ENVIRONMENTAL RESEARCH
LETTERS

PURPOSE-LED PUBLISHING™
Celebrating the 20th anniversary of Environmental Research Letters

LETTER • **OPEN ACCESS**

Long-term global and regional GDP implications of heat stress on crops and labor

To cite this article: Di Sheng *et al* 2026 *Environ. Res. Lett.* **21** 164025

View the article online for updates and enhancements.

You may also like

- Autler–Townes splitting in Rydberg atoms: transition dipole matrix element extraction and field efficiency analysis
Brian C Holloway, Gavin M Chase, Lee E Harrell et al.
- ICRH modelling of DTT in full power and reduced-field plasma scenarios using full wave codes
A Cardinali, C Castaldo, F Napoli et al.
- Application of ANN for the early detection of anomalous conditions in refractory-lined structures: a case study on the blast furnace blowpipe
S Tewary, A Ghosh, Usha Yenni et al.

This content was downloaded from IP address 84.113.107.231 on 07/09/2026 at 08:23

ENVIRONMENTAL RESEARCH
LETTERS

Check for updates

OPEN ACCESS

RECEIVED
1 February 2026

REVISED
8 June 2026

ACCEPTED FOR PUBLICATION
6 August 2026

PUBLISHED
28 August 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

LETTER

Long-term global and regional GDP implications of heat stress on crops and labor

Di Sheng[1,2,*], **Jae Edmonds**[1,*], **Xin Zhao**[1], **Pralit Patel**[1], **Stephanie Morris**[1], **Kalyn Dorheim**[1], **Christoph Bertram**[1,3] **and Allen Fawcett**[1]

[1] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, United States of America
[2] International Institute for Applied Systems Analysis, Laxenburg, Austria
[3] Center for Global Sustainability (CGS), School of Public Policy, University of Maryland, College Park, MD, United States of America
[*] Authors to whom any correspondence should be addressed.

E-mail: sheng@iiasa.ac.at and jae@pnnl.gov

Keywords: heat stress, GDP, agriculture, crop yield, labor productivity

Supplementary material for this article is available online

Abstract

While extensive evidence documents large physical impacts from extreme weather, empirical estimates of macroeconomic responses are often modest. This disconnect calls for stronger integration across Earth system science, impact research, and economic modeling. In this study, we advance the integration of these three dimensions within a global, multisector dynamic model to examine how heat-induced biophysical shocks in agriculture propagate through the economy. By deriving biophysical responses from emission-driven atmospheric projections, our framework links economic activity, emissions, atmospheric change, biophysical impacts, and economic responses in an internally consistent way. Under a business-as-usual future, and conditional on the selected biophysical response functions and model structure, agricultural heat stress reduces global GDP by approximately 1% by 2100, with losses reaching up to 3% in tropical regions. While heat stress directly affects both crop yields and labor productivity, macroeconomic losses associated with labor heat stress are larger than those associated with crop heat stress. To offset heat-induced labor productivity losses, roughly 79 million workers who could otherwise transition to higher-paying non-agricultural sectors remain in agriculture in 2100, slowing structural transformation and disproportionately reducing GDP in tropical regions. Overall, agricultural heat stress reduces agricultural output, raises food prices and shifts agricultural production toward temperate regions. These findings complement empirically estimated damage functions by revealing the transmission pathways through which biophysical shocks shape broader macroeconomic outcomes, highlighting the value of integrating Earth system and economic processes within a consistent emissions-driven framework.

1. Introduction

A well-recognized gap remains between the extensively documented large micro-level biophysical effects of warming and the mild corresponding macroeconomic consequences [1, 2]. This gap calls for stronger integration across Earth system science, impact research, and economic modeling [3, 4]. Shifts in atmospheric conditions, like temperature and precipitation, pose substantial risks to economy [2, 5–9], particularly agricultural sector [10–13]. Given agriculture's pronounced sensitivity to atmospheric conditions and its central role in food systems and economic development [14, 15], it is critical to investigate the economic implication of long-term uncertainty in atmospheric conditions in agriculture.

Agriculture is particularly sensitive to atmospheric conditions through two key biophysical channels, crop yield and labor productivity. There is a rich literature assessing the sensitivity in crop yield to temperature [16, 17], precipitation [18, 19] and elevated atmospheric CO_2 [10, 20]. In parallel, there is a growing body of literature investigating how labor productivity responds to the heat stress [11, 21–24], mainly driven by four ambient factors, temperature, humidity, wind speed and radiation [25, 26].

© 2026 The Authors and Battelle Memorial Institute. Published by IOP Publishing Ltd. Contribution of US Government authors is not subject to copyright in the USA.

Agricultural labor is particularly vulnerable to heat stress due to the high work intensity and the outdoor working environment. While biophysical crop yield responses have long been incorporated into impact analyses of future atmospheric conditions on agriculture and economic outcomes, biophysical labor productivity responses have only recently begun to be included [23, 24, 27].

Previous studies [23, 24] that investigate the macroeconomic responses to agricultural heat stress considering both crop and labor impact relied on a static-economy framework, which does not capture long-term structural dynamics, featured by shifts of labor out of agriculture and sustained growth in labor productivity. These dynamics are not only central to economic development [28] but also influence patterns of heat exposure in agricultural labor [27, 29]. Incorporating these dynamics can help build a more comprehensive understanding of the economic implications of agricultural heat stress. In addition, previous studies (table S1) adopted established Representative Concentration Pathways or a selected increase of global mean temperature level to prescribe future atmospheric conditions and simulate biophysical impacts. However, the specified pathways might not align with the emissions generated from the underlying economic activities.

Here, we build on recent advancements in the Global Change Analysis Model (GCAM), which captures long-term interactions across multiple sectors of the economy and implements consistent biophysical shocks from agricultural heat stress by adopting atmospheric projections based on the model's emissions outcomes (figure 1). Our framework captures the feedback loop from economic activity to emissions, atmospheric conditions, biophysical impacts, and economic responses, ensuring internal consistency across these components. In doing so, our results complement empirically estimated damage functions by illustrating how biophysical shocks propagate across sectors and regions through endogenous market responses.

2. Methods

To align with growing advocacy for emission driven atmospheric projections [30] and ensure consistency between the emissions generated by economic activities and the associated biophysical impacts, we adopt the Hector-STITCHES-basd three-model suite which emulates Earth System Models' (ESMs) atmospheric variable projections, driven by emissions from the GCAM reference scenario (table S2). The main results presented in this study are based on the configuration emulating a moderate ESM, MRI-ESM2-0. For reporting purposes, GCAM regions are aggregated to the Sixth Assessment Report (AR6) 10 regions (table S3) for some plots, and GCAM crops are grouped into key and other crops (table S4). Unless stated otherwise, results refer to the year 2100, and monetary values are reported in constant 2015 USD.

We design a suite of experiments (figure S1) that feature alternative representations of agricultural heat stress and evaluate their macroeconomic implications by comparing outcomes across these experiments. Recent advancements in GCAM enable the implementation of heterogeneous heat stress impacts on regional crop yield and labor productivity across agricultural commodities and production technologies, while also capturing labor and investment competition between agricultural and non-agricultural sectors. GCAM calculates GDP using the income method and the expenditure method, where the former measures the total returns to production factors, i.e. labor, capital, and land, and the latter aggregates the total spending on new, final consumption by households and government, investment and net exports. Together, these features provide complementary perspectives on the macroeconomic responses to agricultural risk.

