

Estimating sectoral climate impacts in a global production network

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Abstract

Despite intensified international trade patterns and production fragmentation, local weather shocks have only been shown to affect local economic activity. This paper introduces input-output interlinkages as a transmission mechanism of extreme heat in a production network model. Using global sectoral production data from 1975 to 2020, I find that local extreme heat that reduces agricultural production induces substantial losses to downstream sectors by distorting intermediate input prices. Counterfactual scenarios reveal a threefold underestimation of global aggregate economic costs omitting sectoral interlinkages. The analysis also highlights a positive gradient between a country's centrality in the production network and heat-induced global losses.

Keywords: Climate impacts, extreme heat, input-output supply chain interlinkages, production network, spillovers, weather shocks

JEL Classification: E23, E32, L14, O11, Q54, R15

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1 Introduction

Estimates of macroeconomic damages induced by global warming are crucial for optimal climate policy design (Golosov et al., 2014; Barrage, 2020), quantifying economic benefits of temperature targets (Burke et al., 2018), and informing public and policy debates about resource allocation for adaptation. To answer these pressing questions, econometric models of temperature impacts on economic output are increasingly used (Burke et al., 2015). The traditional approach estimates the response of local economic production to isolated local variation in weather fluctuations. In spite of uncertainty around the magnitude of the damages, most studies conclude that larger economic costs are borne by low and middle income countries (Dell et al., 2012), due to the agriculture-intensive nature of domestic economic production (Nath, 2020).

In an increasingly interconnected world, intermediate inputs are a growing force of production networks through which local productivity shocks in agriculture can propagate to the rest of the economy (Farrokhi and Pellegrina, 2023). The role of sectoral interlinkages in the aggregate effect of weather fluctuations in the economy is *ex ante* ambiguous. On the one hand, openness to international trade and production fragmentation can help increase diversification in the supply chain and lower volatility, if the production network endogenously adjusts in response to shocks (Caselli et al., 2020). On the other hand, however, interlinkages can increase exposure to shocks with effects rippling through the supply chain (di Giovanni and Levchenko, 2009).

This paper quantifies the implications of sectoral interlinkages in propagating extreme heat in agriculture on downstream sectors and beyond cross-national borders. I quantify the global losses caused by agriculture-specific extreme heat exposure by compiling a global data set at the country-sector level of value added combined with high-resolution daily temperature and precipitation realizations and input-output sectoral interlinkages since 1975. I construct sector-specific extreme heat measures that allow me to empirically disentangle the effect of local shock from domestic and foreign agricultural shocks, by making use of the geography of crop acreage, population distribution and sub-national sectoral economic activity, and of agro-physical information

on the optimal crop-specific growing temperature.

My analysis starts by showing five empirical patterns that inform my theoretical model and empirical approach: (1) in a global cross-country sample of value added for six sectors, extreme heat conditions negatively affect only the agriculture sector.¹ An additional degree day reduces agricultural per capita value added growth rate by 4.6% at the mean; (2) the aggregate negative productivity effect that extreme heat has on agriculture induces a short-lasting distortion to crop prices; (3) extreme heat shocks in the agricultural sector are increasingly spatially correlated across the world, underlining the importance to account for spatial interlinkages in empirical analyses of temperature impacts. The last two patterns use input-output interlinkages data: (4) downstream sectors' interlinkages with agriculture do not respond to extreme heat conditions, suggesting that the production network does not endogenously adjust to temperature fluctuations; (5) income does not differentially affect countries' ability to reduce extreme heat exposure in upstream agricultural sectors.

Armed with these empirical patterns, I formalize a model of input price distortions (Hsieh and Klenow, 2009), which I extend to a production network model where sectoral output is also a function of intermediate inputs (Acemoglu et al., 2012). The objective of the model is two-fold. First, it highlights how the traditional conceptual framework behind quasi-experimental research designs that estimate the effect of local weather fluctuations on output ignores spatial linkages and derives estimates obtained by holding weather in other locations fixed. This approach neglects the spatial correlation structure of weather and the trade interconnections across sectors and space, violating one of the identifying assumptions, the stable unit treatment value assumption. This is equivalent to say that the estimated (and projected) damages due to *global warming*, e.g., in France, are computed under *local warming*, i.e., without accounting for simultaneous temperature increases in Spain and Germany. Second, the model illustrates how sector-location specific shocks can affect downstream output

¹The other five sectors whose response to extreme heat is small and statistically indistinguishable from zero include: Mining, manufacturing and utilities; Construction; Wholesale, retail trade, restaurants, and hotels; Transport, storage, and communication; Other activities (including government and financial sector).

through intermediate input interlinkages. Extreme heat, by inducing a reduction in a supplier’s output, distorts agricultural input prices, which lead downstream sectors to reduce their demand for the intermediate input good, thus reducing their output.

Based on the empirical patterns and on the theoretical model, I design an empirical methodology that examines how agricultural extreme heat conditions propagate through input-output interlinkages and affect downstream sectors’ economic production domestically and abroad. Extreme heat shocks in agriculture are weighted by downstream interlinkages with buyer sectors, distinguishing by location into domestic and foreign. By allowing the production network to vary every decade, the empirical strategy exploits quasi-random variation in extreme heat, while exposure share are allowed to be endogenous (Borusyak et al., 2022).

My main findings show that domestic and foreign extreme heat conditions in the agriculture sectors have a strong negative effect on downstream sectors’ per capita value added growth rate, which, however, does not respond to local extreme heat. The magnitude of the indirect effect of network extreme heat is substantial and comparable to the local effect of extreme heat on agricultural production. Results are stronger when accounting for the full propagation using the Leontief inverse matrix. As predicted by the theoretical model, I document that the direction of the propagation travels downstream from supplier to buyer sectors. Extreme heat is a (negative) productivity shock on agriculture production, which can thus be interpreted as a supply-side shock that does not affect upstream prices (Carvalho and Tahbaz-Salehi, 2019). I empirically validate this theoretical hypothesis by showing that agricultural extreme heat has a negligible and insignificant effect on upstream sectors.

Finally, I use the estimated parameters from the reduced-form specification as the basis of two counterfactual exercises. First, I quantify the contribution of input-output interlinkages between sectors to the average annual output loss due to recent warming from 2000 onwards. I consider a counterfactual world with no input-output linkages and with linearly trended daily temperatures from their baseline climate in 1970-2000. Accounting for network shocks, recent warming is responsible for an average annual output loss of 0.33%, compared to a 0.1% average loss when omitting

spillovers. Second, I obtain the average annual global cost for an additional hot day in a specific country. Average annual global costs are larger when extreme heat occurs in countries with stronger supply chain interlinkages in the production networks, such as China, Brazil, France, India, and the United States, which are the major global agricultural producers (Costinot et al., 2016).

Altogether, these findings provide evidence of the role of input-output sectoral interlinkages as an important mechanism for the propagation and amplification of extreme heat conditions in agriculture. They also highlight a substantial underestimation when omitting sectoral linkages and underline the importance of this channel as a component of the total economic impact of climate change.²

This paper contributes to the literature on the macroeconomic impacts of climate change. There are two main empirical approaches that rely on quasi-experimental variation. First, a vast majority of studies analyzes the impact of temperature on national or sub-national GDP per capita around the world exploiting variation in weather in a given location in a panel structure (Akyapi et al., 2024; Burke et al., 2015; Burke and Tanutama, 2019; Dell et al., 2012; Kahn et al., 2021; Kalkuhl and Wenz, 2020; Kotz et al., 2021, 2024; Nath et al., 2024; Newell et al., 2021). The identification of the causal effect of local temperatures relies, among others, on the stable unit treatment value assumption, which can be undermined by spatial and trade linkages between locations. Second, a more recent emerging approach uses time-series variation in global temperature to estimate its effect on economic activity (Berg et al., 2024; Bilal and Känzig, 2024). While this method has the advantage of accounting for the spatial correlation structure of temperature and the trade interconnections across sectors and space, it cannot disentangle the relative importance of each of these components from the impact of local temperature variation.

This paper introduces a new mechanism in the climate impact literature. Besides spatial correlation as a channel for the global nature of climate change (Dingel et al., 2023), shocks can also propagate through production networks across sectors

²For example, Kahn et al. (2021) show that an average increase in temperature by 0.01°C is associated with a 0.02% decrease in the annual growth rate of global economic output (see Tol (2022) for a complete meta-analysis of the economic impact of climate change).

and space. Micro level studies examine endogenous adjustment of firms in a sector in response to natural disasters in the US (Barrot and Sauvagnat, 2016), Pakistan (Balboni et al., 2023), India (Castro-Vincenzi et al., 2024) and across the world (Pankratz and Schiller, 2024), or after a localized single event such as the 2011 Japan earthquake (Boehm et al., 2019; Carvalho et al., 2021). At a more aggregate level, and closer to my approach, input-output interlinkages across states and sectors have been shown to matter for the economic cost of climate change in the US (Rudik et al., 2024). This paper contributes to the macroeconomic literature on the propagation of shocks by providing the first global estimate of the economic cost of temperature increases accounting for sectoral interlinkages.

