate mitigation scenarios (2021b). Carbon prices translate directly into increased input costs for fossil fuel plants, and thus future profits are modified under a 1.5 or 2^{o}C scenario.

$$Modified\ generator\ profits_{it} = G_{it}EP_{it} - G_{it}(FP_f + CP_t)\vartheta_i - m_{it} - rK_{it}$$

Where CP is the carbon tax on fossil fuel (f) at time (t) consistent with either a 1.5 or 2 ^{o}C emissions scenario. Here we also take the simplified assumption that the utility will be unable to pass on any of the costs to ratepayers by keeping the price of electricity static in both profit equations. However, in actuality, costs have been passed down to taxpayers and consumers in regions where climate mitigation policy has forced the early retirement or underutilization of fossil-fired power generators (Bos and Gupta, 2019, Wasserman and Cramer, 2016).

We define stranded assets as the difference in future asset profits with and without climate policy that limits warming:

$$Stranded\ Assets_i = \sum_{t=0}^{\infty} \frac{\mathrm{GP}_i - \widehat{GP_i}}{(1+r)^t}$$

We further aggregate unit level monetary value and assign these assets to their parent company (corporate or state- enterprise owners), and select the top 100 companies with the largest stranded asset holdings. To investigate the national economic risk from stranded fossil-fired capacity, we quantify and assign the monetary of value of fossil-fired power generators within each nation’s borders.

CHAPTER 5.

CONCLUSION AND FUTURE RESEARCH DIRECTION

5.1 Summary and conclusion

The current rate and magnitude of planetary warming experienced over the last hundred years is unpresented and has not been observed by humanity in thousands of years (Marcott et al., 2013, IPCC, 2013, Masson-Delmotte et al., 2021). Over the past 12,000 years our distant relatives lived with a relatively stable climate with global temperatures never varying more than 1°C (Burke et al., 2018, Marcott et al., 2013). While early humans withstood large and long-lasting temperature fluctuations (Burke et al., 2018), relatively stable temperatures during the mid- and late-Holocene era facilitated humanity in the development of agriculture and permanent settlements. Nevertheless, regional changes in climate have occurred over the last millennia, providing some historical insight to the consequences of unmitigated climate warming. For instance, regional climate change has long been suspected of having influenced the establishment and collapse of many ancient civilizations around the world (Hodell et al., 2005, Carter et al., 2019, Welc and Marks, 2014), and while ancient societies may have been largely unaware of the perils of climate change, current climate pathways projections suggest devastating consequences for modern civilization if global climate change mitigation and adaptation measures are not implemented or go largely ignored (IPCC, 2013, Masson-Delmotte et al., 2021, Shukla, 2019a).

International climate mitigation agreements require the rapid decarbonization of the global economy (UNFCCC, 2015, Peters, 2016, Masson-Delmotte et al., 2021, Millar et al., 2017, Rogelj et al., 2018b). However, achieving these goals may not be possible without phasing out new fossil-fired power plant construction (Cui et al., 2019, Luderer, 2016, Kriegler et al., 2018, Audoly et al., 2018), and yet many countries are actively increasing or have recently deployed new fossil-electricity generating capacity (Cui et al., 2019, Shearer et al., 2020, Shearer et al., 2017). In climate change mitigation scenarios that successfully avoid anthropogenic warming of 2^{o}C, we observe fossil-fired electricity generating infrastructure retiring up to three decades earlier than they have historically, possibly stranding trillions of dollars in power generating assets. Thus, we find, the continual investment in fossil energy plants is incompatible with climate mitigation efforts and potentially jeopardizes the 2°C climate target.

In order to swiftly decouple economic activity from future emissions, countries must immediately begin to switch to non-CO_2 emitting power generating sources and cease future fossil-energy investments or begin deploying negative emission technologies (Rogelj et al., 2018a). While future climate policy can require the underutilization or closure of fossil-fired electricity generators, abruptly changing policy can increase climate transition risks and the continual investment and deployment of carbon emitting technologies only serves to exacerbate potential financial loses. However, these risks are not evenly distributed across industries or corporate entities around the globe. For instance, in many countries around the world, ageing power generating infrastructure and underdeveloped electrical grids provide an opportunity to minimize financial losses while expeditiously transitioning to carbon neutral electricity sources. We determine the biggest risk for financial losses occurring in state-owned coal-fired power generators in China, where due to the recent economic boom, there has been a marked increase in coal-fired power generating capacity over the last few decades. Collectively five companies (National Energy Investment Group, China Huaneng Group corporation, China Datang

Corporation, China Huadian Corporation, and China Power Investment Corporation) were found to produce roughly almost three quarters of annual CO_2 emissions and hold roughly a third of global stranded assets under a 1.5°C climate target. We show annual power sector CO_2 emissions can be drastically reduced, through strategic and targeted stranded investments. However, steps should be taken to minimize monetary damage to the broader domestic and international economies.

If instead, climate mitigation strategies are largely unsuccessful in limiting future warming, future climate change is expected to reduce crop productivity over this century, particularly in historically warm regions of the planet. Thus, we project potential shifts in cultivation for major cereal crops around the world (i.e., maize, rice, soybean, and wheat). We find that 19% of the global production of these crops are at risk under modest climate warming and are currently cultivated in areas that will reside outside of their historical climate ranges under climate scenarios that successfully avoid 2°C of mean warming (i.e., radiative forcing of 2.6 W/m^2 in 2100), rising to 29% and 35% in scenarios where the increases in mean temperatures approach or exceed 3 °C, respectively (i.e., 4.5 and 7.0 W/m^2 in 2100). Moreover, crops grown in the global south are disproportionately impacted, including almost half (48%) of Asian rice production and more than a quarter (28%) of South American soy in the lower warming (2.6 W/m^2) scenarios. Although the effects of climate change might be partially mitigated through the combination of improved farming practices, shifting cultivation dates, and more resilient cultivars, our results emphasize the risk to regional agricultural in many areas of the planet.

Whether global society is successful in limiting future warming is largely unknown and unpredictable. Nonetheless, future climate pathways provide some insight into the necessary steps required and challenges of achieving climate mitigation and adaptation targets. Additionally, our results emphasize the large extent to which global food and energy production may be impacted under future climate change and climate mitigation pathways. Thus, our findings reenforce the urgent need for international cooperation and planning.

5.3 Future Research Directions - Constraints to land-based biomass sourced climate mitigation strategies.

availability

determines

Apart from the swift decarbonization of future energy production, climate change mitigation pathways also stabilize rising global temperatures at or below 2°C through the rapid and large-scale deployment of biomass sourced CO_2 reduction technologies (e.g., afforestation and reforestation (AR) and bioenergy with carbon capture and storage) (Turner et al., 2018, Nolan et al., 2021, Azar et al., 2013, Muri, 2018, Minx et al., 2018, Peters, 2016). However, the widespread adoption of biomass sourced negative emissions technology (NET) requires considerable land allocation and sizeable investments in energy crop production (Rogelj et al., 2018a, Luderer, 2016, Luderer et al., 2013, Rogelj et al., 2015a, Shukla, 2019a). Furthermore, global AR efforts may negatively impact regional biodiversity and economies (Sills et al., 2020, Bond et al., 2019, Holl and Brancalion, 2020, Fuss et al., 2018), and may not be a fully viable solution for climate change mitigation (Baldocchi and Penuelas, 2019, Anderson et al., 2019, Anderegg et al., 2020). Thus, the extensive land-use demanded by NETs further strain finite terrestrial resources and put climate remediation goals in direct competition with food cultivation, socioeconomic development, and international conservation needs. In addition, climate change will limit the availability of suitable land for energy and food crop cultivation, AR, and wildlife conservation over the next century (Rosenzweig et al., 2014, Masson-Delmotte et al., 2021). As the planet warms, the climatic ranges of habitat and cultivation shift poleward (LoPresti et al., 2015, Diffenbaugh and Field, 2013, Loarie et al., 2009, Walther, 2003, Sloat et al., 2020) and suitable tropical regions become increasingly fragmented, decreasing their viability (Urban, 2015, Hof et al., 2011, Tucker et al., 2018, Otto, 2018, Waters et al., 2016, Haddad et al., 2015). Therefore, the biogeophysical and socioeconomic impacts of NETs and their viability require further investigation before their widespread adoption in climate mitigation strategies.

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APPENDIX A.

SUPPLEMENTARY MATERIAL FOR CHAPTER 2.

Future Energy Demand – Integrated Assessment Modeling Framework

The Integrated Assessment Modeling structure combine both human and natural systems, to explore the future evolution of human society and its interactions with the surrounding environment. This is accomplished by coupling energy, economic, and climate systems into a single integrated model. This framework allows researchers to explore future physical-biogeochemical processes and corresponding sociological interactions, combining key processes into one holistic system (Masson-Delmotte et al., 2021). IAMs can produce a multiple human development and climate projections that vary based on how initial components of the systems and their interactions are represented and quantified (Cantore, 2011). Differences in primary parameterizations lead to various anthropogenic, physical, and biogeochemical responses, thus providing an opportunity to explore a plethora of future development trajectories (Riahi et al., 2017a, O’Neill et al., 2017). The Integrated Modeling Framework was used to develop the Shared Socioeconomic Pathways, or SSPs, to describe five different (yet plausible) consistent future trajectories for human development, each with its own challenges to climate adaptations and mitigation (O’Neill et al., 2017). Unlike the more widely explored Representative Concentration Pathways (RCPs), the SSPs do not have climate stabilization goals inherent within them rather, the SSPs describe a narrative and quantify key parameters associated with human development that could provide insights to the challenges that arise from the human system and the changing earth system (van Vuuren et al., 2017). Key aspects used in developing five of the six models best align with the one of the five SSP narratives, therefore these five IAMs were designated as the reference model one of the five SSP scenarios. Not all of the modeling teams were able to replicate each of the SSPs for each of the radiative forcing trajectories explored and therefore achieving such goals would prove to be extremely challenging under a human development future that fit that narrative.