2.1. GCAM overview

GCAM is a dynamic-recursive, economic model that integrates human and physical Earth systems. The human system consists of four main modules macroeconomy, energy, agriculture and land use, and water. GCAM is open-sourced, with source code, data system, and documentation available online at https://github.com/JGCRI/gcam-core/releases. This study builds on a recent extension of GCAM that incorporates macroeconomic feedback [31] and integrates the agricultural labor and capital market modeling [28] to enable two-way coupling between the agricultural sector and the broader economy (figure S2, supplementary methods S1.1.3). The model is calibrated so that it produces outputs that align the observed data in 2015, and runs at 5 year time steps with a time horizon of 2100 driven by exogenous socioeconomic drivers. It is global in scope with 32 geopolitical regions that interact through international trade.

GCAM takes population, labor productivity growth, resource and technology availability, and policies as exogenous inputs. It produces conditional projections of GDP, detailed market dynamics for energy, agriculture and water markets. GCAM uses a discrete-choice logit framework to determine market shares among competing technologies, and economic agents are assumed to be motivated by profits.

Land use decisions are determined endogenously through a nested logit structure and relative profitability among alternative land uses (supplementary methods S1.1.4). Land-use decisions therefore evolve dynamically in response to changes in commodity prices, yields, carbon prices, bioenergy demand, and

technological change, allowing GCAM to capture interactions among energy-land-water nexus.

Similarly, the model also adopts a logit-structure to endogenously allocate the regional labor force among sectors according to relative wages rate (supplementary methods S1.1.1). Sectoral wage rates are determined through market clearing between labor supply and sectoral labor demand. Through the labor competition with a fixed labor force, labor shocks in one sector propagate through the broader economy.

The savings-investment markets are also connected in GCAM (supplementary methods S1.1.4). Investment demand reflects the capital required across all technologies in all sectors and responds to the price of capital. Savings are modeled as a function of income and exogenously prescribed net foreign capital inflow, which gradually decline to zero by 2035. The equilibrium price of capital adjusts to balance the supply and demand of investment.

Producers pay households and governments to utilize labor, capital, and land for economic production. Total return to factors generates the nation's income, which is then allocated to new, final goods and services, investment, and net exports.

2.2. Long-term atmospheric conditions

To generate atmospheric projections that are internally consistent with socioeconomic assumptions, we leverage a set of tools: ***Hector*** [32, 33], a Reduced Complexity Model of the Earth System Model (RCM); ***STITCHES*** [34, 35], a spatially explicit multivariate ESM emulator; and ***basd*** (https://github.com/JGCRI/basd), a bias correction and spatial downscaling tool inspired by the ***ISIMIP3BASD*** [36]. ***Hector*** can operate as a stand-alone model and has served as the physical Earth system representation for GCAM since 2015. During a GCAM run, emissions for 23 species are passed from GCAM to Hector. Hector uses these emissions to compute changes in atmospheric composition, terrestrial and ocean carbon sinks. Ultimately, these changes alter the Earth's radiative forcing energy balance, resulting in changes in total radiative forcing and global temperature. To capture the uncertainty spread in future global temperature demonstrated by the Coupled Model Intercomparison Project Phase 6 (CMIP6) ESMs, Hector was parameterized to emulate CanESM5, MRI-ESM2-0, and NorESM2-MM. These CMIP6 ESMs were selected as representatives of warm, moderate, and cool CMIP6 ESMs, respectively. Hector total radiative forcing and global mean air temperature results driven with GCAM emissions are shown in figures S10 and S11. The resulting global mean surface temperature trajectories are then used as inputs to STITCHES to generate atmospheric projections consistent with selected CMIP6 ESMs. The output from STITCHES is subsequently processed by basd, which performs bias correction and statistical downscaling to a 0.5° spatial resolution, producing high-resolution atmospheric projections suitable for our analysis.

2.3. Biophysical changes in crop yield and labor productivity

We employed two open-source R packages to quantify the biophysical impacts of future atmospheric conditions on crop yields (supplementary methods S1.2) and labor productivity (supplementary methods S1.3). Both packages integrate gridded atmospheric projections with spatially explicit crop calendar and harvested area data to produce annual, crop-specific estimates of heat-induced biophysical shocks. The **gaia** package [37, 38] estimates annual country-level yield shocks for 12 major crops, by first empirically deriving nonlinear crop yield responses for each crop and irrigation practice using historical relationships between annual crop yields and growing-season minimum, mean, and maximum temperature and precipitation. These estimated relationships are then applied to crop-area-weighted growing-season atmospheric projections based on country- and crop-specific crop calendars to generate annual country-level yield shocks. The resulting yield shocks are smoothed over rolling 20 year periods and combined with GCAM's region-basin-crop-technology level-yield growth rate projections to generate new projected crop productivity under future atmospheric conditions. The **HELPS** package [39] uses changes in surface air temperature, relative humidity, and surface downwelling shortwave radiation to approximate the changes in wet-bulb globe temperature, which is a widely used indicator to represent human heat stress exposure [40]. A nonlinear labor-heat response function from literature [22] is then applied to estimate heat-induced labor productivity losses. The HELPS package aggregates gridded labor productivity shocks to the GCAM water-basin level, and the resulting annual estimates are then smoothed over rolling 20 year periods for model integration. Both crop and labor responses are derived from fine temporal and spatial resolution atmospheric projections that capture extreme heat conditions but are aggregated to annual scales because economic activities and land-use decisions typically operate on annual or longer timescales and are subsequently smoothed over 20 year periods to emphasize long-term trends. We explicitly incorporate country- and crop-specific growing calendars together with harvested-area weighting during the temporal and spatial aggregation process to align the estimated biophysical responses with the most relevant growing conditions represented by the available data.

2.4. Technological change and adaptation

In GCAM, we incorporate adaptation through both exogenous productivity improvements and endogenous technological adjustment. Specifically, the

model includes baseline regional agricultural labor productivity growth trajectories, which implicitly capture technological progress such as mechanization, capital intensification and improved farm management. As a result, agricultural labor intensity declines over time. In addition, we represent alternative agricultural production technologies across crop types with different labor and capital intensities, irrigation practices, and fertilizer applications, allowing endogenous adaptation through technology switching and shifts in crop mix, governed by the relative profitability via a logit structure.

3. Results

3.1. Agricultural heat stress disproportionately reduces tropical GDP

Under the Reference radiative forcing (~7.46 W m^{-2} in 2100), global agricultural labor productivity is projected to decrease by 6% by 2050 and 15% by 2100 (figure S3). Aggregated global crop yields are projected to decrease by 3% by 2050 and by 5% by 2100 (figure S3). Biophysical labor productivity responses, mainly concentrated in tropical regions, show wider ranges compared to biophysical crop yield responses (figure 2(a)). Agricultural labor productivity in Indonesia (−28%), Southeast Asia (−18%), India (−18%), and Western Africa (−17%) are the most impacted by heat stress by 2100.