2 Data

This section provides a summary of the main data sources used to empirically test the hypothesis that weather shocks affect sectoral production and propagate through input-output interlinkages. To do so, I combine data on sector-level economic production (Section 2.1), weather (Section 2.2), and sectoral interlinkages (Section 2.3). Complementary secondary data are described in Appendix Section C.

2.1 Sectoral production data

The Economic Statistics Branch of the United Nations Statistical Division (UNSD, 2022) provides Gross Value Added (GVA) in constant 2015 USD following the International Standard Industrial Classification (ISIC rev. 3.1) for all countries from 1970 through 2020.³ The data set categorizes sectors into six broad groups (ISIC code in parentheses), which provides the most comprehensive source of global economic production disaggregated by sector: agriculture, hunting, forestry, and fishing (A-B); mining, manufacturing and utilities (C-E); construction (F); wholesale, retail trade, restaurants, and hotels (G-H); transport, storage, and communication (I); other ac-

³The final sample of countries and their frequency is reported in Appendix Table B2.

tivities (J-P).⁴ The latter encompasses, among others, the financial sector, real estate, public administration, education and health.⁵

2.2 Weather data

I use daily temperature and precipitation data from the global reanalysis ERA-5 dataset compiled by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Muñoz Sabater, 2019). ERA-5 is available on a $0.25^\circ \times 0.25^\circ$ resolution grid ($\approx 28\text{km}$ at the Equator) from 1940 to the present. Crucial to the analysis is the construction of sectoral weather shocks. Below, I detail how I construct them.

Agricultural shock. First, I construct a measure of weather shock specific to the agricultural sector. Building on extensive prior literature, extreme heat exposure is quantitatively the most important weather determinant of yields (Schlenker and Roberts, 2009; Hultgren et al., 2022). I construct a measure that exploits the fact that locations grow different crops and are differentially exposed to changes in extreme temperatures and each crop is differentially sensitive to a change in extreme heat exposure. First, I use the global geography of agricultural production from the Earthstat database (Monfreda et al., 2008). These land use data combine national, state, and county-level census statistics with a global data set of croplands to construct the area harvested for 175 crops at a 5 min ($\approx 10\text{ km}$) spatial resolution.

To capture crop-specific exposure to temperatures above which cumulative degree days are harmful, I use crop-specific temperature sensitivity from the UN FAO EcoCrop database. The EcoCrop data are compiled from expert surveys and textbooks and provide information on plants characteristics and crop environmental requirements for more than 2,000 plant species, including tolerance ranges for temperature and precipitation, soil pH, light intensity, and other soil characteristics. I use the

⁴The original data are available for seven sectors, including GVA in manufacturing (ISIC D). Unlike previous studies (Hsiang, 2010; Kunze, 2021), I consider mining, manufacturing and utilities (ISIC C-E) as one single sector, since value added across sectors is not additive.

⁵Appendix Table B1 presents summary statistics for sectoral production. Although unbalanced, the sector-country panel dataset covers all countries in the world for most of the 46 years in the analysis. On average, information for each sector-country tuple is available for 44 years. Most of the sectors are covered for the entire time period except for recent geopolitical changes.

crop-specific upper temperature threshold for optimal growing to compute the number of cumulative degree days that are harmful to a specific crop. For example, the harmful degree days for maize occur above 31°C. The use of crop-specific thresholds allays concerns on the balance of the variation in extreme heat exposure across space used in the analysis. For instance, a spatially uniform threshold to compute extreme heat across locations and crops, e.g., 30°C, would completely mask Bolivia’s exposure to above-optimal growing temperature conditions for quinoa (18°C), of which Bolivia is the leading world producer, and whose daily average temperature on agricultural lands was above 25°C only in 2% of the days in the sample.

Extending previous US-specific (Moscona and Sastry, 2023) and crop-specific global (Hsiao et al., 2024) efforts to measure agricultural extreme heat exposure, I construct a country-specific measure across crops k and grid cells g in country n , such that:

$$ExtremeHeat_{nt} = \sum_k \sum_{g \in n} \frac{Area_{gk}}{\sum_k \sum_{g' \in n} Area_{g'k}} DegreeDays_{gt}(T_k^{max}) \quad (1)$$

where $DegreeDays_{gt}(T_k^{max})$ is the total number of degree days in excess of the crop-specific maximum optimal growing temperature T_k^{max} in grid cell g in year t , and $Area_{gk}$ is the fraction of grid cell g in country n growing crop k . To have a crop-weighted measure of extreme heat exposure at the country-level, I weigh crop-specific cumulative extreme heat exposure in a country by the total harvested area of each crop k in country n .

Other sector shocks. Unlike agriculture, production in other sectors is not linked to temperatures through specific geo-physical or agronomic relationships. Instead, output can be affected by weather variations through a variety of channels, including labor supply and productivity (Graff Zivin and Neidell, 2014; Rode et al., 2022), capital equipment (Zhang et al., 2018), and total factor productivity (Letta and Tol, 2019). To construct sector-specific shocks as opposed to agricultural-specific extreme heat exposure in the same country, I adopt a different approach to measure abnormally hot temperatures.

Since the beginning of the reduced-form approaches to the output-temperature relationship, temperature has been used in levels (Dell et al., 2012). The non-stationarity of temperature levels, however, introduces concerns on the identification strategy (for a deeper discussion, see Appendix Section E). To construct an unexpected plausibly exogenous shock in temperature, I rely on people’s climate beliefs being built upon long-run climatic conditions and adaptive responses based on their expectations (Shrader, 2021). I compute the annual number of days that belongs to the top 5th-percentile of each grid-specific temperature distribution relative to a time-varying thirty-year long historical climate norm (Arguez et al., 2012). Using this methodology, the measure is evenly distributed, and any abnormal realization is compared to the grid-specific climatic norm, in contrast to using absolute thresholds (e.g., number of days above 35°C), which only occur in certain areas of the world and might drive the variation without geo-physical justification.

To construct a measure of weather exposure for the average individual in a country, after taking any nonlinear transformation at the grid cell level, I average grid cell values across space using time-invariant population weights from the 2000 Landsat dataset (Bright and Coleman, 2001) and accounting for fractional grid cells that partially fall within a country (Hsiang, 2016). To obtain sectoral variation in weather conditions within a country, I rely on the sub-national geographic distribution of sectoral activities (Appendix Section C provides additional details on the data sources).

2.3 Production network

I use Input-Output (IO) data from EORA26 (Kanemoto et al., 2011; Lenzen et al., 2012) to define the production network and analyze how idiosyncratic weather shocks propagate. This data set contains information on 26 sectors for 189 countries from 1970 to 2021.⁶ I examine the propagation of weather shocks through a slowly evolving production network, where input-output interlinkages are averaged over previous five years for each decade to smooth annual variation and account for the intensification of inter-sectoral production linkages over time with more fragmented global supply

⁶Appendix Table B3 maps the 26 EORA sectors to the six sectors described in Section 2.1.

chains and intensive use of intermediate inputs.