Shared Socioeconomic Pathway narratives:

IAM and SSPs differ in their representation of greenhouse gas emissions, energy sources, energy demand, economic growth, and nation state cooperation (O'Neill et al., 2016, Cantore, 2011). Here we briefly describe the underlying narrative of each of the five shared socioeconomic pathway and the six integrated assessment models as well as some of the relevant components that go into each. For a more detailed account of each of the SSPs we recommend exploring the reference material or visiting each of the integrated assessment modeling teams home website.

The SSP1 narrative, emphasizes resource efficiency and is describe as having low challenges for mitigation and adaptation (van Vuuren et al., 2017). Nation states work towards a more sustainable trajectory and widespread economic growth translate to an emphasis on general human wellbeing (Bosetti et al., 2006). Long term pledges in achieving human sustainability goals, inequality reduces throughout the world (Bosetti et al., 2006, van Vuuren et al., 2017). With a global focus on general human equity, wealthier countries assist developing economies to reach economic and sustainable growth (O’Neill et al., 2017). Through an increase in regulations, SSP1 places an emphasis “green economic growth” and “green” energy technology developments (van Vuuren et al., 2017, Bosetti et al., 2006, Riahi et al., 2017a, O’Neill et al., 2017).

SSP2 has been described as the middle of the road trajectory that follows historical trends in energy (Fricko et al., 2017). Future economic development proceeds unevenly with some regions experiencing strong economic growth while others underperforming when compared to general projections (Fricko et al., 2017, Riahi et al., 2017a). Likewise, GDP per household evolution even in rich countries do not develop evenly across the national population. Education investment fall short and global population growth is moderate through the first half of the 21st century and is reduced in the latter part of the century (O’Neill et al., 2017). The SSP2 narrative results in moderate challenges to climate mitigation and adaptation.

SSP3 is a world where regional rivalry and nation states compete to dominate, leading many states to undertake protectionist and nationalist policies (Fujimori et al., 2017). Countries focus on their own economic wellbeing and seek to secure food, energy, and national security goals even at the expense of nation state cooperation. SSP3 is said to have high levels of challenges to both climate adaptation and climate mitigation. No modeling team were able to produce the SSP3 scenario for the 1.9 or 2.6 forcing trajectory.

In SSP4, social unrest and deepening inequality prevail. SSP4 is a world where there exist highly disproportionate investments in human capital, economic opportunity, and limited cooperation between nation states (Calvin et al., 2017). The global economy remains fragmented, stalling CO_2 emissions however with little cooperation between established and emerging economies, climate change becomes difficult to cope with especially for economically strapped countries. General social cohesion and cooperation between global transnational organizations degrades (Calvin et al., 2017, O’Neill et al., 2017). There is a strong focus on technology development is high and there are strong investments in the energy sector. Thus, this scenario presents high challenges to climate adaptation and low challenges to climate mitigation.

Finally, SSP5 is characterized by rapid development that is fossil-fueled driven with high socioeconomic challenges to mitigation but low challenges to adaptation (Kriegler et al., 2017). There are strong investments in general human wellbeing such as those in health, education, and institutions that provide support to human systems (O'Neill et al., 2017). A future where the SSP5 narrative dominates sees most nation states experiencing economic growth thereby easing some of the challenges to climate adaptation.

Asia-Pacific Integrated Assessment Model (AIM):

The Asia-Pacific Integrated Assessment Model (AIM) is a collective term of several large-scale computational models. For the SSP quantification, AIM/CGE is used. AIM/CGE is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world (Fujimori et al., 2017). The AIM/CGE model includes 17 regions and 42 industrial classifications. Details of the model structure and mathematical formulae are described by Fujimori et al. (2012). The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. Energy transformation sectors input energy and value added are fixed coefficients of output. They are treated in this manner to deal with energy conversion efficiency appropriately in the energy transformation sectors. Power generation values from several energy sources are combined with a Logit function. The household expenditure is determined by the linear expenditure system function of which parameters are recursively updated in accordance with income elasticity assumptions. The core assumptions in AIM are most consistent with those that make up the reference narrative of 3rd shared socioeconomic pathway, thus AIM was selected as the reference scenario for the SSP3 narrative (Fujimori et al., 2017).

Global Change Assessment Model (GCAM):

Like other IAM's, the Global Change Assessment Model (GCAM) combines components from both the natural and human system. GCAM's energy-economic model comprises of 32 regions which cumulative project future anthropogenic gas emissions, by linking key systemic human drivers of greenhouse gas emissions such as the economic, energy, and land-use systems (Calvin). Key human system components that is at the core of GCAM include population and productivity assumptions, agricultural practices, land-use change, water withdrawals and demand, change in price of key commodities and change in household income levels (Calvin). In addition, and most relevant to this study, a detailed representation of energy resources, supply, transformation and demand is included with the GCAM framework (Calvin). The production and use of energy resources depends on their cost, inclusive of capital, fuel, operating/maintenance costs, the price of the product produced, the policies or regulations applied (e.g., carbon price, renewable fuel standard), and the cost, policies, and prices of competing options. For long-lived capital, like electric power plants, GCAM's investment decisions are based on the levelized cost of capital, fuel, and O&M. However, once a plant is constructed, GCAM will operate the plant as long as the price of the produce produced exceeds the operating costs. GCAM uses a simple climate model evaluate the effects of anthropogenic emissions on the global climate (Calvin). GCAM is typically used to explore the effect of technology, policy, and socioeconomics on energy, water, land, emissions, and climate. GCAM was used as the reference scenario for SSP4 which has low challenges to mitigation but high challenges to climate adaptation.

Integrated Model to Assess the Global Environment (IMAGE):

The Integrated Model to Assess the Global Environment *(*IMAGE) is a dynamic integrated assessment model used to address global change in both the human and natural systems. IMAGE quantifies the major earth system processes and subsequent interactions of human society such as socioeconomic development, resource allocation and availability, and regional policy (van Vuuren et al., 2017). The IMage Energy Regional model (TIMER) model contains detailed quantifications on energy for the 26 regions and includes key factors on regional energy demand, supply, and conversion based on socioeconomic drivers. Key input model energy drivers include regional energy resources, GDP per capita, population growth, lifestyle choices, advancements in energy technologies, carbon pricing, and land allocation for bioenergy. TIMER determines required installed power capacity by quantifying the peak demand and an extra reserve. The demand for new investments in power capacity is the result of this required capacity, the current installed capacity and capacity that gets depreciated (either by reaching the end of its lifetime, or by early retirement due to high operational costs). This new need for investments is divided amongst different power generating technologies based on total power plant cost which arise from capital, expected operational costs and system integration costs. SSP1, or the green growth pathway for human development, has been assigned to the IMAGE model as a reference model (Bauer et al., 2017).

Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE):

The Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE) runs quantile regressions on historical GDP, population, and energy to develop future regional energy demand and subsequent anthropogenic CO_2 emissions. Historical for GDP, population, and energy demand are based on projections from the World Bank, United Nations, and International Energy Agency, respectively. The baseline energy demands are not fundamental to MESSAGE rather they are adjusted based on energy prices by integrating the

MESSAGE-MACRO model. The main variables of the MESSAGE-MACRO model are capital stock, labor cost and availability, energy resources, and the total output of an economy. MESSAGE-MACRO energy system costs approximations are based on previous MESSAGE run results (Fricko et al., 2017). MESSAGE's integrated modeling framework allows for future energy, emissions, and climate mitigation planning. MESSAGE was used in developing the marker scenario for SSP2 which follows historical trends in human development otherwise described as the middle of the road trajectory. The SSP2 marker is an extension of historical trends in carbon use and energy expansion with medium level challenges to climate mitigation and adaptation (Fricko et al., 2017).

Regionalized Model of Investments and Development (REMIND):

The Regionalized Model of Investments and Development (REMIND) model is a global multi-regional coupled human and earth system model that encompasses key parameters within the human systems such as economic growth, energy investments, and international trade allowing one to understand the feedback mechanisms between human society and the climate system (REMIND) (Aboumahboub et al., 2020). Like other IAMs explored in this study, REMIND uses macro-socioeconomic drivers such as population, regional GDP, energy cost, and changes in national regional geopolitical polices to project future energy demand, thus projected CO_2 emission pathways (Luderer, 2015). REMIND divides the world into 11 regions and uses an economic Ramsey-type optimal growth model and a non-cooperative Nash Equilibrium to maximizes global economic development without increasing global cooperation between nation states (Luderer, 2015). The investment costs of different power generating technologies are same for each region with the exception of solar and wind power deployments. REMIND has been used as the reference scenario for SSP5 which describes a future that is energy and resource intensive thus posing high challenges to climate mitigation (Kriegler et al., 2017).

World Induced Technical Change Hybrid (WITCH):

The World Induced Technical Change Hybrid (WITCH) model integrates key components of human society with elements of the earth systems. The model uses an economic Ramsey-type intertemporal growth model to boost wellbeing in all 13 global regions used within its framework (Bosetti, Emmerling). This model is used to explore the anthropogenic and natural feedbacks between the earth and human systems. The cost of generating electricity is inherently built into the economic WITCH model and is a function of capital, operational, maintenance, and fuel costs (Emmerling). The WITCH model uses a macroeconomic welfare optimization framework with a hard-linked energy sector including capital and investments in sixteen electricity generation technologies among others (Bosetti, Emmerling). WITCH was not designated as a marker scenario for any SSP therefore its baseline is not in line with any of the key assumptions for the reference SSPs. However, the WITCH modeling framework provides an additional window to explore challenges to climate mitigation and adaptation as well as anthropogenic impacts to the natural systems. The WITCH model was not designated as the marker for any SSP and therefore the baseline components within the model do not fully align with any SSP narrative.