By the end of the century, agricultural heat stress is projected to reduce global GDP by 1%, with the highest regional losses in India (4%), Indonesia (4%), and Africa (2%) (figure 2(b)). Within our modeling framework, labor heat stress alone generally produces larger GDP responses than crop heat stress across most regions (figure 2(c)). Notably, GDP responses with combined agricultural heat stress are larger than the sum of GDP responses to crop heat stress and labor heat stress individually in most regions, implying nonlinear interactions between crop and labor heat stresses. The overall economic impact of agricultural heat stress intensifies over time (figure 2(d)), driven by the increasing biophysical shocks (figure S3).

Interestingly, we observe modest GDP gains in North America, the Reforming Economies, and Latin America in the long-term. In the global north, relatively lower exposure to agricultural heat stress gains these regions relative advantage in agricultural productivity and trade competitiveness, supporting economic growth. In Latin America, the GDP increase is primarily driven by higher sugar crop revenues, where rising prices outweigh local productivity losses from heat stress. These results underscore that the economic implications of agricultural heat stress are shaped not only by local biophysical impacts, but also by comparative advantages and international trade.

3.2. Responses in input markets to agricultural heat stress

Economic activity relies on the use of labor, capital, and land in production. GDP can be calculated as returns to these primary inputs (factors), which sum up to gross value added. In this section we examine how the factor markets respond to the modeled biophysical heat stress in agriculture and their implications for GDP.

Within our modeling framework, agricultural heat stress increases value added in the agricultural sector while declining value added in the non-agricultural sector (figure 3(a)). By the end of the century, relative to the Reference scenario, global returns to agricultural labor and capital are projected to be higher by 791 billion dollars and 21 billion dollars, respectively. In contrast, returns to agricultural land decrease by USD 140 billion dollars, and returns to non-agricultural capital and labor fall by 1558 billion dollars and 2384 billion dollars, respectively.

Heat-induced labor productivity loss in the agriculture sector necessitates a larger agricultural workforce in agricultural production (figure 3(b)). By the end of the century, global agricultural employment under heat stress is 79 million people (14%) higher than in the Reference scenario, raising agriculture's share of total employment by 2 percentage points. The 14% increase in the agricultural labor force helps offset the 15% decline in labor productivity, resulting in only a 2% reduction in effective agricultural labor at the global level. With labor productivity loss, more capital is drawn to agriculture sector to substitute for labor and increases demand for agricultural investment (figure S4).

The largest absolute and relative increases in agricultural employment are projected for Africa (42 million people, 13%), South Asia (23 million people, 18%), and Southeast Asia (8 million people, 14%) (figures 3(c) and (d)). Effective agricultural labor reductions in Indonesia (−12%), Southeast Asia (−11%), and Western Africa (−2%) are much smaller than the biophysical labor productivity loss.

When agricultural heat stress reduces agricultural labor productivity, more labor is required to satisfy relatively inelastic food demand compared to the Reference scenario. Therefore, the agricultural heat stress weakens the labor-push effect and intensifies the labor competition between agriculture and the rest of the economy, leading to higher wage rates in both sectors (figure S5(a)). Although agricultural wages remain lower than non-agricultural wages in absolute terms, the increased demand for agricultural labor narrows the inter-sectoral wage gap and weakens the labor-pull effect toward non-agricultural sectors. Consequently, agricultural heat stress slows the long-term process of structural transformation, with 79 million more workers remaining in agriculture in 2100 relative to the Reference scenario. The slower structural transformation leads to a lower

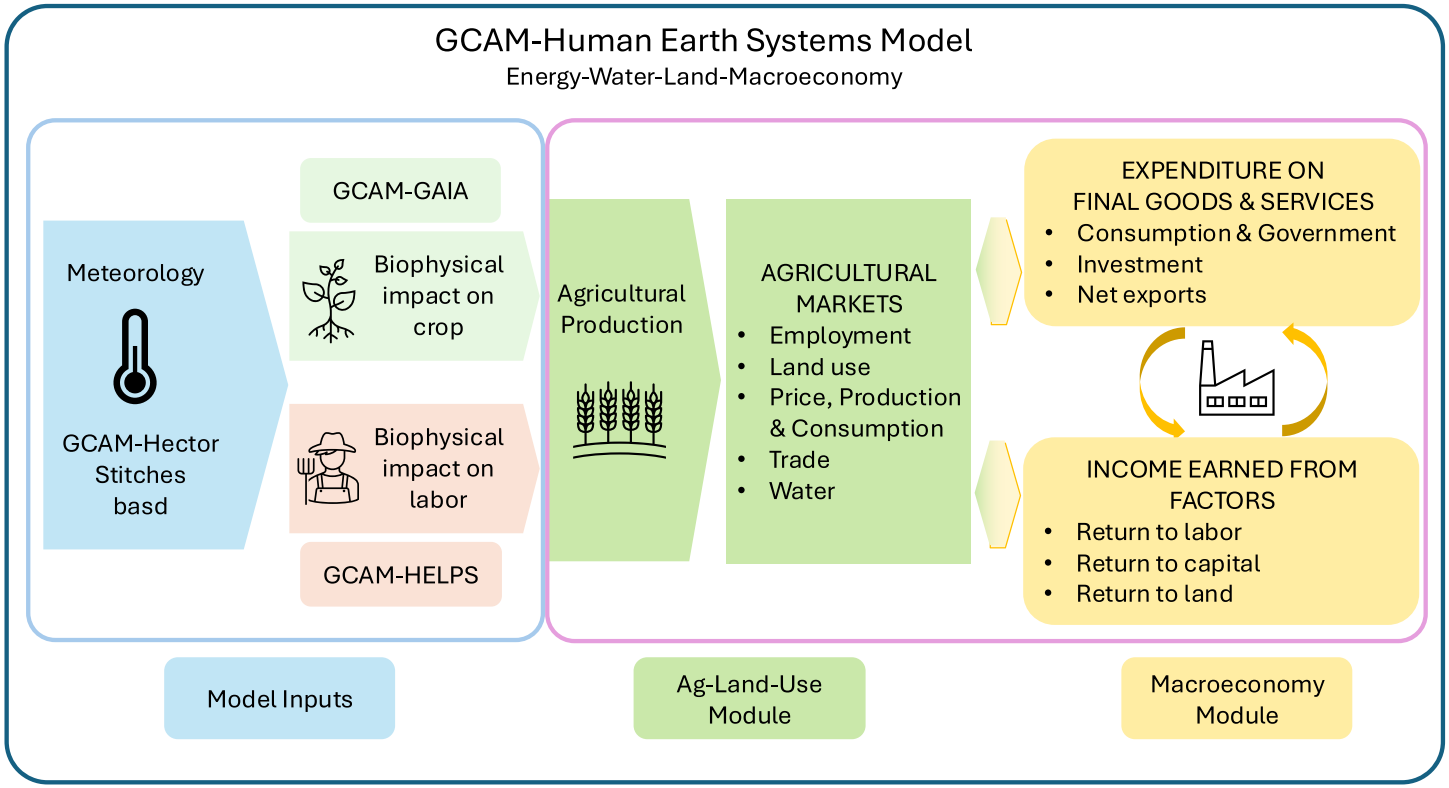

Figure 1. Schematic overview of the modeling framework.