Construction of network shocks. I construct shocks to agriculture that propagate through input-output interlinkages accounting for the geographic location and position in the supply chain of trade partners. First, I distinguish between shocks originating in the same country, *domestic*, and those originating in others, *foreign*. Second, I classify network shocks into downstream and upstream using entries from the inter-country IO tables with different weights depending on the relative importance of agriculture respectively as a supplier or customer of the sector of interest. From the perspective of the sector of interest, downstream shocks originate in agriculture as a supplier sector and travel in the same direction as intermediate inputs. In contrast, upstream shocks hit agriculture as a customer sector and travel upstream to the sector of interest.⁷

From the perspective of sector j in country n , agricultural downstream shocks are weighted by

$$\omega_{n,m,\tau}^{j,Ag} = \frac{\overline{input}_{Ag,m\tau \rightarrow jn\tau}}{\sum_{kf \in \Theta_{jn}} \overline{input}_{jn\tau \rightarrow kf\tau}} \quad (2)$$

i.e., the average ratio of the inputs of j in country n produced by the agriculture sector (Ag) in country m over total inputs supplied to its set of customer sector-countries Θ_{jn} over the previous five years τ for each decade. These weights reflect the inputs sector-country jn needs from the agriculture sector in country m to produce one output unit. Conversely, the weights associated with agricultural upstream shocks are constructed as

$$\hat{\omega}_{n,m,\tau}^{j,Ag} = \frac{\overline{input}_{jn\tau \rightarrow Ag,m\tau}}{\sum_{lf \in \Theta_{jn}} \overline{input}_{jn\tau \rightarrow lf\tau}} \quad (3)$$

i.e., the ratio of the inputs of sector-country jn to the agriculture sector (Ag) in country m over the total inputs supplied to its set of customers Θ_{jn} . These up-

⁷Appendix Figure A1 shows the average upstream and downstream weights of each sector across countries.

stream weights reflect the importance of each the agriculture sector in country m for the sector-country of interest jn . There are four different network shocks based on combinations of geographic location ℓ and supply chain position: downstream domestic (Dn, D), upstream domestic (Up, D), downstream foreign (Dn, F), and upstream foreign (Up, F), constructed as follows:

$$NetworkShock_{j,n,t}^{Dn,D} = \omega_{n,n,\tau}^{j,Ag} ExtremeHeat_{nt} \quad (4)$$

$$NetworkShock_{j,n,t}^{Up,D} = \hat{\omega}_{n,n,\tau}^{j,Ag} ExtremeHeat_{nt} \quad (5)$$

$$NetworkShock_{j,n,t}^{Dn,F} = \sum_{m \neq n} \omega_{n,m,\tau}^{j,Ag} ExtremeHeat_{mt} \quad (6)$$

$$NetworkShock_{j,n,t}^{Up,F} = \sum_{m \neq n} \hat{\omega}_{n,m,\tau}^{j,Ag} ExtremeHeat_{mt} \quad (7)$$

where $ExtremeHeat_{mt}$ measures the crop-weighted extreme heat conditions on agricultural land in country m in year t defined in Equation (1).

3 Empirical patterns

I begin the analysis by bringing together the data presented in Section 2 to document four key empirical facts about i) the relationship between local extreme heat and sectoral production, ii) global patterns of extreme heat conditions, and iii) and iv) on the potential endogenous adjustments of the production network in response to weather variation. Together, these facts help frame the subsequent empirical approach that introduces the role of sectoral interlinkages as a transmission channel of agricultural heat exposure to sectoral economic production domestically and abroad.

Pattern 1: Local extreme heat reduces agriculture value added. To validate my measure of extreme heat exposure, I estimate the sectoral response in per capita GVA growth rate to local extreme heat conditions. Differently than previous cross-country evidence on the channels of the impact of weather shocks on sectoral outcomes (Acevedo et al., 2020; Dell et al., 2012), I estimate sector-specific response functions in

a pooled, multi-country multi-sector sample. This model allows me to jointly estimate responses of sectoral economic production to extreme heat and compare the different response functions, in an econometric specification of the form:

$$\Delta \log(GVA)_{jnt} = f_j(\mathbf{W}_{nt}) + \alpha_{jn} + \mu_{jt} + \varepsilon_{jnt} \quad (8)$$

where I regress the growth rate of GVA per capita in sector j in country n in year t (approximated by the first difference in logarithms) on a sector-specific function of weather variables \mathbf{W} in country n in year t , which includes extreme heat and a second order polynomial of total precipitation. Country-sector α_{jn} fixed effects account for unobserved heterogeneity that influences countries' average sectoral growth rates, such as history, culture, or topography and time-invariant sectoral compositions of national output, and sector-year μ_{jt} fixed effects capture year-specific worldwide shocks, such as El Niño events or global recessions, and shocks to specific sectors (e.g. agricultural commodity price shocks).⁸ Standard errors are clustered at the country level to account for spatial correlation of the error terms across sectors in the same country over time. Equation (8) relies on conventional identifying assumptions in climate impact studies, exploiting plausibly exogenous within-country variation in annual weather fluctuations (Hsiang, 2016).

Figure 1 shows the sector-specific coefficients associated with local extreme heat conditions on sectoral per capita gross value added growth rate. An additional degree day in the extreme heat measure constructed in Equation (1) ($\approx 1\%$ at the sample mean) reduces the agricultural growth rate by 4.6% at the mean. All other five sectors do not respond to extreme heat, with the effect very small in magnitude and statistically indistinguishable from zero. Together, these estimates indicate that extreme heat exposure has substantial negative effects on agricultural value added and does not significantly affect any other sector's production. These average treatment effects may mask heterogeneous effects of local extreme heat by adaptation potential

⁸I do not include any other traditional time-varying determinants of sectoral production - such as investments or capital stocks - since they are endogenous to weather variations and may thus introduce bias in the estimates (Dell et al., 2014).

as measured by income and climate, which I describe in Appendix Section F.⁹

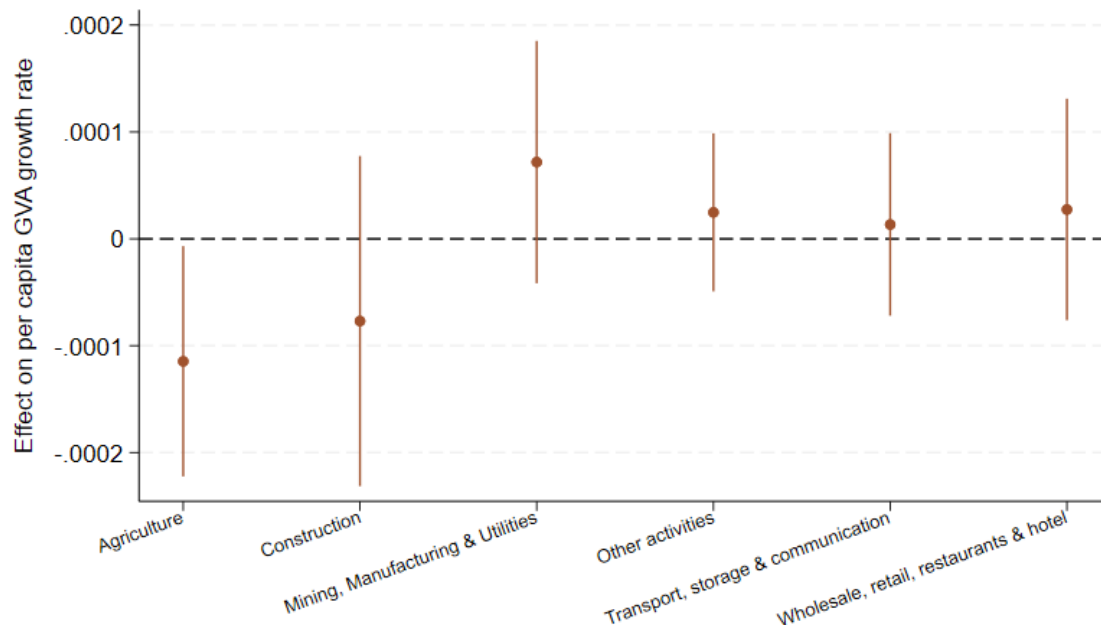
This empirical pattern resonates with previous findings that agriculture is the mostly affected sector in the economy (Dell et al., 2012; Acevedo et al., 2020; Nath et al., 2024). The confidence intervals, however, cannot rule out moderate impacts of extreme heat on other sectors, in particular the construction sector, which would be consistent with this sector’s vulnerability because of investment good production rather than consumption services as provided by the retail sector (Casey et al., 2024). Sectoral heterogeneous impacts of extreme temperatures are also documented in previous micro-level estimates (Nath, 2020), with climate damages on agriculture substantially larger than on non-agricultural production.

Pattern 2: Extreme heat induces a short-lasting price distortions to crops.

Negative effects of extreme heat on agriculture value added combine a price and a quantity effect. To disentangle how much of the local response in supply is driven by changes in price and quantities, I use FAO crop price data measured in current US dollars per ton for the 1991-2020 period. In a crop-country-year event study specification, I estimate the response of crop prices to the crop-specific measure of extreme heat counting degree days and accounting for five lags and leads. Figure 2 shows a substantial price distortion induced by heat conditions that, however, is not persistent over time. Only extreme heat at time t increases crop prices, with the effect vanishing after one year. Appendix Table B4 reports the results in a country-crop panel regression of crop prices on a measure computed as the average exposure to crop-specific maximum optimal growing temperature thresholds on land cultivating a given crop. The empirical pattern documented here is the source for the propagation

⁹I find a comparable and quantitatively similar result with the measure of abnormal heat shocks constructed using the number of days above the 95th percentile of the daily distribution in temperature (Appendix Figure A4). Appendix Figure A5 plots the response in agricultural value added per capita growth rate to changes in terciles or quintiles of the extreme heat distribution. Results are robust to estimating the baseline equation in a balanced panel, excluding large countries (i.e., Brazil, China, India, Russia, US), controlling for lagged growth and to alternative specification and fixed effects (linear and quadratic country-specific trends, sub-region by year fixed effects) (Appendix Figure A6).