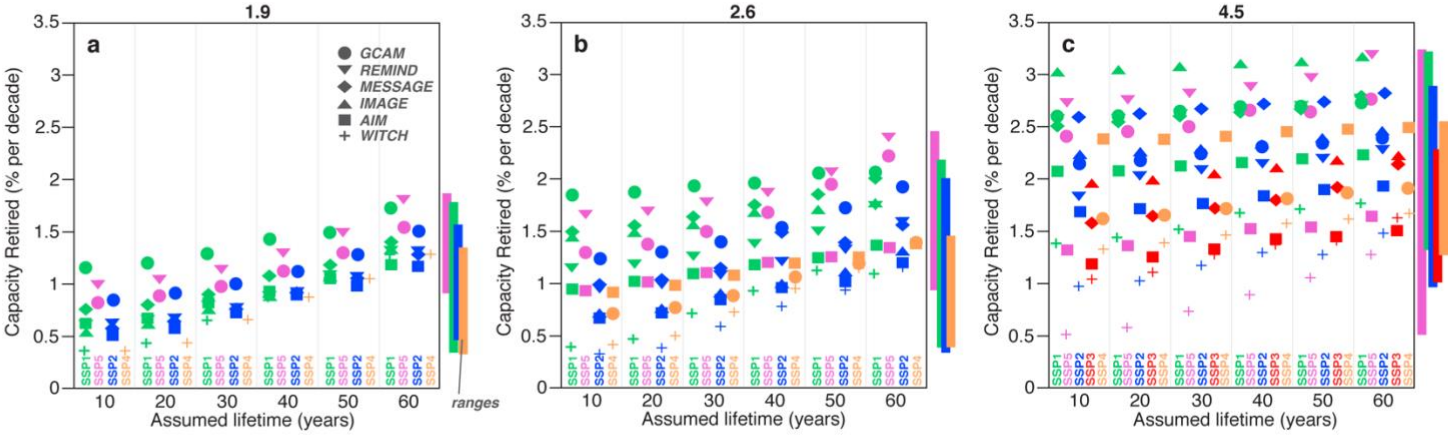

Figure A.1 | Decadal mean installed capacity retirement rates. Decadal reductions in nameplate capacity from coal and gas electrical generators decline with an increase in assumed power plant lifetime and with increased inertia from electricity production. Here we see the results from individual SSP and models represented by the colors and shapes, respectively. The horizontal lines represent the SSP means according to their color coordination across all IAMs used.

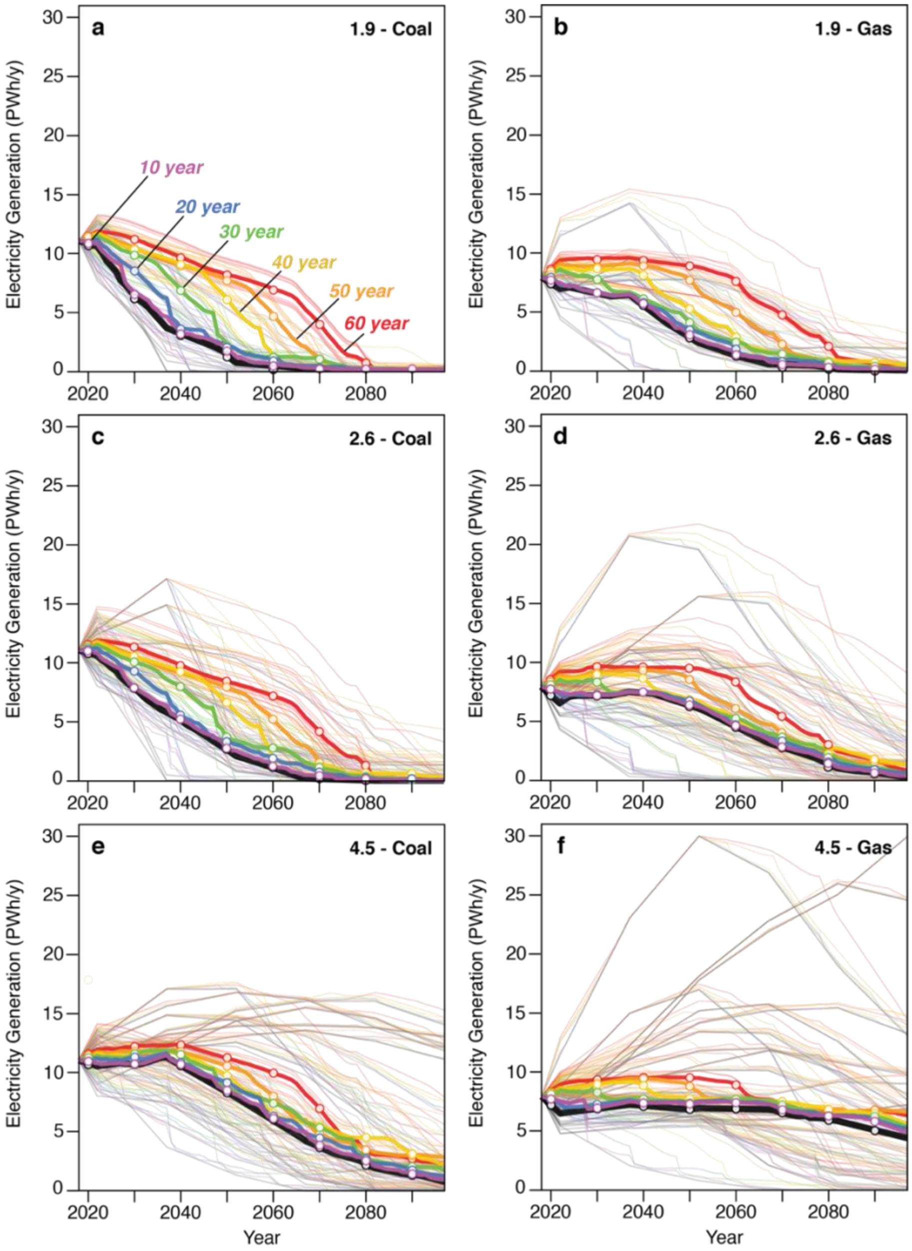

Figure A.2 | Inertia in power sector electricity. Future electricity generation from coal and gas-fired power plants in a 1.9, 2.6, and 4.5 (black curves in a - f, respectively) decrease more rapidly than electricity generation from power plants which operate at region-specific mean capacity factors. Colored lines depict future electricity generation assuming region and fuel-specific mean capacity factors and power plant lifetimes ranging from 10 years (purple curves) to 60 years (red curves).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**Japan**	**Coal**	62.9	1187.98
2	**China**	**Coal**	44.9	1128.46
3	**India**	**Coal**	60.4	1049.12
4	**Southeast Asia**	**Coal**	63.6	1230.20
5	**Other Asia**	**Coal**	47.1	1198.29
6	**Oceania**	**Coal**	71.5	1134.36
7	**E.U. 25**	**Coal**	37.3	1245.83
8	**Other Europe**	**Coal**	59.0	1125.78
9	**Former Soviet Union**	**Coal**	51.9	1281.55
10	**Turkey**	**Coal**	40.1	1095.03
11	**Canada**	**Coal**	54.6	1151.80
12	**USA**	**Coal**	71.6	1293.09
13	**Brazil**	**Coal**	73.1	1276.01
14	**Latin America**	**Coal**	68.2	1138.61
15	**Middle East**	**Coal**	60.1	1099.80
16	**North Africa**	**Coal**	83.8	1165.87
17	**Other Africa**	**Coal**	76.3	1093.72
1	**Japan**	**Gas**	38.8	583.60
2	**China**	**Gas**	44.4	596.17
3	**India**	**Gas**	36.3	606.69
4	**Southeast Asia**	**Gas**	47.7	592.82
5	**Other Asia**	**Gas**	46.7	581.28
6	**Oceania**	**Gas**	25.3	575.99
7	**E.U. 25**	**Gas**	71.4	621.09

8	**Other Europe**	**Gas**	36.7	618.64
9	**Former Soviet Union**	**Gas**	37.2	595.71
10	**Turkey**	**Gas**	38.8	599.44
11	**Canada**	**Gas**	52.5	593.02
12	**USA**	**Gas**	53.1	589.70
13	**Brazil**	**Gas**	71.3	563.86
14	**Latin America**	**Gas**	55.4	587.46
15	**Middle East**	**Gas**	70.4	621.08

Table A.1 | Historical mean regional capacity factors and carbon intensities for the Asia-Pacific Integrated Assessment Model (AIM).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**United States**	**Coal**	69.9	934.15
2	**Canada**	**Coal**	60.6	980.60
3	**Japan**	**Coal**	68.6	1037.41
4	**E.U. 12**	**Coal**	51.8	1228.34
5	**E.U. 15**	**Coal**	54.7	1138.91
6	**European Free Trade Association**	**Coal**	58.5	1060.53
7	**Non-E.U.**	**Coal**	61.1	1262.04
8	**Eastern Africa**	**Coal**	67.8	1037.15
9	**Western Africa**	**Coal**	77.0	1000.81
10	**Southern Africa**	**Coal**	31.7	1152.84
11	**Northern Africa**	**Coal**	70.8	1159.96
12	**Australia & New Zealand**	**Coal**	63.1	1147.28
13	**Brazil**	**Coal**	44.8	1086.58
14	**Central America & Brazil**	**Coal**	67.1	973.54
15	**South Africa**	**Coal**	70.9	1148.14
16	**China**	**Coal**	47.2	1235.85
17	**India**	**Coal**	73.2	1381.44
18	**Indonesia**	**Coal**	72.0	938.24
19	**Mexico**	**Coal**	55.6	1064.39
20	**Middle East**	**Coal**	44.6	1613.99
21	**Pakistan**	**Coal**	56.1	992.44
22	**Southeast Asia**	**Coal**	62.4	1078.53