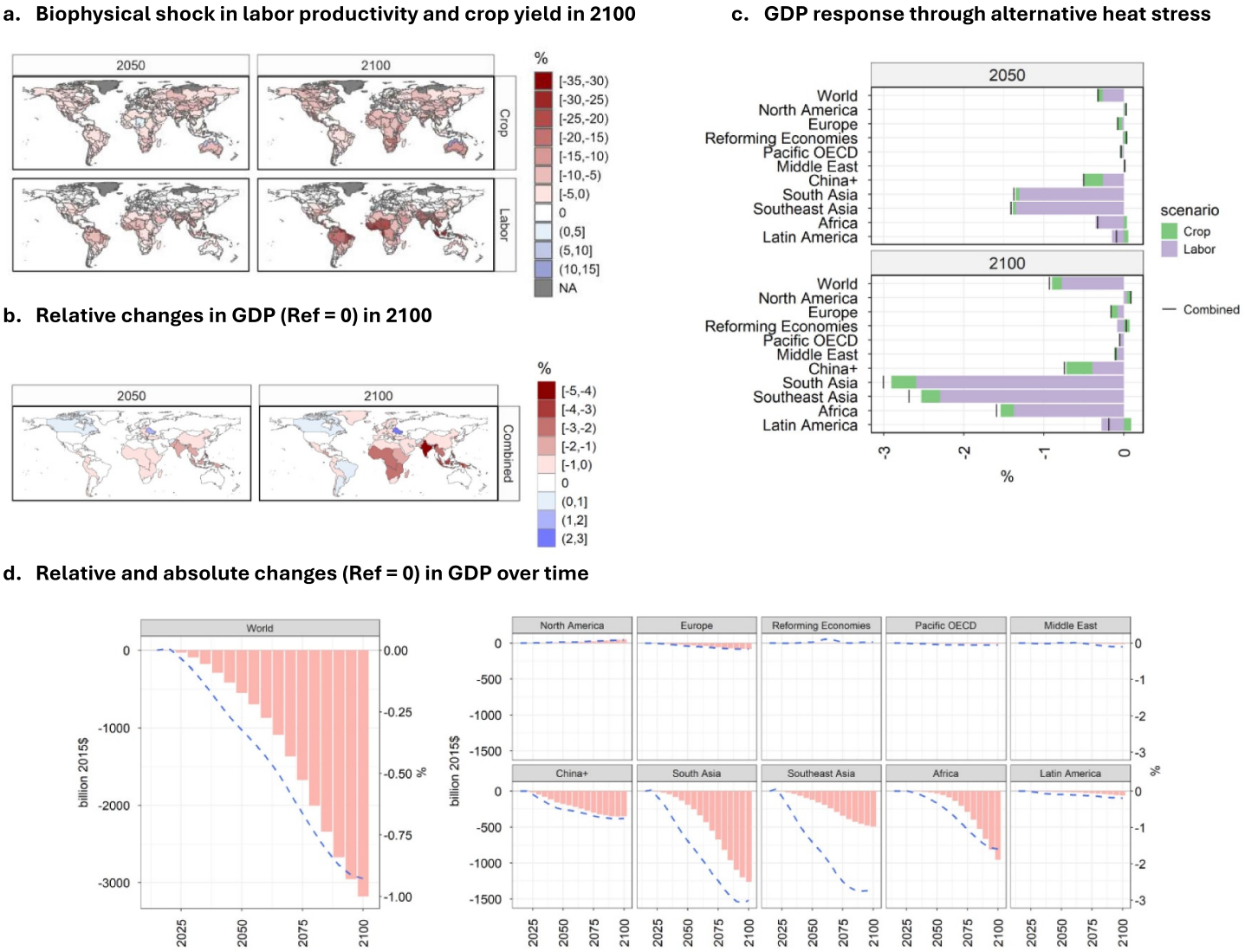

Figure 2. Agricultural heat stress and its implications on regional GDP. Panels a and b show the biophysical shocks in crop yield and labor productivity (a), and the regional GDP responses (b) in 2050 and 2100. Values between −0.1% and 0.1% are grouped to 0 in panels a and b. Panel c shows the regional GDP responses to alternative agricultural heat stress, i.e. crop heat stress only, labor heat stress only and combined crop and labor heat stress, in 2050 and 2100. Panel d shows the trend in relative (blue dashed line) and absolute (red bar) regional GDP response to agricultural heat stress over time. Regions are grouped into AR6 10 regions (tables S3) in panels c and d. *Source*: GCAM results.