Figure 1. Effect on local extreme heat on sectoral per capita value added growth rate

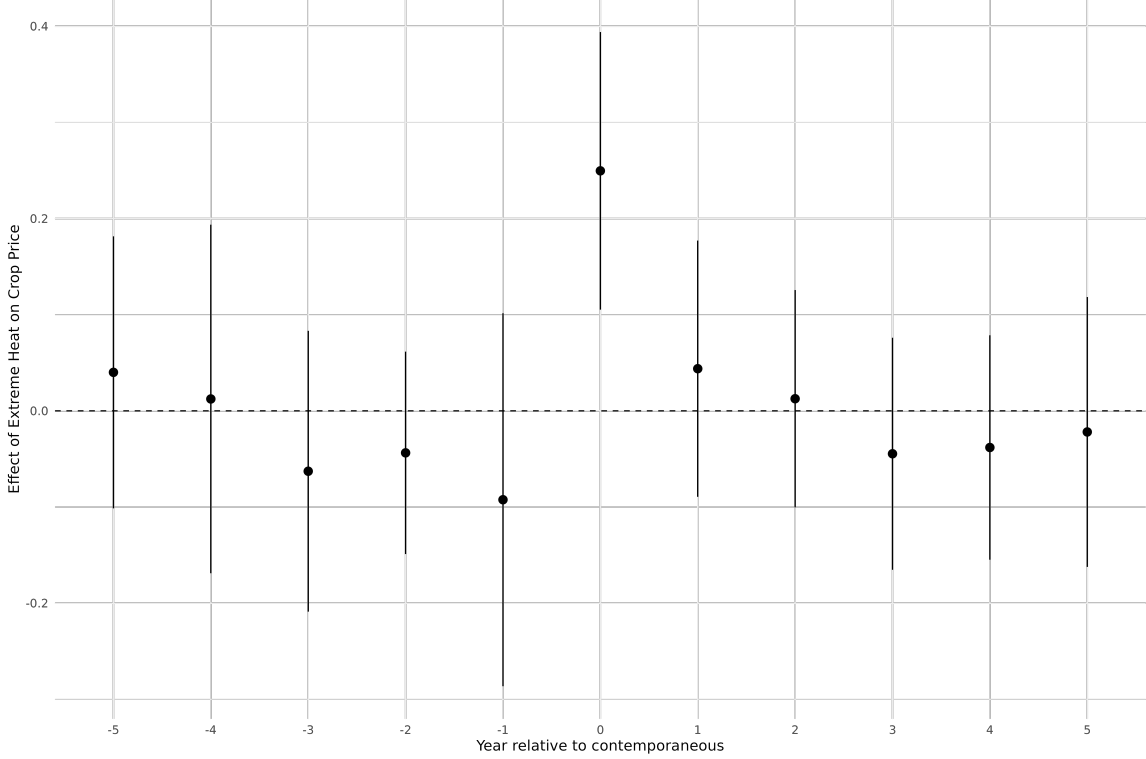


Notes: The figure shows the regression estimates for the country-average number of degree days in the extreme heat exposure for the agricultural sector (constructed as in Equation (1)) and country-sector average number of days above the 95th percentile of the daily distribution in temperature. All sector-specific coefficients are estimated jointly in a stacked regression model fully saturated with country-sector and sector-year fixed effects and allowing for sector-specific response to a quadratic functional form in precipitation. Bins represent the 95% confidence intervals around point estimates. Standard errors are clustered at the country level.

throughout the economy of extreme heat damaging agricultural production that the theoretical model in Section 4 builds upon. A rise in price attributable to extreme heat induces downstream sectors to decrease their demand for the intermediary inputs, consequently leading to a reduction in the production of downstream goods.

Pattern 3: Extreme heat shocks are increasingly spatially correlated. The third empirical pattern relates to the geography of the measure of extreme heat EH exposure for the agricultural sector. I measure the global spatial correlation of extreme heat in each year t using Moran's I, a statistics for spatial autocorrelation that ranges from -1 to 1:

Figure 2. Dynamic Price Effect of Extreme Heat



Notes: The figure reports the regression coefficients on extreme heat from an event study specification where the outcome variable is the crop price (in \$/tonne) from UN FAOStat Crop Price (see Appendix Section C for additional details on the data source). The specification includes five leads and lags of extreme heat exposure controls for a second order polynomial in precipitation, country-crop, crop-year fixed effects and a linear country-specific trend. Bins represent the 95% confidence intervals with standard errors clustered at the country-level.

$$I_t \equiv \frac{N}{\sum_n \sum_{m \neq n} a_{nm}} \frac{\sum_n \sum_{m \neq n} a_{nm} (EH_{nt} - \overline{EH}_t) (EH_{mt} - \overline{EH}_t)}{\sum_\ell (EH_{\ell t} - \overline{EH}_t)^2} \quad (9)$$

where N is the number of countries, $a_{nm} = a_{mn}$ is a (symmetric) spatial weight that depends on the distance between countries n and m , and \overline{EH}_t is the world average extreme heat exposure in year t across countries. Figure 3 plots the time series of the Moran's I statistics. In the 45 years in the sample, the Moran's I ranges from 0.55 to 0.62 with an average equal 0.59 and a strong positive trend over time. This fact suggests that, despite crop-specific temperature thresholds, extreme heat exposure is spatially correlated across countries and increasingly so over time, indicating that crop specialization patterns also follow a similar spatial structure (Dingel et al., 2023).

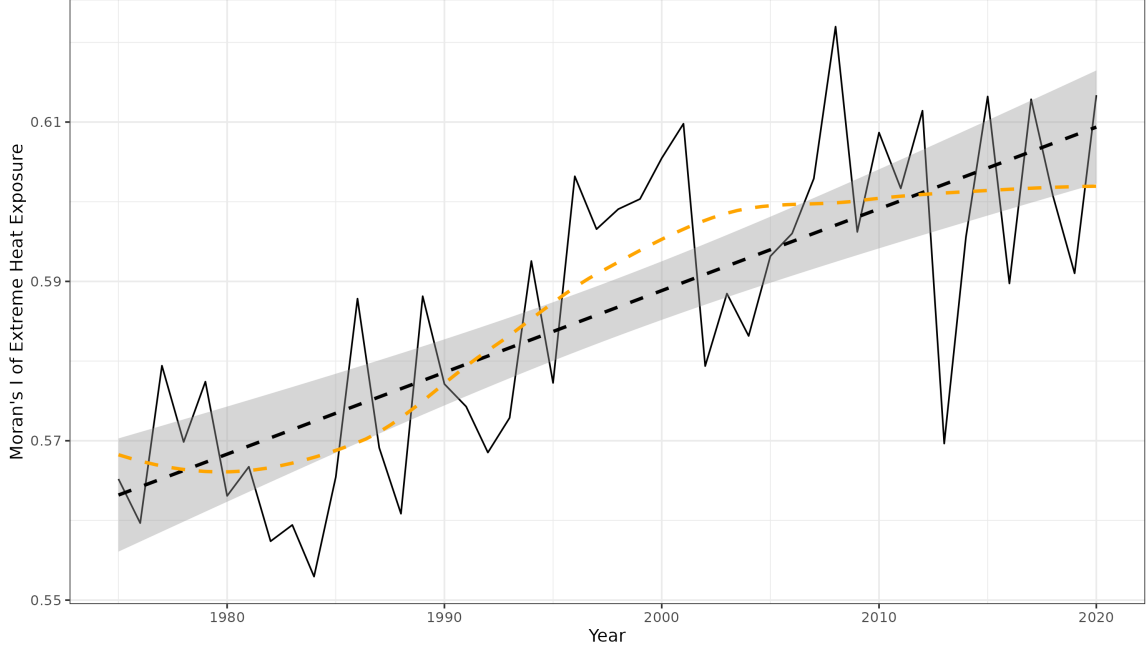
The spatial correlation structure of extreme heat exposure is an additional aggra-

vating factor to well-documented agricultural losses induced by extreme temperatures. Trade costs lead to stronger trade relationships with neighboring countries rather than distant ones (Chaney, 2018). In spite of accounting for differential crop composition of agricultural production across countries, this empirical result suggests that a country experiencing reduced yields due to increases in temperatures is likely to be near other similarly affected countries. This spatial correlation pattern might diminish the potential adaptive role of international trade compared to scenarios where shocks are not spatially correlated.