23	**Taiwan**	**Coal**	77.2	961.55
24	**Argentina**	**Coal**	71.0	768.19
25	**Colombia**	**Coal**	35.0	1026.75
26	**Russia**	**Coal**	40.0	1130.67
27	**Northern South America**	**Coal**	55.0	1125.82
28	**Southern South America**	**Coal**	80.9	1054.59
29	**South Asia**	**Coal**	69.3	1107.11
30	**South Korea**	**Coal**	60.2	963.23
31	**Central Asia**	**Coal**	62.4	1305.74
32	**Eastern Europe**	**Coal**	37.4	1178.50
1	**United States**	**Gas**	60.0	537.49
2	**Canada**	**Gas**	36.0	575.18
3	**Japan**	**Gas**	55.1	617.10
4	**E.U. 12**	**Gas**	39.1	600.73
5	**E.U. 15**	**Gas**	52.6	579.19
6	**European Free Trade Association**	**Gas**	32.1	561.56
7	**Non-E.U.**	**Gas**	64.1	575.71
8	**Eastern Africa**	**Gas**	45.6	605.09
9	**Western Africa**	**Gas**	41.1	617.71
10	**Southern Africa**	**Gas**	43.7	591.25
11	**Northern Africa**	**Gas**	58.8	587.07
12	**Australia & New Zealand**	**Gas**	39.0	616.19
13	**Brazil**	**Gas**	44.1	511.39

14	**Central America & Brazil**	**Gas**	72.6	593.05
15	**South Africa**	**Gas**	66.8	773.92
16	**China**	**Gas**	46.7	616.73
17	**India**	**Gas**	71.5	648.63
18	**Indonesia**	**Gas**	53.3	589.00
19	**Mexico**	**Gas**	64.9	572.66
20	**Middle East**	**Gas**	54.7	552.87
21	**Pakistan**	**Gas**	54.2	704.80
22	**Southeast Asia**	**Gas**	73.6	550.94
23	**Taiwan**	**Gas**	61.8	614.93
24	**Argentina**	**Gas**	52.6	566.17
25	**Colombia**	**Gas**	26.0	602.99
26	**Russia**	**Gas**	69.6	595.91
27	**Northern South America**	**Gas**	41.0	581.29
28	**Southern South America**	**Gas**	59.0	623.57
29	**South Asia**	**Gas**	74.2	665.74
30	**South Korea**	**Gas**	70.1	586.83
31	**Central Asia**	**Gas**	47.7	594.17
32	**Eastern Europe**	**Gas**	71.4	771.50

Table A.2 | Historical mean regional capacity factors and carbon intensities for the Global Change Assessment Model (GCAM).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**Canada**	**Coal**	60.6	980.60
2	**United States**	**Coal**	69.9	934.15
3	**Mexico**	**Coal**	65.6	1064.39
4	**Central America**	**Coal**	87.1	973.54
5	**Brazil**	**Coal**	44.8	1086.58
6	**Rest of South America**	**Coal**	63.5	1029.26
7	**Northern Africa**	**Coal**	70.8	1159.96
8	**Western Africa**	**Coal**	77.0	1000.81
9	**Eastern Africa**	**Coal**	67.8	1037.15
10	**South Africa**	**Coal**	70.9	1148.14
11	**Western Europe**	**Coal**	54.7	1138.56
12	**Central Europe**	**Coal**	52.7	1286.39
13	**Turkey**	**Coal**	53.2	1013.20
14	**Ukraine**	**Coal**	37.4	1178.50
15	**Central Asia**	**Coal**	63.8	1346.54
16	**Russia**	**Coal**	40.0	1130.67
17	**Middle East**	**Coal**	73.2	970.34
18	**India**	**Coal**	73.2	1381.44
19	**Korea**	**Coal**	69.6	1006.86
20	**China**	**Coal**	47.5	1233.22
21	**Southeast Asia**	**Coal**	79.3	1057.99
22	**Indonesia**	**Coal**	69.7	974.05
23	**Japan**	**Coal**	68.6	1037.41
24	**Oceania**	**Coal**	63.1	1138.00

25	**South Asia**	**Coal**	56.1	978.14
26	**Southern Africa**	**Coal**	31.7	1152.84
1	**Canada**	**Gas**	36.0	575.18
2	**United States**	**Gas**	60.0	537.49
3	**Mexico**	**Gas**	64.9	572.66
4	**Central America**	**Gas**	72.6	593.05
5	**Brazil**	**Gas**	44.1	511.39
6	**Rest of South America**	**Gas**	47.3	590.27
7	**Northern Africa**	**Gas**	58.8	587.07
8	**Western Africa**	**Gas**	41.9	617.83
9	**Eastern Africa**	**Gas**	52.2	387.00
10	**South Africa**	**Gas**	66.8	773.92
11	**Western Europe**	**Gas**	52.5	578.99
12	**Central Europe**	**Gas**	35.3	604.89
13	**Turkey**	**Gas**	58.5	569.72
14	**Ukraine**	**Gas**	71.4	771.50
15	**Central Asia**	**Gas**	48.0	618.72
16	**Russia**	**Gas**	68.3	593.43
17	**Middle East**	**Gas**	56.2	550.03
18	**India**	**Gas**	71.5	648.63
19	**Korea**	**Gas**	70.1	586.83
20	**China**	**Gas**	48.2	616.56
21	**Southeast Asia**	**Gas**	73.5	553.71
22	**Indonesia**	**Gas**	54.5	583.11
23	**Japan**	**Gas**	55.1	616.26
24	**Oceania**	**Gas**	38.9	680.23
25	**South Asia**	**Gas**	79.4	680.47

26	**Southern Africa**	**Gas**	39.1	607.10

Table A.3 | Historical mean regional capacity factors and carbon intensities for the Integrated Model to Assess the Global Environment (IMAGE).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**Sub-Saharan Africa**	**Coal**	65.1	1136.42
2	**Centrally Planned Asia and China**	**Coal**	47.4	1233.33
3	**Central & Eastern Europe**	**Coal**	52.7	1286.02
4	**Former Soviet Union**	**Coal**	44.1	1180.68
5	**Latin America & the Caribbean**	**Coal**	65.3	1041.15
6	**Middle East and North Africa**	**Coal**	77.0	1065.15
7	**North America**	**Coal**	68.5	935.79
8	**Pacific OECD**	**Coal**	66.7	1074.93
9	**Other Pacific Asia**	**Coal**	75.4	981.73
10	**South Asia**	**Coal**	72.9	1375.51
11	**Western Europe**	**Coal**	54.8	1116.81
1	**Sub-Saharan Africa**	**Gas**	43.3	624.30
2	**Centrally Planned Asia and China**	**Gas**	52.6	598.52
3	**Central & Eastern Europe**	**Gas**	37.1	603.31
4	**Former Soviet Union**	**Gas**	67.1	616.42
5	**Latin America & the Caribbean**	**Gas**	63.9	574.81
6	**Middle East and North Africa**	**Gas**	56.8	558.52
7	**North America**	**Gas**	56.2	539.71

8	**Pacific OECD**	**Gas**	48.7	616.74
9	**Other Pacific Asia**	**Gas**	65.6	573.46
10	**South Asia**	**Gas**	76.5	668.59
11	**Western Europe**	**Gas**	54.7	578.44

Table A.4 | Historical mean regional capacity factors and carbon intensities for the Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE-GLOBIOM).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**China**	**Coal**	47.2	1235.85
2	**India**	**Coal**	73.2	1381.44
3	**Japan**	**Coal**	68.6	1037.41
4	**United States**	**Coal**	69.9	934.15
5	**Russia**	**Coal**	40.0	1130.67
6	**Sub-Saharan Africa**	**Coal**	47.9	1102.10
7	**Members of the E.U.**	**Coal**	52.5	1233.37
8	**Latin America**	**Coal**	65.3	1041.15
9	**Middle East & North Africa**	**Coal**	65.7	1306.58
10	**Other Asian Countries**	**Coal**	71.1	1004.96
11	**Rest of the World**	**Coal**	58.0	1134.89
1	**China**	**Gas**	46.7	616.73
2	**India**	**Gas**	71.5	648.63
3	**Japan**	**Gas**	55.1	617.10
4	**United States**	**Gas**	61.0	537.49
5	**Russia**	**Gas**	69.6	595.91
6	**Sub-Saharan Africa**	**Gas**	41.5	613.38
7	**Members of the E.U.**	**Gas**	51.0	581.59
8	**Latin America**	**Gas**	63.9	574.81
9	**Middle East & North Africa**	**Gas**	55.8	562.53

10	**Other Asian Countries**	**Gas**	71.4	612.05
11	**Rest of the World**	**Gas**	56.1	618.72

Table A.5 | Historical mean regional capacity factors and carbon intensities for the Regionalized Model of Investments and Development (REMIND).

	Region	Hydrocarbon	Capacity Factor (%)	Carbon Int. (gCO2/kWh)
1	**Canada, Japan, & New Zealand**	**Coal**	65.3	1028.22
2	**China**	**Coal**	47.3	1232.84
3	**East Asia**	**Coal**	71.3	1012.34
4	**India**	**Coal**	73.2	1381.44
5	**Korea, Australia & South Africa**	**Coal**	76.9	1086.90
6	**Mexico, Caribbean, & Latin America**	**Coal**	65.3	1041.15
7	**Middle East & North Africa**	**Coal**	77.0	1065.15
8	**Eastern Europe (EU12+EITs)**	**Coal**	52.3	1256.96
9	**Western Europe (EU15 +EFTA)**	**Coal**	54.7	1138.56
10	**South Asia**	**Coal**	56.1	978.14
11	**Sub-Saharan Africa**	**Coal**	53.4	1108.84
12	**Transition Economies**	**Coal**	46.3	1197.42
13	**United States**	**Coal**	69.9	605.83
1	**Canada, Japan, & New Zealand**	**Gas**	50.3	616.56
2	**China**	**Gas**	48.2	565.69
3	**East Asia**	**Gas**	65.7	648.63
4	**India**	**Gas**	71.5	614.79
5	**Korea, Australia & South Africa**	**Gas**	45.8	574.81

6	**Mexico, Caribbean, & Latin America**	**Gas**	63.9	558.52
7	**Middle East & North Africa**	**Gas**	56.8	602.26
8	**Eastern Europe (EU12+EITs)**	**Gas**	38.7	579.03
9	**Western Europe (EU15 +EFTA)**	**Gas**	52.4	680.23
10	**South Asia**	**Gas**	79.4	613.38
11	**Sub-Saharan Africa**	**Gas**	41.5	608.13
12	**Transition Economies**	**Gas**	69.1	537.49
13	**United States**	**Gas**	60.0	605.83

Table A.6 | Historical mean regional capacity factors and carbon intensities for the World Induced Technical Change Hybrid (WITCH).