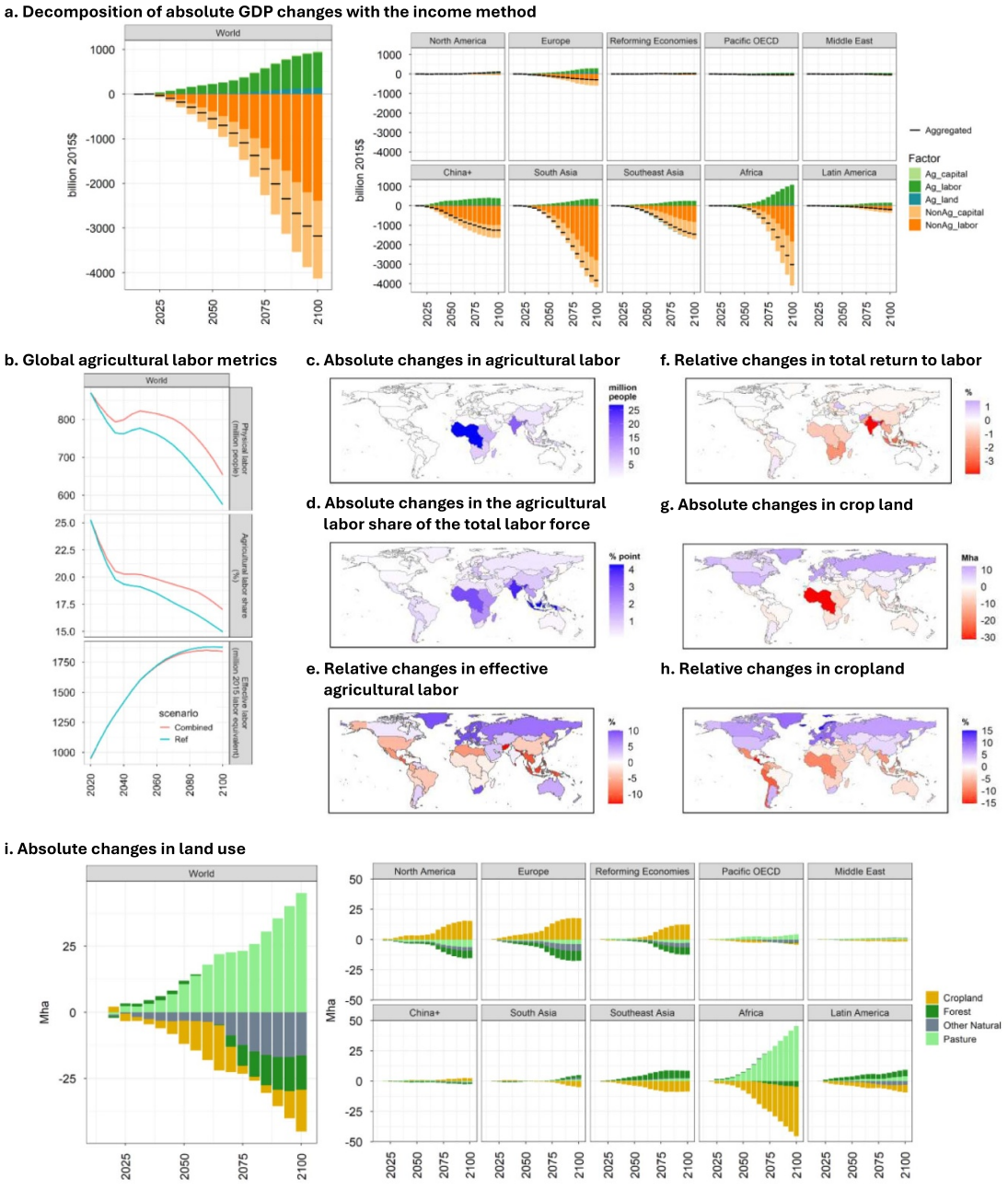

Figure 3. Input market response to agricultural heat stress. Panel a shows the decomposition of GDP response using the income method, and the black solid line denotes the aggregated GDP response. Panel b shows agricultural labor level, share of the total labor force and effective agricultural labor with (Combined) and without (Ref) agricultural heat stress. Panels (c) and (e) summarize regional labor market responses in terms of agricultural labor level (c), share of total labor force (d), and effective agricultural labor. Panel f shows relative changes in total return to labor. Panels (g) and (h) summarize the land use changes to agricultural heat stress in terms of absolute (g) and relative (h) changes in total crop land in 2100. Panel i shows detailed cropland use changes due to agricultural heat stress. Regions are grouped into AR6 10 regions (table S3). *Source*: GCAM results.

economy-wide wage rate and a global loss of 1593 billion dollars in labor returns in 2100 (figures 3(f) and S5(b)).

In addition to shifts in labor across sectors, agricultural heat stress also reshapes the spatial distribution of cropland, with crop production shifting from tropical regions toward temperate and high-latitude areas (figures 2(g) and (h)). At global scales, agricultural heat stress results in a loss of 14 million hectares (Mha), or 1%, relative to the Reference scenario (figure 2(i)). Regionally, when comparing the scenario with agricultural heat stress with the Reference, cropland declines in Africa (42 Mha, 7%) and Southeast Asia (11 Mha, 12%), while expanding in Europe (19 Mha, 9%), North America (19 Mha, 6%), and the Reforming Economies (16 Mha, 7%) to meet global crop demand.

This spatial reallocation of cropland is accompanied by heterogeneous land use change across regions (figure 2(i)). When comparing the scenario with agricultural heat stress with the Reference, cropland area in Africa is projected to decline by 42 Mha (7%),

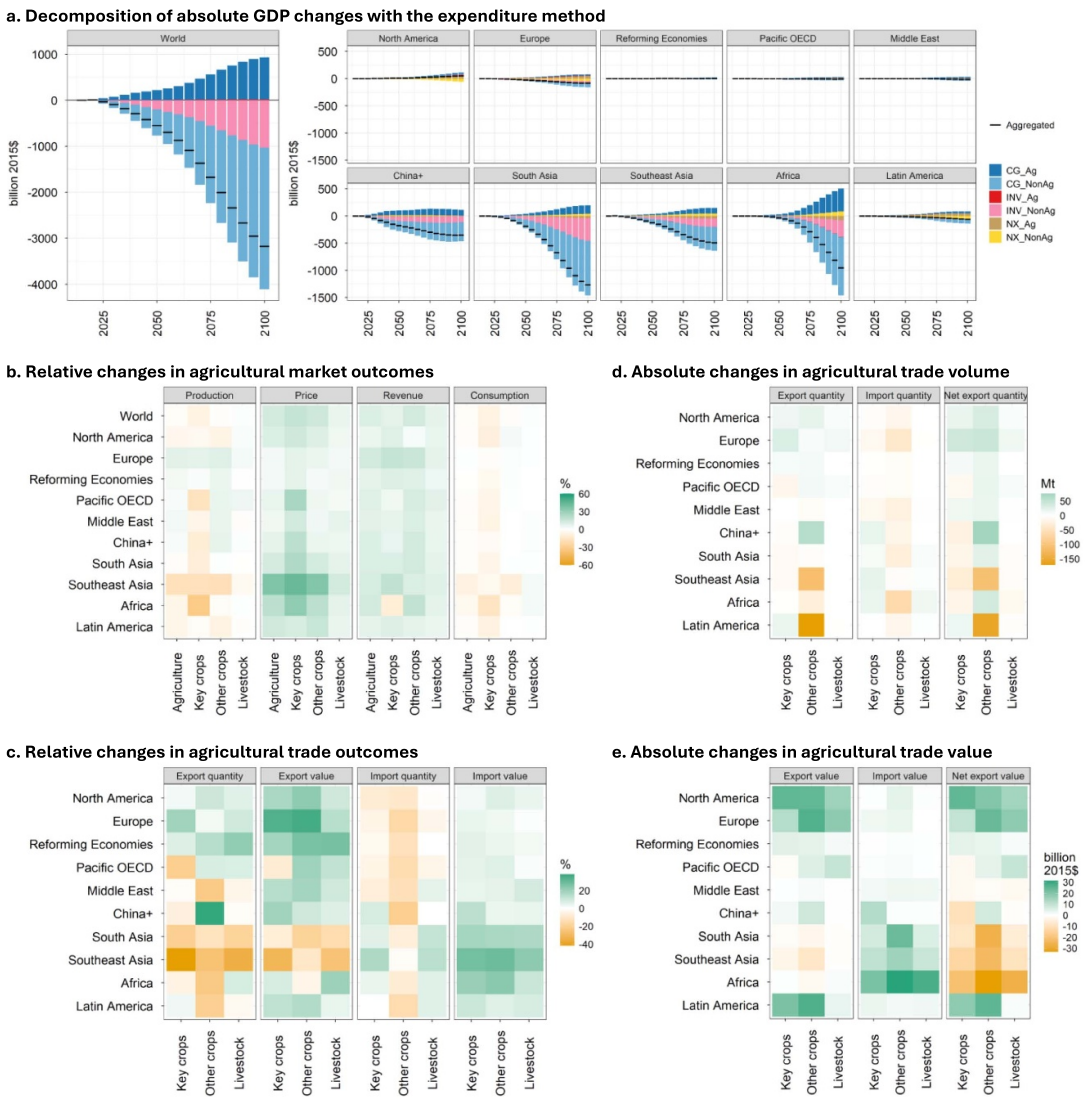

Figure 4. Output market response to agricultural heat stress. Panel a shows the GDP response decomposition with the expenditure method, and the black solid line denotes the aggregated GDP response. CG denotes final consumption from household and government, INV denotes investment, and NX denotes net export. Ag is agriculture. Panels b and c show the relative changes in agricultural market outcomes and trade outcomes in 2100. Panels d and e show the absolute changes in agricultural trade volume (d) and value (e) in 2100. Regions are grouped into AR6 10 regions (tables S3). *Source*: GCAM results.

with most of the cropland converting to pasture. This shift is largely driven by feed source switching. Since the modeled agricultural heat stress imposes greater productivity losses on crops than on pasture, pasture becomes a more competitive source of livestock feed under heat stress conditions. Similar land-use transitions are observed in other major livestock-producing regions, including Brazil and New Zealand (figure S6).

3.3. Responses in output markets to agricultural heat stress

Economic impacts of agricultural heat stress are also reflected in the value of new, final goods and services within an economy. In this section we consider how the macroeconomy responds to the modeled heat-induced biophysical shocks in agriculture through changes in the composition of final consumption, disposition of savings and investment, and international trade (figure 4).