Furthermore, local temperature fluctuations have been used in quasi-experimental studies that inform climate impact projections (e.g., Burke et al., 2015). In this literature, the effect of local temperatures on an economic outcome is traditionally estimated using quasi-random variation implicitly holding temperatures in other locations fixed. Climate change’s global impact is then computed as the sum of projected local impacts, which, however, hold fixed the spatial structure of temperature and thus correspond to considering many scenarios in which in each scenario only one location experiences warming. Two approaches so far account for the global nature of climate change, in which all locations experience warming simultaneously: cereal productivity depending on spatial correlation induced by global climatic phenomena (Dingel et al., 2023) and controlling for spillovers from neighbouring regions using a spatial-lag model (e.g., Kotz et al., 2024). In either cases, incorporating changes in the spatial correlation exacerbates global welfare inequality and losses induced by changes in climate conditions.

Pattern 4: Downstream agricultural sectoral interlinkages do not respond to extreme heat. One potential concern is that the input-output network described in Section 2.3 is endogenous to the extreme heat. Countries may endogenously respond to extreme heat conditions that hit the agricultural sector by altering sectoral interlinkages and thus the production network structure. A productivity shock

Figure 3. Spatial Correlation of Extreme Heat Exposure



Notes: The figure shows the time series evolution between 1975 and 2020 of the Moran's I Statistic computed as in Equation (3) for the Extreme Heat Exposure constructed in Equation (1). The dashed black line represents the linear fit with the 95% confidence intervals displayed in the gray shaded areas (the coefficient on the linear trend is equal to 0.001, with standard error equal to 0.0001), and the dashed orange line is a local polynomial.

to agriculture may result in a reallocation of resources across sectors in the economy.¹⁰

Previous micro level empirical evidence documents that firms systematically respond to changes in weather conditions by altering their location choice, their supply partner composition and characteristics (Balboni et al., 2023; Castro-Vincenzi et al., 2024; Pankratz and Schiller, 2024). For example, firms may relocate to safer locations, shift purchases towards suppliers in less exposed regions and use less exposed routes. Such endogenous changes in the production network can, in turn, significantly alter the economy's response to exogenous disturbances. To examine whether the production network endogenously adjusts in response to weather shocks, I exploit the time-varying nature of the input-output matrix and estimate the following

¹⁰In a perfectly competitive efficient closed-economy with Cobb-Douglas preferences and technologies, a sector's Domar weight (i.e., the sales share of a sector with respect to the economy's output) is a sufficient statistic for how shocks to that sector impact aggregate output. This result is commonly known as Hulten's theorem (Hulten, 1978). In open-economy models, as the one assumed in Section 4, the sales shares are no longer universal sufficient statistics (Baqae and Farhi, 2024).

specification:

$$IO_{n,m,t}^{Ag,j} = f_{j,\ell}(\mathbf{W}_{n,t}^{Ag}) + \alpha_{jnm} + \mu_{jmt} + \varepsilon_{jnmt} \quad (10)$$

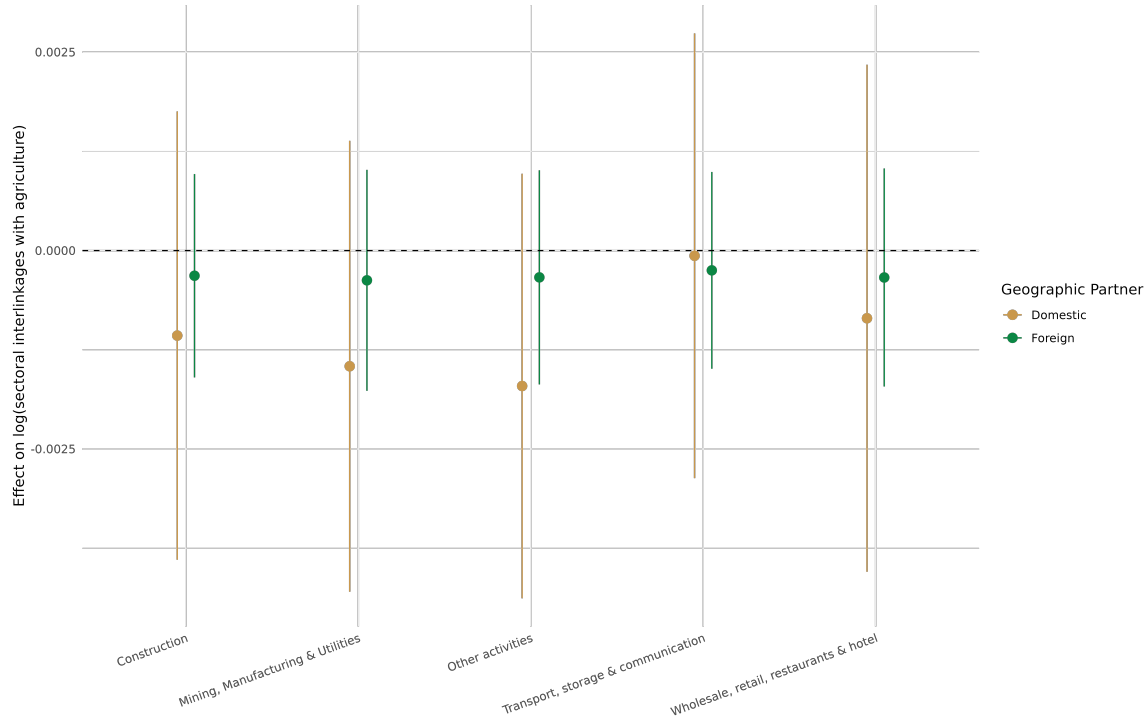
where the outcome variable $IO_{n,m,t}^{j,Ag}$ is the (log) ratio of inputs that sector j in country m sources from the agricultural sector in country n in year t over the total inputs sourced by sector-country (j, m) .¹¹ I exploit inter-annual variation in extreme heat conditions and precipitation $\mathbf{W}_{n,t}^{Ag}$ in the agricultural sector in country n to test for within country-pair-sector changes in intermediate inputs sourced from the agricultural sector. The specification accounts for country-pair-sector α_{inm} and customer country-sector by year μ_{imt} fixed effects (which effectively also accounts for weather conditions in the customer country). To allow for heterogeneous elasticities of substitution, I estimate sector-specific response functions to extreme heat and precipitation conditions and allow elasticities to differ also by location ℓ of the agricultural sector (either domestic or foreign).

Figure 4 reports the sector-location specific coefficients associated with extreme heat on the sectoral interlinkages with agriculture. The ten coefficients, on domestic and foreign agricultural inputs for five downstream sectors, are small and not statistically significant at any conventional level. This pattern suggests that sectors do not endogenously respond to extreme heat hitting their agricultural trade partners by altering their expenditure shares, providing suggestive evidence of the stickiness of production processes.¹² As previously conjectured (Carvalho and Tahbaz-Salehi, 2019), this fact suggests that the Cobb-Douglas model may serve as a good approximation at the sector level, in contrast with previous micro level evidence on firms' ability to substitute inputs and trading patterns in response to idiosyncratic shocks.

¹¹Sector-specific density distribution of the sectoral interlinkages with agriculture are reported in Appendix Figure A3.

¹²Kunze (2021) also documents a small and negligible shift of sectoral interlinkages in response to tropical cyclones.

Figure 4. Response of downstream sectoral interlinkages to extreme heat in agriculture



Notes: The figure shows the sector-location specific coefficients associated with extreme heat on agriculture in a regression where the outcome variable is the log of the ratio of inputs that a sector (in the x-axis) sources from the agricultural sector over the total inputs sourced by each sector-country. All coefficients are estimated jointly in a stacked regression model saturated with country-pair-sector and country-sector-year fixed effects and sector-location specific coefficients on linear and squared term of total precipitation. Bins represent the 95% confidence intervals around point estimates. Standard errors are clustered at the country level.

Pattern 5: Downstream exposure to extreme heat in agriculture does not vary systematically across countries with different GDP per capita. Income is one of the most important factors governing the economics of climate adaptation (Carleton et al., 2022). High-income countries have less binding budget constraints, which could in turn facilitate adaptive behavior and make them less affected by temperature. While this result holds for the economic output response to local weather fluctuations (Dell et al., 2012, and Appendix Section F), I document that downstream exposure to extreme heat in agriculture has been relatively constant over the past forty years across income groups.