SSP	Challenges	Qualitative Assumptions	IAM Marker
1	Low for mitigation Low for adaptation	Energy resource efficiency, high development, reduced carbon intensity, sustainable production methods and human, development	IMAGE
2	Middle of the road	Historical trends in energy development	MESSAGE-GLOBIOM
3	High for mitigation High for adaptation	Moderate economic growth, rapid human population growth, low technological advancements in the energy sector, global trade is low, inequality is high, and low investments in human wellbeing	AIM/CGE
4	Low for mitigation High for adaptation	Rapid technological advances in key regions and low advances in developing areas, inequality remains high, economies are isolated.	GCAM
5	High for mitigation Low for adaptation	Carbon based fuel demand is high, large investments in human capital, social inequality is low, slower population growth.	REMIND-MAgPIE

Table A.7 | Shared Socioeconomic Pathway Narrative Summary. The Shared Socioeconomic Pathways (SSPs) have inherent attributes that allow researchers to explore various plausible trajectories of human development. Presented here are the five reference Integrated Assessment Models whose quantitative baseline most replicates one of the SSPs. WITCH was not assigned as reference IAM, nonetheless all IAMs teams, including WITCH, were able to replicate some of the SSPs based on the radiative forcing objective.

APPENDIX B.

SUPPLEMENTARY MATERIAL FOR CHAPTER 3.

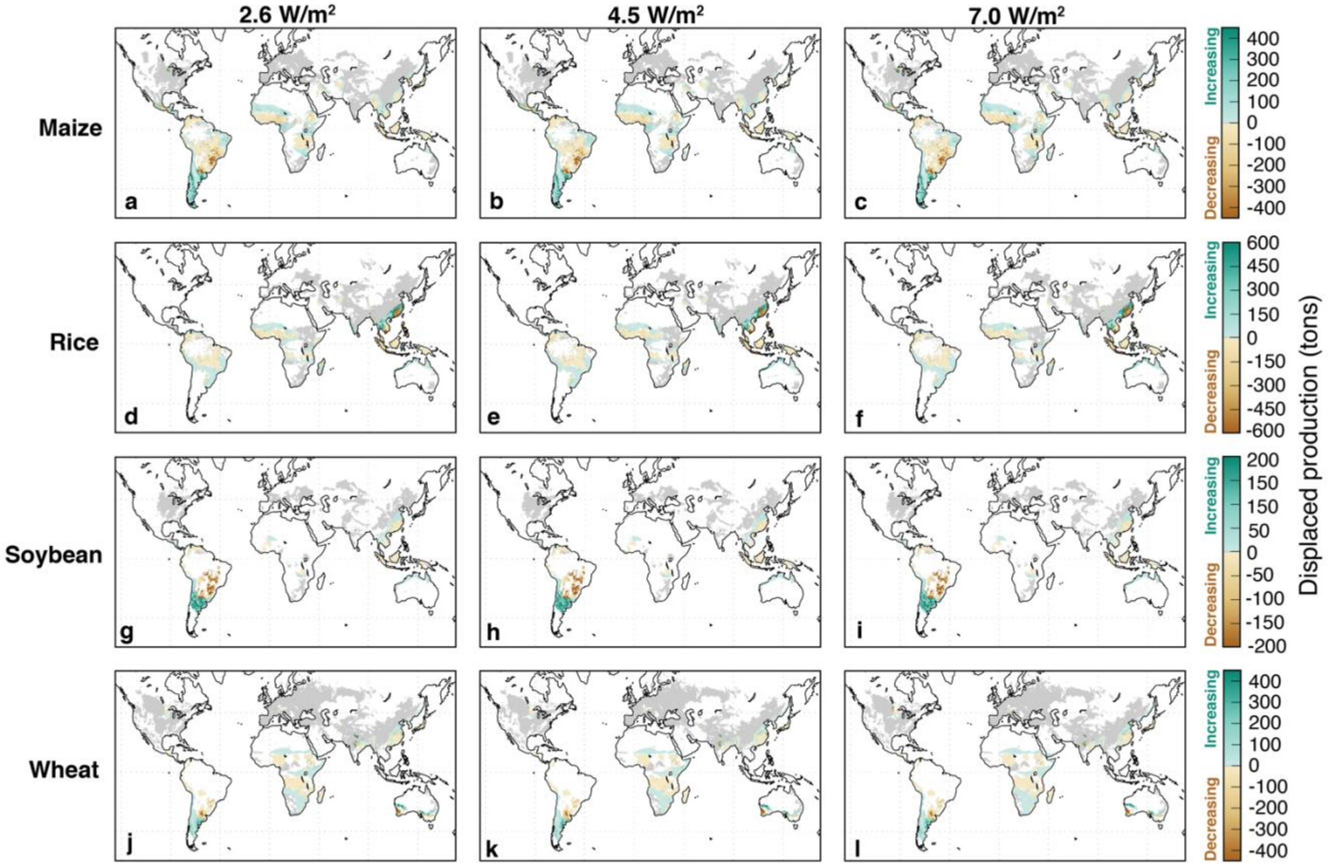

Fig. B.1 | Potential crop migration due to changes in growing season precipitation. Brown and green shading indicate areas of outmigration and new cultivation, respectively, with darker colors showing the magnitude of production affected in tons and gray shading shows currently cultivated areas where both the temperature and precipitation remain within crops' historical range.

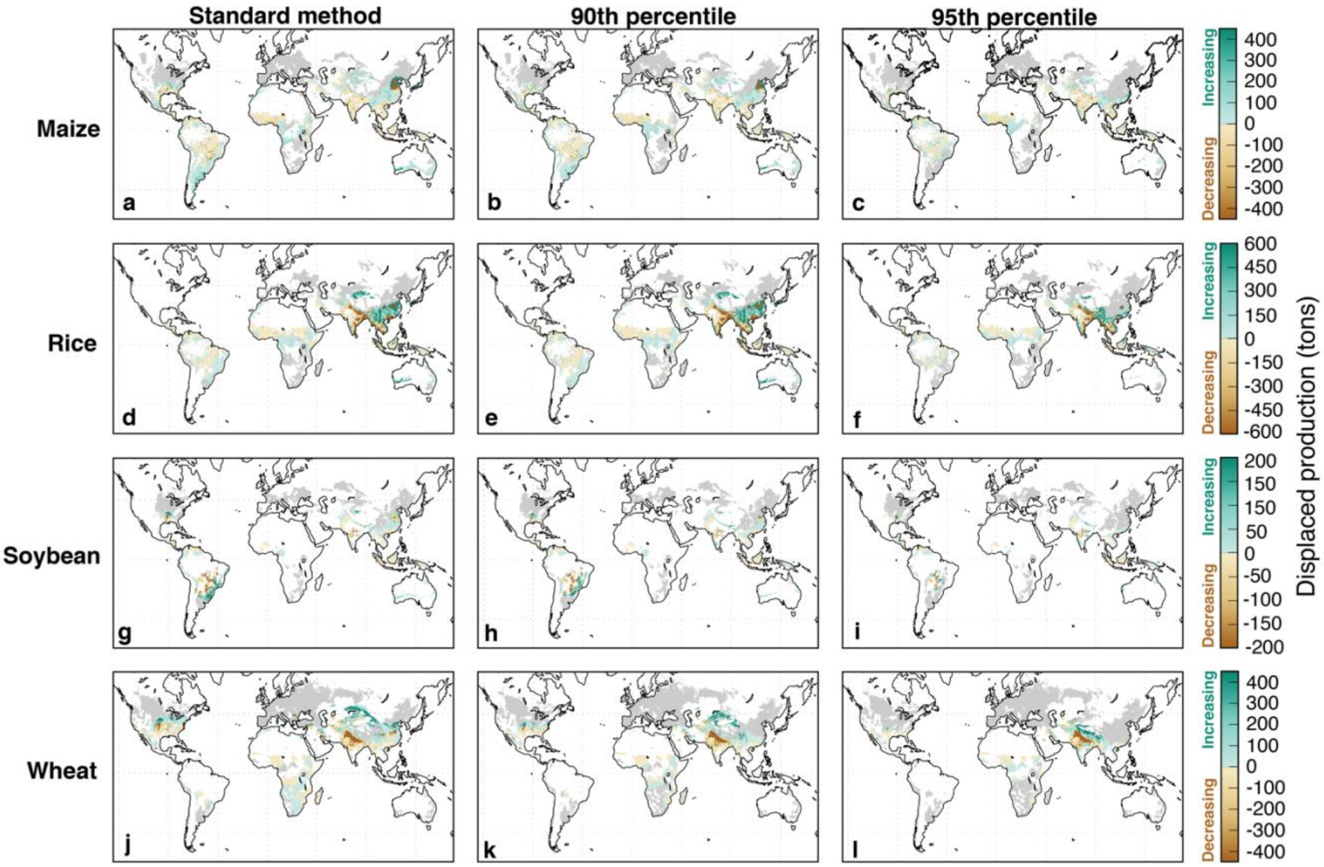

Fig. B.2 | Potential crop migration under different temperature bounds. Crop temperature bounds are set using the cumulative density function's upper inflection point, 90th percentile, and 95th percentile using mean growing season temperatures. Brown and green shading indicate areas of outmigration and potential future cultivation, respectively, under a 4.5 W/m^2 climate warming scenario.