Under agricultural heat stress, the value of global agricultural consumption increases, while the value of non-agricultural consumption declines. That is, less food costs more. As GDP decreases, total savings diminish, reducing the supply of investment. In turn, lower investment further constrains GDP growth. This feedback loop results in declining investment across regions (figure 4(a)). In the agricultural sector, rising labor costs under heat stress incentivize producers to adopt more capital-intensive technologies to maintain profitability (figure S7). Therefore, under the modeled agricultural heat stress, by the end of the century, global agricultural investment increases by 14 billion dollars. With a lower total investment supply, global non-agricultural investment decreases by approximately 1 trillion dollars.

The agricultural markets are sensitive to heat stress (figure 4(b)). When compared with the Reference scenario, agricultural heat stress introduces a 7% (324 Mt) reduction in global production of key crops (corn, wheat, rice and soybeans), with sharp reductions in Africa (150 million tons [Mt], 32%) and Southeast Asia (44 Mt, 17%). For other crops, agricultural heat stress reduces global production by 1% (125 Mt), and shifts production away from Southeast Asia (−217 Mt, −18%) and Latin America (−171 Mt, −7%) toward temperate regions such as Europe (+260 Mt, +9%).

Heat stress-induced production declines lead to a 13% increase in global agricultural producer prices. Significant price increases are expected in Southeast Asia (+36%), Africa (+20%), Latin America (+14%), South Asia (+12%), and North America (+11%). Among commodities, key crop prices increase slightly more than others. Globally, prices rise by 17% for key crops, 15% for other crops, and 6% for livestock. In most regions, the increase in prices more than offsets the decline in production, leading to higher agricultural producer revenues, except in Africa, where production losses dominate (figure 4(b)).

Key crops are major calorie sources with low price elasticity, therefore, price increases in key crops lead to higher expenditures and only modest declines in consumption. In contrast, other crops and animal products exhibit more elastic demand and experience an overall decline in consumption as average prices rise. However, relative price movements drive substitution across commodities. Specifically, livestock prices increase less than those of crops in general, which shifts consumption toward animal products despite rising prices overall, resulting in modest increases in livestock consumption in Southeast Asia (3%) and Africa (3%) that partially offset caloric losses from key crops in these regions.

International trade buffers regions from local production shocks, resulting in regional consumption responses that diverge from the corresponding production shocks (figure 4(b)). Agricultural heat stress also shifts global trade patterns, particularly in tropical regions, where it reduces export volumes and increases reliance on imports for key crops (figures 4(c) and (d)). Relative to the Reference scenario, the heat-induced decline in key crops export volume is most pronounced in Southeast Asia (−42%), Pacific OECD (−21%), and South Asia (−20%), while Europe exhibits a notable increase in key crop export volumes (+19%). Despite noticeable percentage changes across regions, absolute trade volume shifts are concentrated in China+, Southeast Asia, and Latin America (figure 4(d)). By the end of the century, agricultural heat stress introduces reductions in key crops net exports volume in Southeast Asia (−30 Mt), China+ (−21 Mt), Africa (−17 Mt), and South Asia (−16 Mt) relative to the Reference scenario. To satisfy global demand, agricultural heat stress induces an expansion in net exports from temperate regions, including Europe (+41 Mt), North America (+17 Mt), and Latin America (+16 Mt), highlighting a spatial shift in global export capacity.

For other crops, substantial reductions in export volumes are projected for Latin America (−171 Mt, −20%) and Southeast Asia (−111 Mt, −26%). While China+ increases its exports of other crops (+60 Mt, +38%) to partially offset the global decline, the overall contraction in supply leads to reduced import volumes across multiple regions. This tightening of supply exerts upward pressure on trade prices. Consequently, despite lower export volumes, the export value of other crops in Latin America increases by 16 million dollars (16%) (figures 4(c) and (e)). The overall changes in other crops largely reflect the changes in sugar crops (figure S8).

4. Discussions

Agricultural heat stress has profound impacts on global and regional agriculture. While crop heat stress has been widely studied, less attention has been paid to labor heat stress. Additionally, impact studies have shown pronounced biophysical impact while observed macroeconomic responses remain modest. In this study, we investigate the connections between agricultural heat stress, agricultural and primary factor market dynamics, and macroeconomic ramifications using a global economic model.

Our results show that agricultural heat stress reduces global GDP, with disproportionate losses in tropical regions. By the end of the century, global GDP declines by about 1% in our modeling framework, while losses reach up to 3% in South and Southeast Asia. This spatial pattern is consistent with long-standing findings in the economic literature [1, 7, 41], and the magnitude of percentage GDP losses is broadly comparable to previous estimates [23, 42–44]. Differences in heat-stress scope considered and in radiative forcing levels contribute to the variation across studies. For example, economy-wide heat-stress assessments tend to produce larger GDP losses than our agriculture-focused analysis [42–44], while lower radiative forcing tends to reduce projected damages [23].

These uneven impacts between tropical and temperate zones can be understood through the IPCC risk framework of hazard, exposure, vulnerability, and response [45]. Tropical regions face greater labor heat stress hazards because high baseline temperatures and humidity intensify the negative biophysical response to heat stress [23, 46]. High labor-intensity in tropical agriculture sector leads to overall higher heat stress exposure [27, 47]. Given the non-linear [2] relationship between economic output and temperature, even modest additional warming

can trigger large economic losses, making tropical economies inherently more vulnerable. Limited adaptive capacity, access to capital, technology, and institutional support, further increases vulnerability in lower-income regions [48, 49].

Within our modeling framework, labor heat stress generates larger macroeconomic impacts than crop heat stress. Heat-induced crop yield responses vary across commodities and regions, creating greater flexibility to mitigate damages through crop substitution, trade, and shifts in production, and lead to moderately small market responses [12, 23, 50]. In contrast, labor is less mobile across regions and sectors in the short term, and adaptation through additional labor or capital substitution propagates impacts through the broader economy because both factors are competed across sectors. As a result, labor heat stress tends to slow down the structural transformation and produce larger and more persistent economy-wide damages, which align with previous studies [24, 27]. At the same time, substantial uncertainties remain in atmospheric projections, biophysical responses and economic parameterizations.

Many previous studies apply externally prescribed warming scenarios that may not be fully consistent with the socioeconomic assumptions underlying the impact assessment. With the emerging advocacy of emission-driven atmospheric projections [30], our biophysical responses are derived based on emission-driven atmospheric projections, and importantly, we verify that radiative forcing and global mean temperature trajectories remain closely aligned with the Reference radiative forcing even after accounting for biophysical feedbacks from agricultural heat stress (figures S10 and S11), thereby 'closing the loop' [51] that has often been overlooked in previous studies. We explore the atmospheric sensitivity using alternative ESM emulators driven by the same emissions trajectory yields comparable estimates of global GDP losses from agricultural heat stress, ranging from −1.2% to −0.9% (figure S9).