As Pattern 4 establishes that sectors do not substantially differ in response to agricultural extreme heat, I pool downstream exposure to extreme heat conditions across sectors in a country and divide the global sample by terciles of income. I construct downstream heat exposure in two ways. First, I measure a country’s exposure to extreme heat allowing the production network to evolve over time and constructing sectoral interlinkages which vary annually. Second, I construct downstream extreme heat exposure using a time-invariant production network where sectoral interlinkages are constructed from the earliest available five-year period of input-output linkages (1970 to 1974). A ratio between these two measures of downstream heat exposure below one would indicate that countries have been able to reduce their exposure to downstream non-local extreme heat conditions. Figure 5 shows a relatively stable and flat ratio statistically indistinguishable from one across income classes, suggesting that, differently than in the case of local extreme heat responses, income does not explain differences in downstream exposure to extreme heat.

Together, these five facts suggest that extreme heat causes substantial economic damage in the agricultural sector, raising crop prices. Downstream sectors are increasingly exposed to upstream extreme heat and do not reallocate input-output interlinkages with the agricultural sector in response to heat, with limited evidence of adaptation potential across income terciles. In the next section, I present a theoretical model that rationalizes the importance of sectoral interlinkages and intermediate input price distortions in climate damage quantification and then bring this model to the empirical estimation.

4 Theoretical framework

I outline a static model of perfect competition with output and input distortions (Hsieh and Klenow, 2009), extending it to a production network where sectors use intermediate inputs (Acemoglu et al., 2012). This model is able to capture how

Figure 5. Downstream exposure to agricultural extreme heat by income terciles



Notes: Each panel in the figure displays the income tercile-specific average (black solid line) ratio of downstream heat exposure computed between a production network where sectoral interlinkages are varying annually and one where sectoral interlinkages are fixed in time averaged between 1970 and 1974. Income terciles are defined averaging for the whole 45-year time period the log of per capita GDP using data from the World Bank’s World Development Indicators. The gray shaded areas represent the 95% confidence intervals.

weather shocks can propagate through the production network, affecting sectors not directly hit by the shock (Acemoglu et al., 2016; Carvalho and Tahbaz-Salehi, 2019). In Appendix Section D, I describe the traditional conceptual framework adopted to derive empirical estimates of the effect of local weather shocks on local economic output.

To match the theoretical framework with the empirical approach, I consider an economy consisting of N regions indexed by $n \in \{1, \dots, N\}$ (or m), each populated with J sectors indexed by $j \in \{1, \dots, J\}$ (or k). A representative firm in each sector produces good j in region n with production possibilities described by a constant returns-to-scale Cobb-Douglas technology whose inputs are capital, labor, and intermediate inputs:

$$Y_n^j = \mathcal{Z}_n^j [(\mathcal{K}_n^j)^\lambda (L_n^j)^{1-\lambda}]^{\omega_n^j} \prod_{k,m}^{J,N} (x_{nm}^{jk})^{\omega_{nm}^{jk}} \quad (11)$$

where total factor productivity \mathcal{Z}_n^j is a product of three components: (i) a region-sector specific component \bar{z}_n^j , (ii) a sector-year specific component \tilde{z}_t^j (capturing for instance differential time trends in technology across sectors), (iii) an exponential vector of Hicks-neutral temperature shocks T_n^j with sector-specific elasticities β_j . Most importantly, intermediate inputs x_{nm}^{jk} enter the production function with constant returns to scale ($\omega_n^j + \sum_{j,m}^{J,N} \omega_{nm}^{jk} = 1$), so that the exponent $\omega_{nm}^{jk} \in [0, 1]$ represents the share of good k from region m in the total intermediate input use by sector j in region n , which can be equal to zero if it is not used. The larger ω_{nm}^{jk} , the more important the good from the sector-region tuple (j, m) . To keep the model simple, all production technologies have the same capital intensity λ and the only difference arises from the intensity with which each sector's good is used as an intermediate input by other sector-regions.

The empirical analysis further differentiates between imported and domestically produced intermediate inputs, keeping the Cobb-Douglas formulation of the production function. This means that I assume that the elasticity of substitution between foreign and domestic intermediate inputs is equal to one.

Expanding Hsieh and Klenow (2009), I introduce heat-induced output distortions $\tau_{Y_n^k}$ and input distortions not only for local factors, $\tau_{KL_n^k}$, but also for intermediate inputs $\tau_{X_n^k}$. In this manner, I introduce heat-induced idiosyncratic distortions accounting for multiple ways in which temperature fluctuations can impact sectoral production.¹³ The representative firm in sector j in region n maximizes profits taking prices as exogenously given and equal to w for labor, r for capital, and q for intermediate inputs, according to the following equation

¹³Firms in regions experiencing extreme heat are more likely to incur additional costs, such as increased energy expenses for cooling, losses due to heat-induced equipment. An example of heat-induced output distortions are border taxes, quantity restrictions, and output subsidies for example documented in Hsiao et al. (2024). I do not distinguish between capital and labor as local factors' distortions, both documented in the literature, respectively, for labor supply and productivity (Graff Zivin and Neidell, 2014; Rode et al., 2022), and capital equipment (Zhang et al., 2018), since they cannot be further disentangled in the data.

$$\max_{\kappa_n^j, L_n^j, x_{nm}^{jk}} \pi_n^j = (1 - \tau_{Y_n^j}) P_n^j Y_n^j - (1 + \tau_{L_n^j})(wL_n^j + rK_n^j) - (1 + \tau_{x_n^j}) \sum_{k,m}^{J,N} q_{k,m} x_{nm}^{jk} \quad (12)$$

Profit maximization under perfect competition gives the usual condition that the firm's output price is equal to its marginal cost. The price is given by

$$P_n^j = \left[\left(\frac{r}{\lambda \omega_n^j} \right)^\lambda \left(\frac{w}{(1-\lambda)\omega_n^j} \right)^{1-\lambda} \right]^{\omega_n^j} \left[\prod_{k,m}^{J,N} \left(\frac{q_{j,m}}{\omega_{jk}^{nm}(1-\omega_n^j)} \right)^{\omega_{jk}^{nm}} \right]^{1-\omega_n^j} \frac{(1 + \tau_{KL,i})^{\omega_n^j} (1 + \tau_{X,i})^{1-\omega_n^j}}{z_n^j (1 - \tau_{Y_i})} \quad (13)$$

in particular, the last term indicates the temperature-induced distortions borne in sector-country j, n which increases optimal price P_n^j , which, in turn, induces customer sectors to decrease their demand for the good Y_n^k and thus leading to a reduction in the production of good Y_n^j . Rewriting input levels as a function of sectoral price P_n^j and deriving the demand of inputs given sector-level production and prices, obtain the output value in sector j in country n is

$$P_n^j Y_n^j = \left[\left(\frac{1}{\lambda \omega_n^j} \right)^\lambda \left(\frac{1}{(1-\lambda)\omega_n^j} \right)^{1-\lambda} \right]^{\omega_n^j} \left[\prod_{k,m}^{J,N} \left(\frac{1}{\omega_{jk}^{nm}(1-\omega_n^j)} \right)^{\omega_{jk}^{nm}} \right]^{1-\omega_n^j} \frac{(1 + \tau_{KL_n^j})^{\omega_n^j} (1 + \tau_{X_n^j})^{1-\omega_n^j}}{1 - \tau_{Y_n^j}} (rK)^{\lambda \omega_n^j} (wL)^{(1-\lambda)\omega_n^j} \left(\prod_{km}^{JN} q_{k,m} x_{jk}^{nm} \right)^{\omega_{nm}^{jk}} \quad (14)$$

which indicates that a supply-side negative shock on intermediate inputs reduces the output value in sector i in country n

To understand the role of production network in propagating local sector-specific weather shocks, consider the example of two sectors j and k in two different regions n and m and assume for simplicity that the latter's output is the only intermediate input that sector j uses. Therefore, sector j 's output (with lowercase letters indicating logs) is written as:

$$\begin{aligned}
y_{nt}^j &= \underbrace{\log \bar{z}_n^j + \log \bar{z}_t^j + f(T_{nt}^j, \beta_j) + \omega_n^j \lambda k_n^j + \omega_n^j (1 - \lambda) l_{nt}^j}_{\Xi_{nt}^j} + \omega_{nm}^{jk} \log(x_{nm}^{jk}) \\
&= \Xi_{nt}^j + \omega_{nm}^{jk} (\dots + f(T_{mt}^j, \beta_j) + \dots)
\end{aligned} \tag{15}$$

Using Equation (D.18) to move from the first to the second line, this example showcases that a temperature shock would reduce input production k in region m and thus affect sector j 's output in region n with elasticity ω_{nm}^{jk} due to the effect of temperatures on its suppliers. In particular, the increase in sector k 's output price due to temperature changes induces sector j , which uses sector k 's output in their input bundle, will reduce its demand for sector k 's output, therefore reducing its own output.