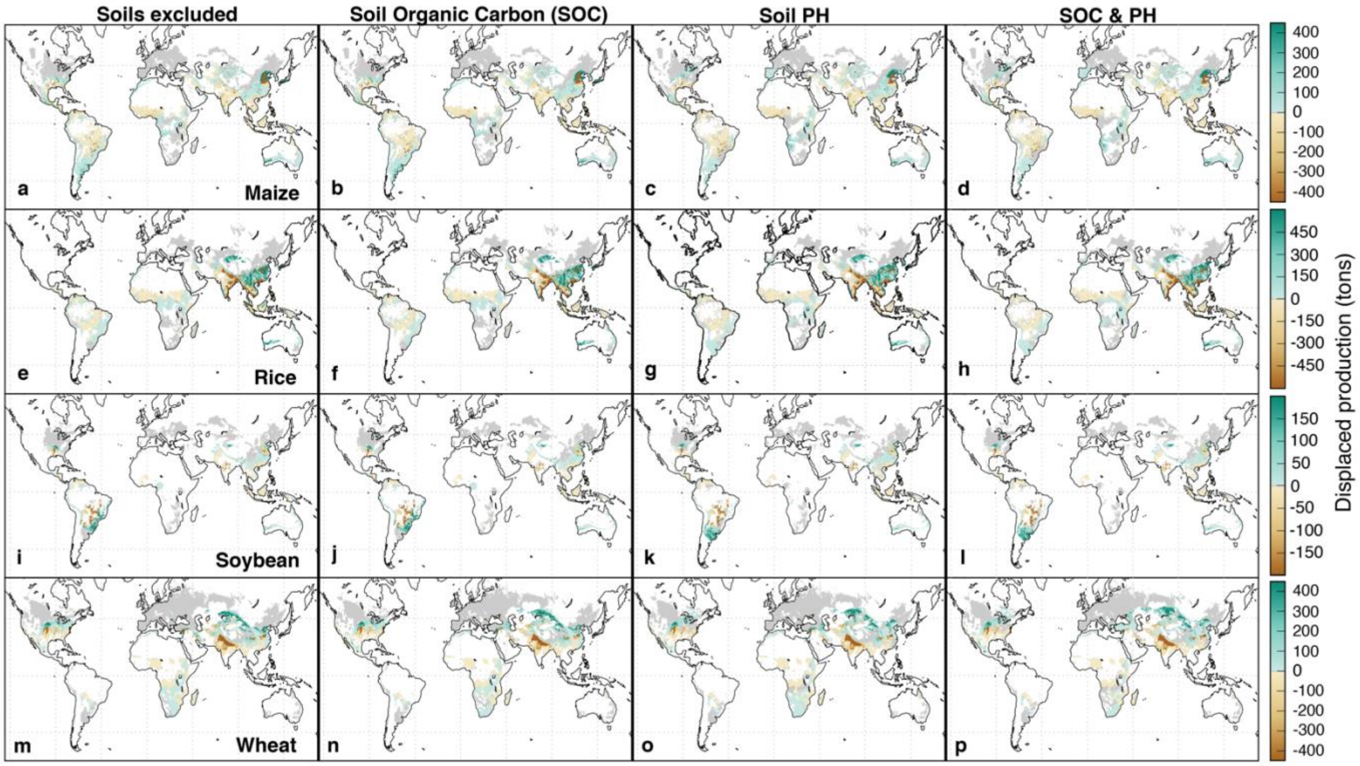

Fig. B.3 | Potential crop migration soil properties comparison. Displaced crop production due to changes in mean growing season temperature under the ssp2 - 4.5W/m^2 scenario. The first column only tests temperature effects on crop displacement while the following three columns shows newly cultivated regions where the nearest areas with suitable temperatures and soils from where crops are initially displaced.

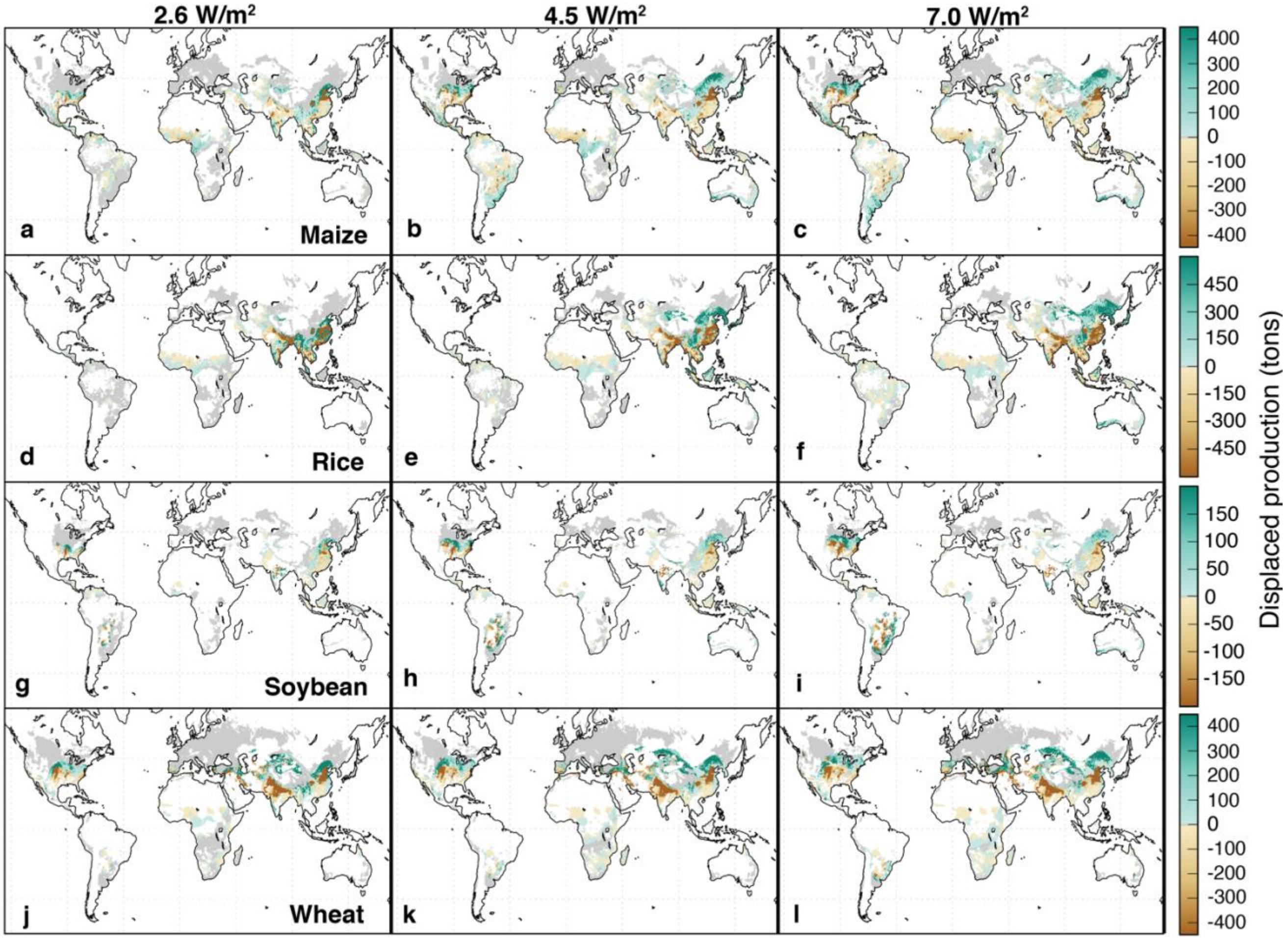

Fig. B.4 | Potential crop migration due to changes in growing season temperature extremes. Crop cultivation migrates further towards the poles when changes in growing season extremes are considered (i.e., changes in the 95th percentile within the growing season). Brown and green shading indicate areas of outmigration and potential future cultivation, respectively, under a 4.5 W/m^2 climate warming scenario.