Crop yield impacts are sensitive to the choice of empirical versus process-based response functions, with empirical estimates generally producing larger damages, largely due to differences in the representation of CO_2 fertilization [52, 53]. Crop responses to heat stress also vary strongly by developmental stage [54, 55] and water deficit [56]. Future work incorporating stage-specific heat responses and compound heat-drought effects could improve the representation of crop damages and refine estimates of downstream economic impacts. Similarly, heat-induced labor productivity responses remain highly uncertain [57] due to uncertainties in the bioclimate models, future adaptive capacity, population diversity and the natural atmospheric variability. Existing labor-heat response functions are often calibrated using context-specific field data which have limited applicability across regions and sectors [58]. Future studies should develop time-varying, region-specific labor-heat response functions that better account for capacity in acclimatization and technological adaptation.

Additional uncertainty arises from the economic modeling framework itself, including assumptions regarding trade dynamics [59], labor mobility and factor substitution [28]. While the parameterization choices in this study are grounded in previous literature [28, 59, 60], the quantitative estimates presented here should be interpreted primarily as an illustration of how agricultural heat stress propagates through interconnected economic systems, rather than as precise forecasts of future economic damages. Future work should systematically characterize uncertainties across atmospheric projections, biophysical responses, and socioeconomic dimensions to better present the plausible range of economic outcomes.

5. Conclusion

This study advances the integration of Earth system science, impact research, and economic modeling to examine how heat-induced biophysical shocks in agriculture propagate through the economy. Our results show that global GDP losses due to labor heat stress are higher than that of crop heat stress. Overall, the GDP responses appear mild relative to the scale of underlying biophysical changes. Agricultural heat stress disproportionately reduces GDP in tropical regions, shifts agricultural production toward temperate regions, and slows structural transformation as workers remain in agriculture to offset declining productivity.

Overall, our findings underpin the interdisciplinary efforts that link economic activity, emissions, atmospheric change, biophysical responses, and economic responses for understanding the economy-wide consequences of extreme weather and for informing future estimates of sectoral damage functions.

Acknowledgments

The authors are grateful for support from the US Department of Energy, Office of Science, as part of research in the Multi-Sector Dynamics, Earth and Environmental System Modeling Program. The Pacific Northwest National Laboratory is operated for the DOE by Battelle Memorial Institute under contract DE-AC05-76RL01830. The views and opinions expressed in this paper are those of the authors alone. We extend our gratitude to Noah Prime, Kanishka Narayan, Matthew Binsted, Marshall Wise for their valuable comments and suggestions, and K Jokerst, S Eustis, and P Land for their administrative support.

Data availability statement

GCAM model and code used in this paper are hosted at: https://github.com/realxinzhao/paper-kleam-heatstress.

Data Visualization: https://github.com/dsheng1026/MacroHeatStressDisplayItems.

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/dsheng1026/MacroHeatStressDisplayItems/tree/main/data [61].

Supplementary material available at: https://doi.org/10.1088/1748-9326/ae9627/data1.

Author contributions

Di Sheng 0009-0006-7567-380X
Conceptualization (equal), Formal analysis (lead), Methodology (equal), Visualization (lead), Writing – original draft (lead), Writing – review & editing (equal)

Jae Edmonds 0000-0002-3210-9209
Conceptualization (equal), Methodology (equal), Writing – original draft (lead), Writing – review & editing (equal)

Xin Zhao 0000-0002-1801-4393
Conceptualization (equal), Methodology (equal), Writing – review & editing (equal)

Pralit Patel
Methodology (equal), Writing – review & editing (equal)

Stephanie Morris 0000-0002-8073-0868
Methodology (supporting), Writing – review & editing (equal)

Kalyn Dorheim 0000-0001-8093-8397
Methodology (supporting), Writing – review & editing (equal)

Christoph Bertram 0000-0002-0933-4395
Writing – review & editing (equal)

Allen Fawcett 0000-0002-2980-0402
Writing – review & editing (equal)

References

[1] Dell M, Jones B F and Olken B A 2012 Temperature shocks and economic growth: evidence from the last half century *Am. Econ. J.* **4** 66–95
[2] Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9
[3] Stern N 2013 The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models *J. Econ. Lit* **51** 838–59
[4] Rising J, Tedesco M, Piontek F and Stainforth D A 2022 The missing risks of climate change *Nature* **610** 643–51
[5] Dell M, Jones B F and Olken B A 2014 What do we learn from the weather? The new climate-economy literature *J. Econ. Lit* **52** 740–98
[6] Tol R S J 2018 The economic impacts of climate change *Rev. Environ. Econ. Policy* **12** 4–25
[7] Kahn M E, Mohaddes K, Ng R N C, Pesaran M H, Raissi M and Yang J-C 2021 Long-term macroeconomic effects of climate change: a cross-country analysis *Energy Econ.* **104** 105624
[8] Bjordal J, Storelvmo T and Smith Jr A A Jr 2022 Quantifying uncertainty about global and regional economic impacts of climate change *Environ. Res. Lett.* **17** 094020
[9] Neal T, Newell B R and Pitman A 2025 Reconsidering the macroeconomic damage of severe warming *Environ. Res. Lett.* **20** 044029
[10] Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci.* **111** 3268–73
[11] Nelson G C *et al* 2014 Climate change effects on agriculture: economic responses to biophysical shocks *Proc. Natl Acad. Sci.* **111** 3274–9
[12] Orlov A *et al* 2024 Human heat stress could offset potential economic benefits of CO_2 fertilization in crop production under a high-emissions scenario *One Earth* **7** 1250–65
[13] Bajaj K, Mehrabi Z and Ramankutty N 2025 Exposure of global agricultural lands to extreme weather using CMIP6 projections of future climate *Environ. Res. Lett.* **20** 124077
[14] Moore F C, Baldos U, Hertel T and Diaz D 2017 New science of climate change impacts on agriculture implies higher social cost of carbon *Nat. Commun.* **8** 1607
[15] Dellink R, Lanzi E and Chateau J 2019 The sectoral and regional economic consequences of climate change to 2060 *Environ. Resour. Econ.* **72** 309–63
[16] Lobell D B, Schlenker W and Costa-Roberts J 2011 Climate trends and global crop production since 1980 *Science* **333** 616–20
[17] Zhao C *et al* 2017 Temperature increase reduces global yields of major crops in four independent estimates *Proc. Natl Acad. Sci.* **114** 9326–31
[18] Ray D K, Gerber J S, MacDonald G K and West P C 2015 Climate variation explains a third of global crop yield variability *Nat. Commun.* **6** 5989
[19] Mohammadi S, Rydgren K, Bakkestuen V and Gillespie M A K 2023 Impacts of recent climate change on crop yield can depend on local conditions in climatically diverse regions of Norway *Sci. Rep.* **13** 3633
[20] Asseng S *et al* 2019 Climate change impact and adaptation for wheat protein *Glob. Change Biol.* **25** 155–73
[21] Kjellstrom T, Holmer I and Lemke B 2009 Workplace heat stress, health and productivity—an increasing challenge for low and middle-income countries during climate change *Glob. Health Action* **2** 2047
[22] Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6
[23] Orlov A, Daloz A S, Sillmann J, Thiery W, Douzal C, Lejeune Q and Schleussner C 2021 Global economic responses to heat stress impacts on worker productivity in crop production *Econ. Disasters Clim. Change* **5** 367–90
[24] de Lima C Z, Buzan J R, Moore F C, Baldos U L C, Huber M and Hertel T W 2021 Heat stress on agricultural workers exacerbates crop impacts of climate change *Environ. Res. Lett.* **16** 044020
[25] Mora C *et al* 2017 Global risk of deadly heat *Nat. Clim. Change* **7** 501–6
[26] Kong Q and Huber M 2022 Explicit calculations of wet-bulb globe temperature compared with approximations and why it matters for labor productivity *Earths Future* **10** e2021EF002334
[27] Sheng D, Zhao X, Edmonds J A, Morris S T, Patel P, O'Neill B C, Tebaldi C and Wise M A 2025 Omitting labor