The relative weight of shocks in the production network is given by the share of good j within the total intermediate inputs used by sector j , which corresponds to the entries of the $(J \cdot N \times J \cdot N)$ input-output matrix $\mathbf{\Omega} = [\omega_{nm}^{jk}]$.¹⁴ The matrix (whose rows sum up to one because of constant return-to-scale technologies, and whose columns are the shares of sector j 's output within the total inputs used by the other sectors) accounts for first-order effects of propagation through first-degree sectoral interlinkages. To account for higher-order interlinkages, one can compute the Leontief inverse matrix as $\mathbf{L} = (\mathbf{I} - \mathbf{\Omega})^{-1}$, whose (j, k) elements denote the importance of sector k as a direct and indirect supplier to sector j . The inner product of elements ω in the input-output matrix $\mathbf{\Omega}$ (or ℓ in the Leontief matrix) and the temperature vector gives the aggregate economic cost of warming. Hereinafter, I explain how I bring this model to the data and quantify the cost of local and network weather shocks on the economy.

¹⁴The assumption on the Cobb-Douglas production technology has two main implications. First, downstream effects emerge only in the case of supply-side shocks. Vice versa, upstream effects would be detected only in the case of demand shocks. Second, it ensures that a sector's expenditure on various inputs as a fraction of its output is invariant to the shocks and is thus exogenous in the model. Carvalho et al. (2021) study a more complex case with production functions with a nested constant elasticity of substitution structure and show the propagation of shocks through two distinct channels using a first-order approximation in the elasticities of substitution between various intermediate inputs or between the intermediates and primary factors of production.

5 Empirical approach

The baseline empirical approach builds on the conventional methodology adopted in quasi-experimental climate impact studies and it introduces a parametric measure of spillovers to analyze how extreme heat conditions in agriculture affect sectoral economic production domestically and abroad.

The traditional fixed-effect model (e.g., Dell et al., 2012; Burke et al., 2015) typically estimates local direct effects of temperatures but ignores spatial linkages, by implicitly assuming that the residual variation in weather is orthogonal to variations in weather elsewhere. Estimates obtained from traditional equations in the style of Equation (8) may thus be biased when omitting trade linkages across observational units by violating the stable unit treatment value assumption. Potential outcomes for a sector-country may vary with the treatment assigned to other sector-countries they use inputs from. Spatial considerations are of first-order relevance because the economy and climate are linked across space, which results in violations of common identifying assumptions with first-order effects.

To introduce a new impact channel of weather shocks rippling through the supply chain via sectoral interlinkages, I design an econometric specification that builds on Equation (8), but parametrically accounts for *network* shocks:

$$\Delta \log(GVA)_{jnt} = f_j(\mathbf{W}_{jnt}; \beta_j) + \sum_{\ell \in \{D; F\}} \gamma_{j,\ell} NetworkShock_{jnt}^{Dn,\ell} + \alpha_{jn} + \mu_{jt} + \eta_{jnt} \quad (16)$$

where I regress the growth rate of GVA per capita in sector j in country n in year t for all five sectors in the economy on a sector-specific function of local weather conditions \mathbf{W} in country n in year t , including abnormal hot days and a second order polynomial of total precipitation.¹⁵ Most importantly, the specification includes a measure of $NetworkShock_{jnt}^{Dn,\ell}$, defined as extreme heat conditions in agriculture weighted by downstream interdependence of sector j with the agricultural sector

¹⁵The estimation sample does not account for agriculture since local and domestic network shocks would be collinear up to a constant.

in geographic location ℓ (where $\ell \in \{\text{Domestic}; \text{Foreign}\}$). The specification also accounts for country-sector α_{jn} and sector-year μ_{jt} fixed effects.

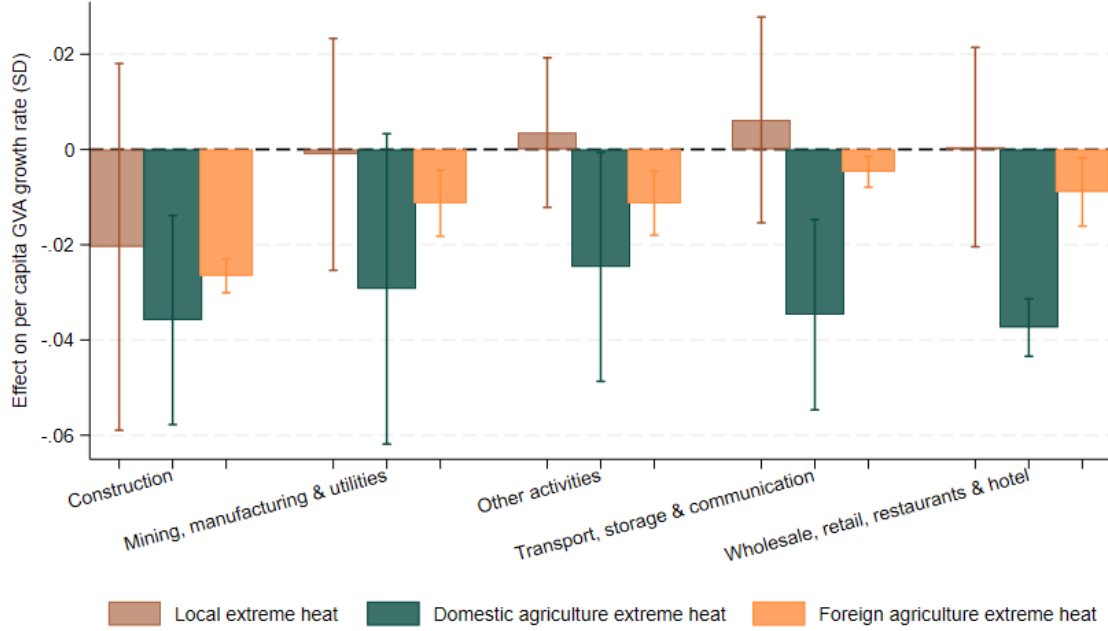
This approach aims at quantifying the impact on sectoral production of trade-induced exposure to harmful extreme heat conditions in agriculture. As formulated in the theoretical framework and supported by the empirical evidence, extreme heat reduces agricultural productivity. By only considering the *direct* impact of local weather conditions on a given sector, one is omitting the amplification and transmission of these shocks due to the intersectoral reliance. A negligible or null effect of local weather conditions on a given sector may be amplified by extreme heat conditions hitting agricultural sectors around the world with strong commercial interlinkages with that sector. The effect would ripple down to downstream customer sectors that then use agricultural inputs less intensively in response to increases in agricultural prices and thus reduce their own production.

6 Heat shocks in a production network

In this section, I report the results from the estimation of Equation (16) that quantifies the propagation of extreme heat on agriculture across the economy through the production network. Figure 6 displays the (standardized) coefficients associated with local extreme heat conditions and downstream agricultural *network* heat decomposed into domestic and foreign.

Starting from the coefficients on local extreme heat, the estimated effect on all sectors is not statistically distinguishable from zero. Both domestic and foreign extreme heat conditions in agriculture have a negative and sizable effect on economic production in all the five sectors of the economy. Aggregating domestic and foreign estimates, the magnitude of network shocks is substantially larger for the construction sector, which relies heavily on various inputs from agriculture (e.g., timber, bamboo, straw and hay, natural fibers, plant-based binders, soil and gravel, biofuels, geotextiles) and produces investment goods, more vulnerable to climate change than e.g. the retail sector, which primarily produces consumption services (Casey et al., 2024).

Figure 6. Local and downstream agricultural extreme heat on sectoral production



Notes: Bars represent the (standardized) sector-specific coefficients associated with local shocks and domestic and foreign downstream shocks, using the extreme heat exposure measure constructed as in Equation (1). Domestic and foreign downstream shocks are constructed respectively as in Equations (4) and (6). The specification jointly estimates all sector-specific coefficients in a stacked regression model fully saturated with country-sector and sector-year fixed effects and sector-specific responses to a second-order polynomial of total precipitation. Bins represent the 95% confidence intervals with standard errors clustered at the country level.