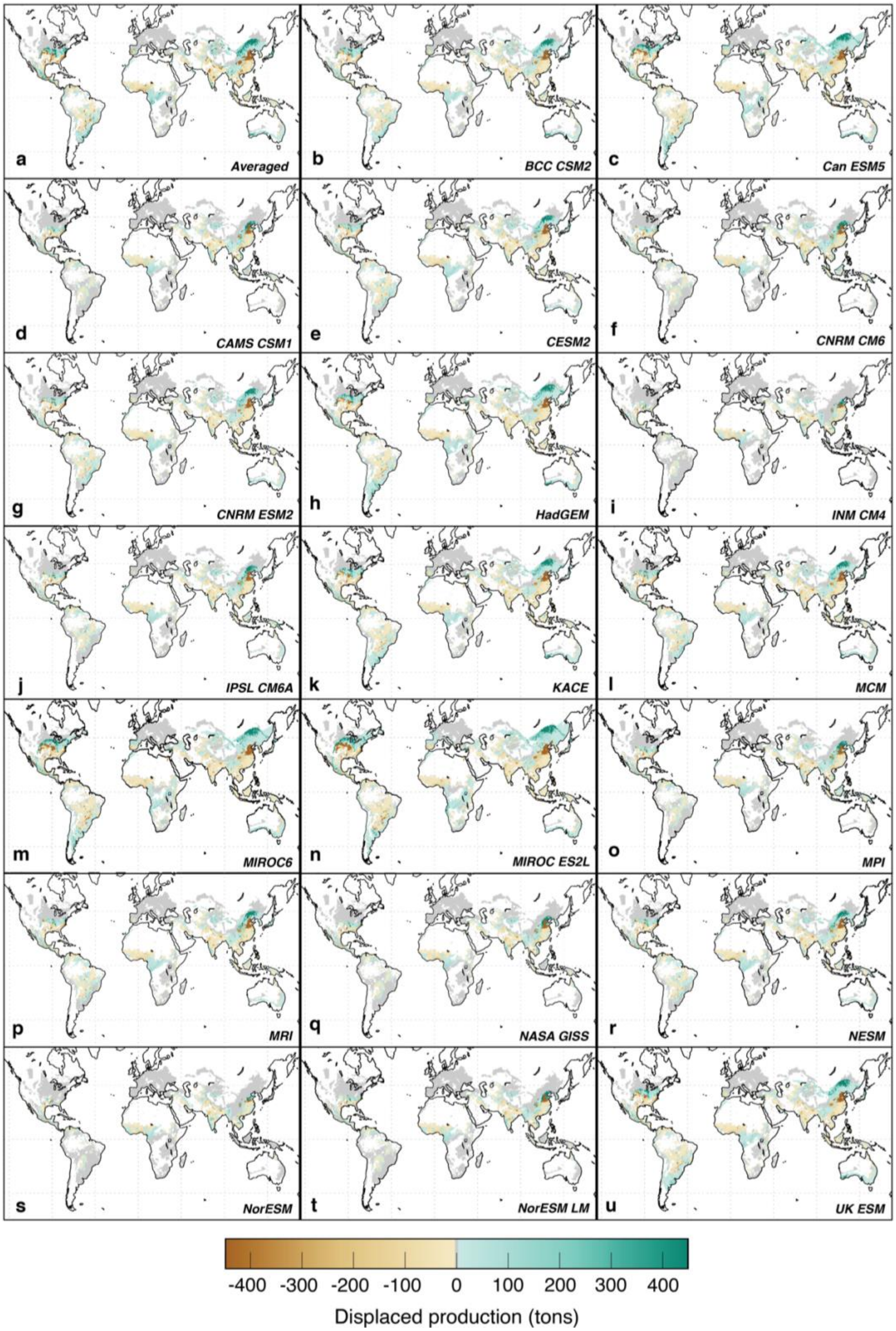

Fig. B.5 | Maize migration due to changes in growing season temperature extremes in a 4.5 W/m^2 scenario.

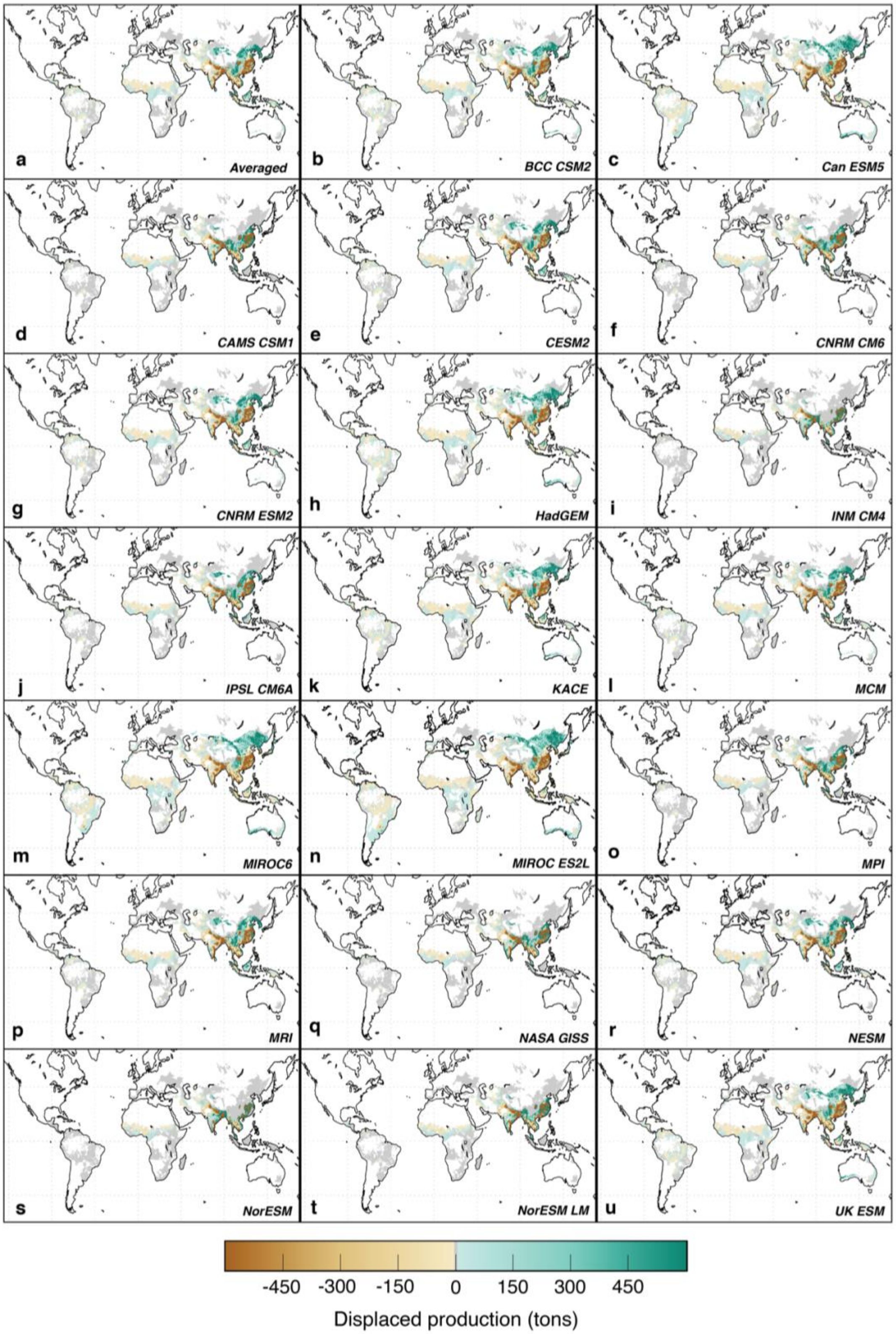

Fig. B.6 | Rice migration due to changes in growing season temperature extremes in a 4.5 W/m^2 scenario.

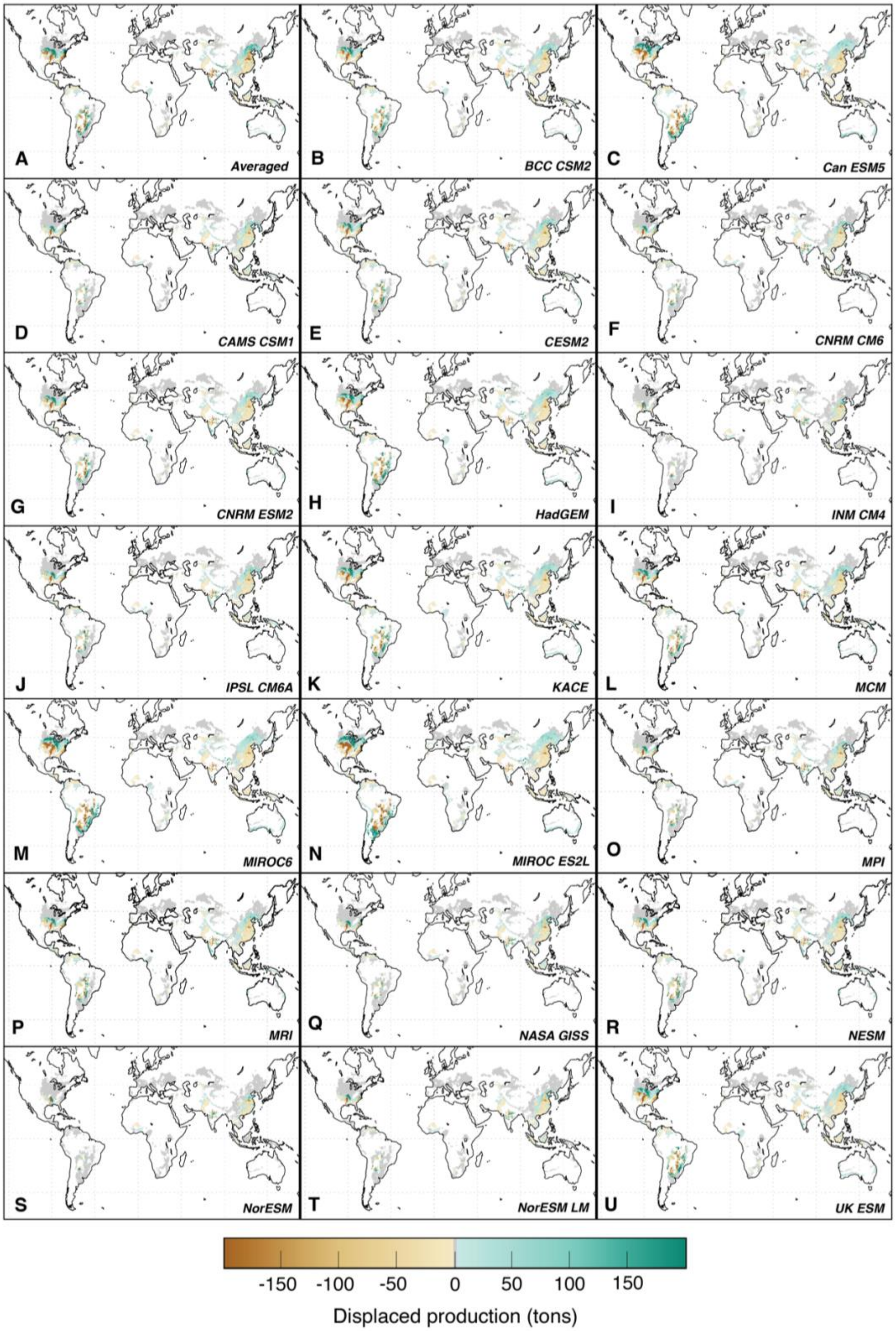

Fig. B.7 | Soybean migration due to changes in growing season temperature extremes in a 4.5 W/m^2 scenario.