responses underestimates the effects of future heat stress on agriculture *Commun. Earth Environ.* **6** 400
[28] Sheng D, Edmonds J A, Patel P, Waldhoff S T, O'Neill B C, Wise M A and Zhao X 2025 Labour market evolution is a key determinant of global agroeconomic and environmental futures *Nat. Food* **6** 139–50
[29] Jones B, O'Neill B C, McDaniel L, McGinnis S, Mearns L O and Tebaldi C 2015 Future population exposure to US heat extremes *Nat. Clim. Change* **5** 652–5
[30] Sanderson B M *et al* 2024 The need for carbon-emissions-driven climate projections in CMIP7 *Geosci. Model Dev.* **17** 8141–72
[31] Edmonds J, Zhao X, Patel P, Sheng D, Lochner E, Bertram C, Iyer G, Westphal M, Fawcett A and Waldhoff S 2025 Sensitivity of future regional and global energy markets and macroeconomic activity to a hypothetical global energy market disruption *iScience* **28** 111449
[32] Dorheim K, Gering S, Gieseke R, Hartin C, Pressburger L, Shiklomanov A N, Smith S J, Tebaldi C, Woodard D L and Bond-Lamberty B 2024 Hector V3.2.0: functionality and performance of a reduced-complexity climate model *Geosci. Model Dev.* **17** 4855–69
[33] Hartin C A, Patel P, Schwarber A, Link R P and Bond-Lamberty B P 2015 A simple object-oriented and open-source model for scientific and policy analyses of the global climate system—hector v1.0 *Geosci. Model Dev.* **8** 939–55
[34] Tebaldi C, Snyder A and Dorheim K 2022 STITCHES: creating new scenarios of climate model output by stitching together pieces of existing simulations *Earth Syst. Dyn.* **13** 1557–609
[35] Snyder A C, Dorheim K R, Tebaldi C and Vernon C R 2024 STITCHES: a Python package to amalgamate existing Earth system model output into new scenario realizations *J. Open Source Softw.* **9** 5525
[36] Lange S 2019 Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0) *Geosci. Model Dev.* **12** 3055–70
[37] Zhao M, Morris S T, Tebaldi C and Snyder A 2025 gaia: an R package to estimate crop yield responses to temperature and precipitation *J. Open Source Softw.* **10** 7538
[38] Waldhoff S T, Wing I S, Edmonds J, Leng G and Zhang X 2020 Future climate impacts on global agricultural yields over the 21st century *Environ. Res. Lett.* **15** 114010
[39] Sheng D, Zhao X, Snyder A, Morris S and Vernon C 2025 HELPS: an R package to project future heat effects on labor productivity by sector *J. Open Source Softw.* **10** 8415
[40] Flouris A D, Dinas P C, Ioannou L G, Nybo L, Havenith G, Kenny G P and Kjellstrom T 2018 Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis *Lancet Planet. Health* **2** e521–31
[41] Auffhammer M 2018 Quantifying economic damages from climate change *J. Econ. Perspect.* **32** 33–52
[42] Dasgupta S, Robinson E J Z, Shayegh S, Bosello F, Park R J and Gosling S N 2024 Heat stress and the labour force *Nat. Rev. Earth Environ.* **5** 859–72
[43] Borg M A, Xiang J, Anikeeva O, Pisaniello D, Hansen A, Zander K, Dear K, Sim M R and Bi P 2021 Occupational heat stress and economic burden: a review of global evidence *Environ. Res.* **195** 110781
[44] Orlov A, Sillmann J, Aunan K, Kjellstrom T and Aaheim A 2020 Economic costs of heat-induced reductions in worker productivity due to global warming *Glob. Environ. Change* **63** 102087
[45] Intergovernmental Panel on Climate Change (IPCC). 2023 Point of departure and key concepts *Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ed Intergovernmental Panel on Climate Change (IPCC)* (Cambridge University Press) pp 121–96
[46] Nelson G C, Vanos J, Havenith G, Jay O, Ebi K L and Hijmans R J 2024 Global reductions in manual agricultural work capacity due to climate change *Glob. Change Biol.* **30** e17142
[47] Im E-S, Pal J S and Eltahir E A B 2017 Deadly heat waves projected in the densely populated agricultural regions of South Asia *Sci. Adv.* **3** e1603322
[48] Grossi A and Dinku T 2022 Enhancing national climate services: how systems thinking can accelerate locally led adaptation *One Earth* **5** 74–83
[49] Singh C and Nirwan 2024 Effective heat adaptation must engage with unequal heat risk *One Earth* **7** 1320–3
[50] Fujimori S, Iizumi T, Hasegawa T, Takakura J, Takahashi K and Hijioka Y 2018 Macroeconomic impacts of climate change driven by changes in crop yields *Sustainability* **10** 3673
[51] Tebaldi C, O'Neill B, Sheng D, Prime N, Zhao M, Dorheim K and Brown J 2026 Implications of climate change impacts for emission and land use scenario development *Environ. Res. Lett.* **21** 074018
[52] Lobell D B and Asseng S 2017 Comparing estimates of climate change impacts from process-based and statistical crop models *Environ. Res. Lett.* **12** 015001
[53] Moore F C, Baldos U L C and Hertel T 2017 Economic impacts of climate change on agriculture: a comparison of process-based and statistical yield models *Environ. Res. Lett.* **12** 065008
[54] Ullah A, Nadeem F, Nawaz A, Siddique K H M and Farooq M 2022 Heat stress effects on the reproductive physiology and yield of wheat *J. Agron. Crop Sci.* **208** 1–17
[55] Ren W *et al* 2025 Growth stage-dependent extreme temperature stresses on crop yield *J. Agric. Food Res.* **24** 102443
[56] Cohen I, Zandalinas S I, Huck C, Fritschi F B and Mittler R 2021 Meta-analysis of drought and heat stress combination impact on crop yield and yield components *Physiol. Plant.* **171** 66–76
[57] Vanos J K, Baldwin J W, Jay O and Ebi K L 2020 Simplicity lacks robustness when projecting heat-health outcomes in a changing climate *Nat. Commun.* **11** 6079
[58] Foster J, Smallcombe J W, Hodder S, Jay O, Flouris A D, Nybo L and Havenith G 2021 An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity *Int. J. Biometeorol.* **65** 1215–29
[59] Zhao X, Wise M A, Waldhoff S T, Kyle G P, Huster J E, Ramig C W, Rafelski L E, Patel P L and Calvin K V 2022 The impact of agricultural trade approaches on global economic modeling *Glob. Environ. Change* **73** 102413
[60] Edmonds J A, Link R, Waldhoff S T and Cui R 2017 A global food demand model for the assessment of complex human-earth systems *Clim. Change Econ.* **08** 1750012
[61] Sheng D 2025 MacroHeatStressDisplayItems (available at: https://github.com/dsheng1026/MacroHeatStressDisplayItems)