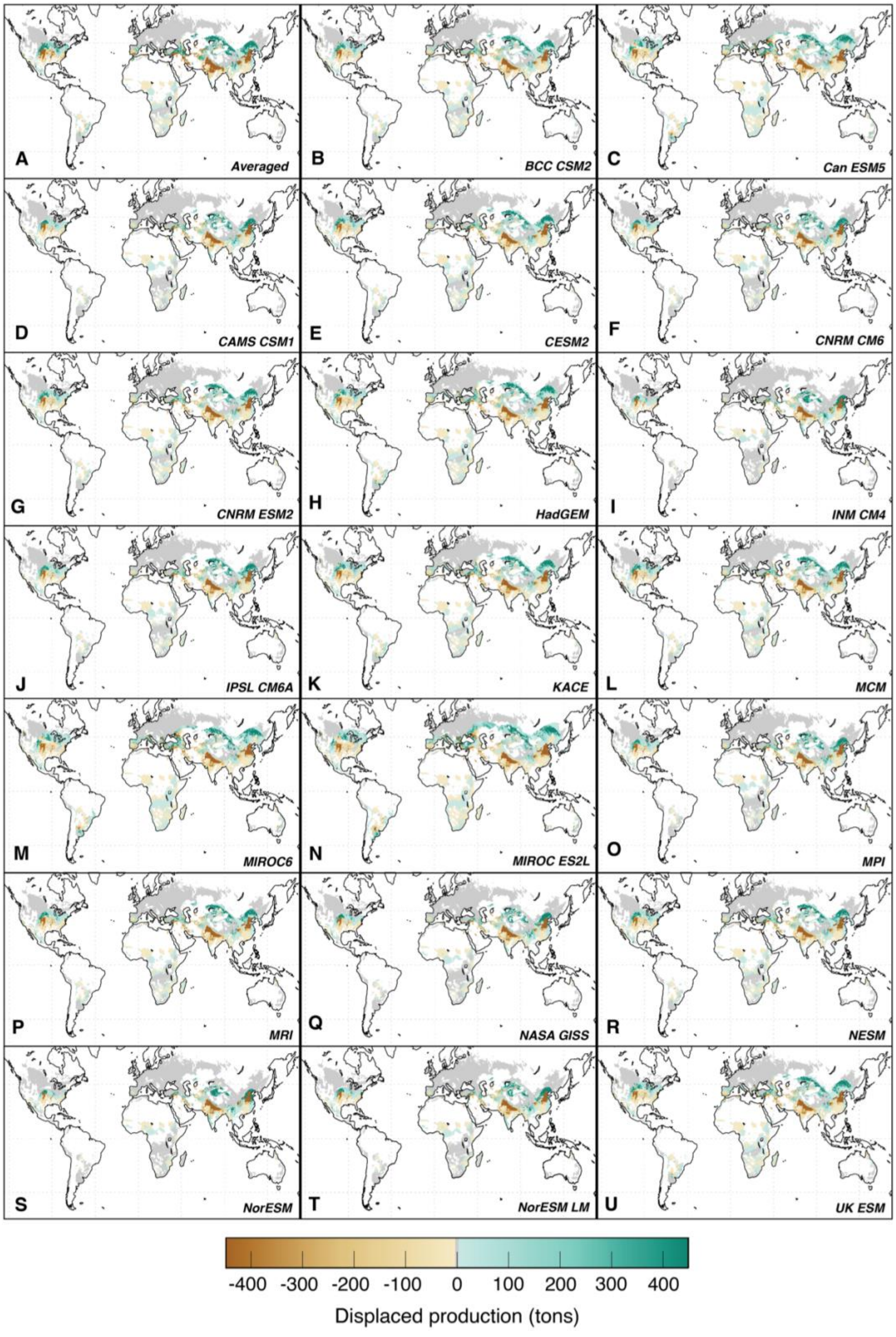

Fig. B.8 | Wheat migration due to changes in growing season temperature extremes in 4.5 W/m2 scenarios

APPENDIX C.

SUPPLEMENTARY MATERIAL FOR CHAPTER 4.

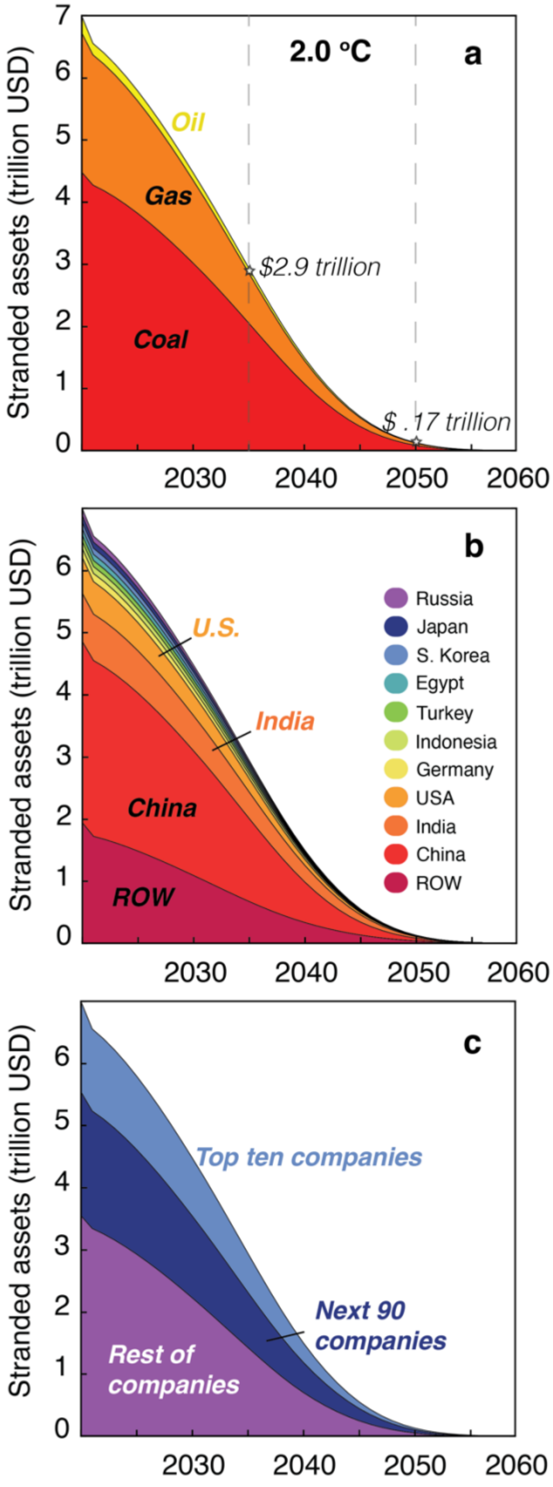

Figure C.1 | Annual stranded assets under a 2.0ºC temperature target.

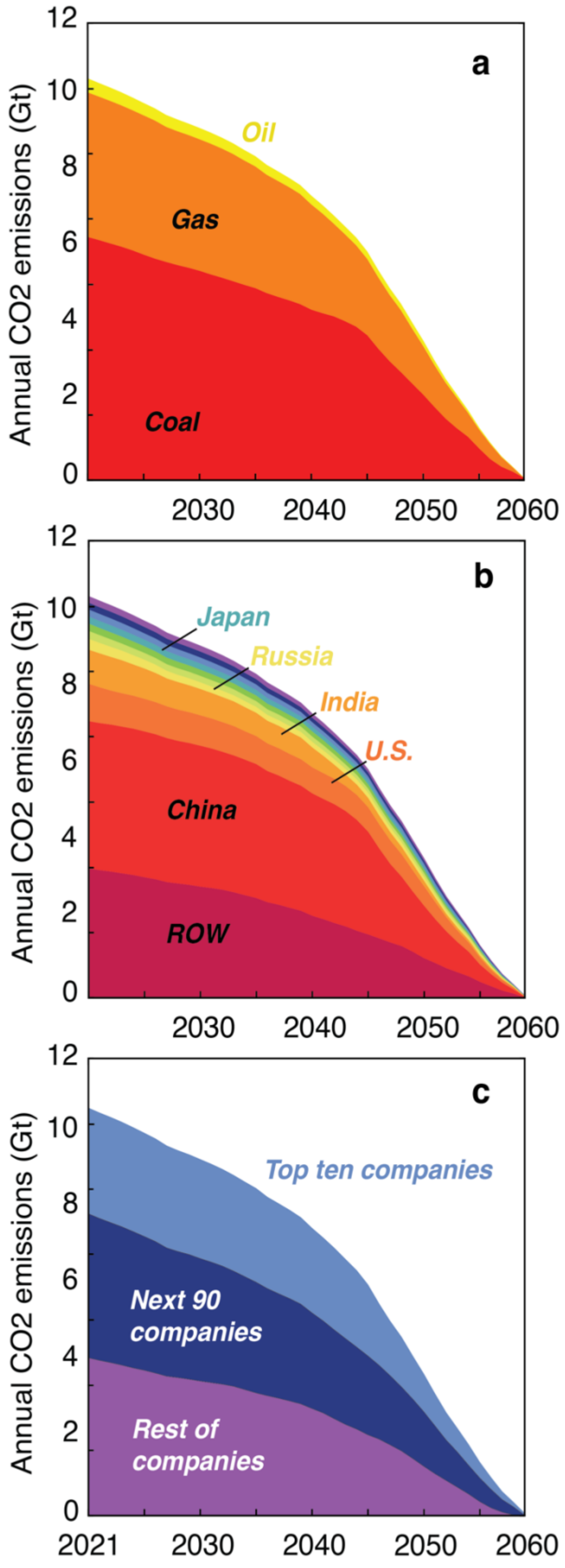

Figure C.2 | Annual CO_2 emissions from existing power plants.