Altogether, these findings have two consequences in the interpretation of previous temperature-output relationships. First, from a methodological perspective, sector-specific estimates that only account for local weather shocks may be biased since the treatment status of other units in the sample alters the potential expected outcome through shocks propagating from the agriculture sector. The statistical and economic significance of foreign network shocks suggests that also geographically distant weather fluctuations matter through trade interlinkages. Second, from an economic perspective, agriculture-specific extreme heat conditions are amplified through input-output interlinkages, affecting other sectors beyond agriculture and also travelling beyond national borders. As a result, recent estimates on the economic damage of temperature increases may have been largely underestimated due to the omission of

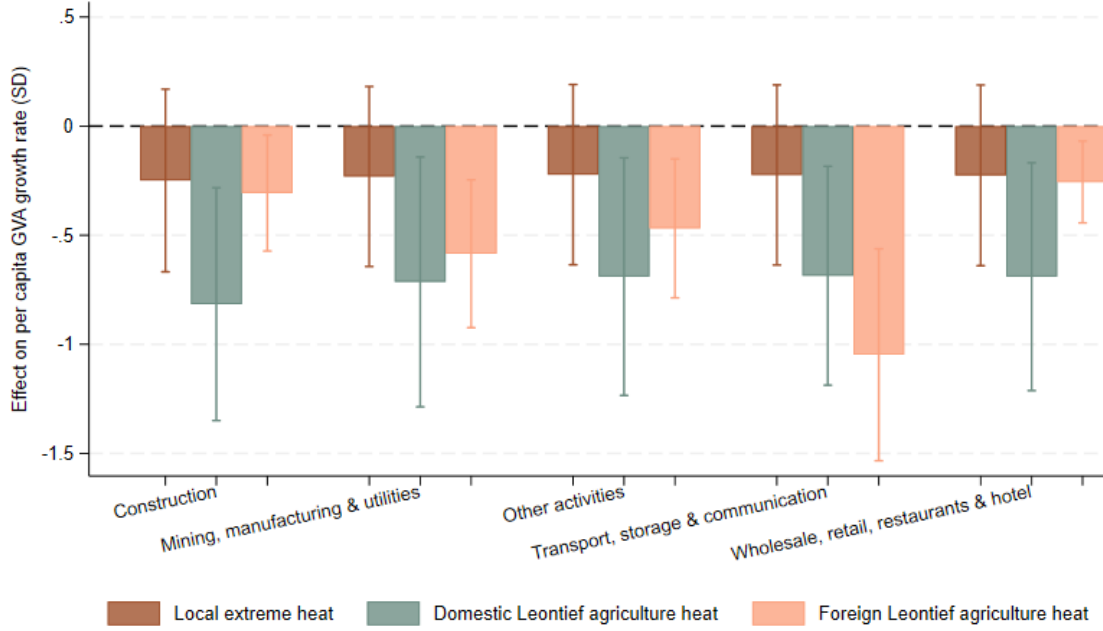
this propagation channel.

To address potential concerns on spatially correlated patterns in extreme heat, I exploit local variation in extreme heat uncorrelated with contemporaneous weather elsewhere within the same region, by accounting for year-specific fixed effects at the regional level (Deschênes and Meng, 2018) (Appendix Figure A7). Results are also robust to estimating the equation with country-specific linear trends, using a balanced panel, and excluding large countries.

As a test for the validity of the Cobb-Douglas production function assumed in Section 4, Appendix Figure A8 shows that agriculture extreme heat does not propagate upstream, as a demand-side shocks would do, but only downstream, confirming the interpretation of extreme heat in agriculture as a supply-side productivity shock.

Beyond first-degree sectoral interlinkages. The analysis has so far relied on first-degree sectoral interlinkages in the production network. To account for the full transmission of shocks over the network, I construct the Leontief inverse matrix, which summarizes the sector-specific technical coefficients of the shock propagation through a power series representation of the Leontief inverse (Leontief, 1970). By taking the inner product of agricultural heat shocks and the Leontief inverse matrix, I obtain a sector-specific shock that takes full inter-sectoral relations into account. I estimate a specification with agricultural heat shocks weighted by the Leontief-derived downstream coefficients and report the coefficients in Figure 7. Both domestic and foreign agricultural heat shocks are strongly negative and statistically significant, with domestic shocks larger in magnitude and both shocks larger in magnitude than when only accounting for first-degree sectoral interlinkages. The results suggest that downstream propagation of heat-induced productivity shocks in the agricultural sector has quantitatively sizable effects on the rest of the economy both from direct and indirect suppliers.

Figure 7. Sector-specific response to agriculture extreme heat in a Leontief matrix



Notes: Bars represent the (standardized) sector-specific coefficients associated with local extreme heat shocks and domestic and foreign downstream shocks constructed using , using the extreme heat exposure measure constructed as in Equation (1). Domestic and foreign downstream shocks are constructed respectively as in Equations (4) and (6), with sectoral interlinkages obtained from the Leontief inverse matrix obtained from the downstream sectoral interlinkages obtained as in Section 2.3. The specification jointly estimates all sector-specific coefficients in a stacked regression model fully saturated with country-sector, country-year, and sector-year fixed effects and accounting for sector-specific responses to a second-order polynomial of total precipitation. Bins represent the 95% confidence intervals with standard errors clustered at the country level.

7 Counterfactuals: Cost of recent warming in a production network

To assess the economic importance of the propagation of extreme heat in agriculture through production networks, I perform two counterfactual analyses. First, I compare the differential sectoral output losses/benefits as a result of recent historical warming omitting and accounting for extreme heat conditions in the agriculture sector in the production network. Prior research quantifies and projects the impact of temperature increases assuming a counterfactual with no further warming (Burke et al., 2015; Burke and Tanutama, 2019; Kalkuhl and Wenz, 2020). To account for adaptive adjustments to changes in climate, I simulate how much slower or faster each sector

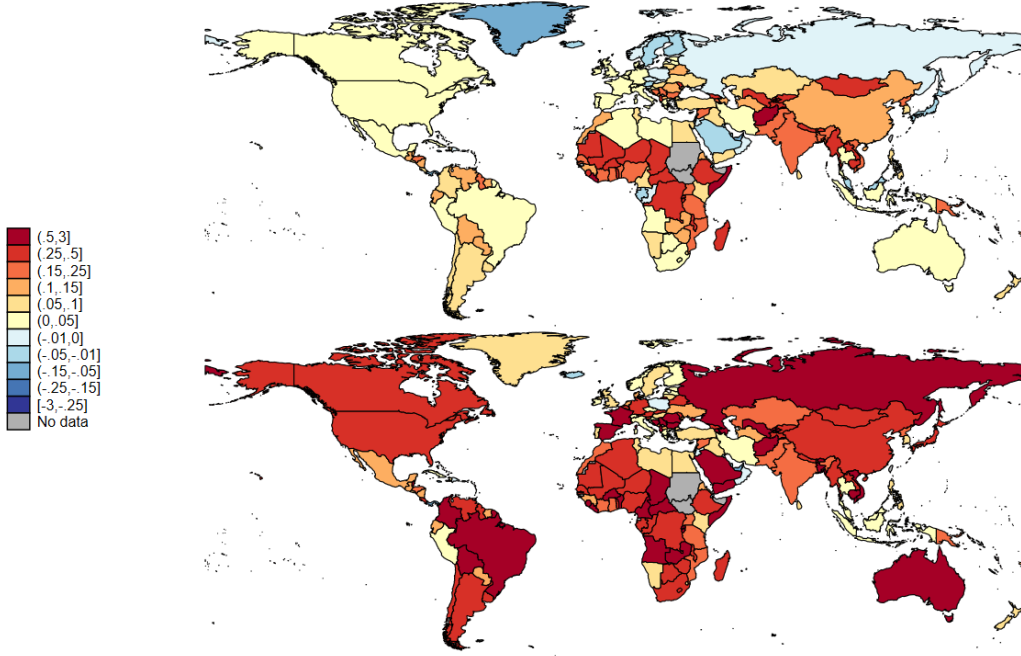
would have grown over the 2001-2020 period, compared to a counterfactual in which daily temperature linearly evolves from its 1970-2000 long-run average (see Appendix Section G for additional details).

Omitting shocks in the agricultural sector partners substantially underestimates the losses due to recent warming. The pooled average loss in annual GVA per capita across sectors using only local shocks is 0.02% (-0.08% median, IQR [-0.29, 0.09]), whereas it is 0.32% (0.15% median, IQR [-0.13, 0.73]), accounting for network shocks. Damages are particularly larger in those sectors that appear sheltered from local shocks (other activities; transport, storage and communications), while there is larger heterogeneity in relative losses in construction and wholesale, retail, hotel and restaurants: larger damages in Sub-Saharan Africa, Latin America and South-East Asia are offset by modest benefits in Northern Europe and the Middle East. Using the country's baseline sectoral breakdown of total GVA between 1996 and 2000, I aggregate sector-specific damages to obtain the total national average relative losses, displayed in Figure 8. Accounting for network extreme heat in agriculture, country-level damages are substantial (0.33% mean, 0.26% median, IQR [0.06, 0.53]) and around three times larger than when omitting shock propagation (0.10% mean, 0.05% median, IQR [0.00, 0.17]).

In a second exercise, I quantify the macroeconomic impact of an increase in one degree day in extreme heat conditions in a region or country from 2000 onwards. Figure 9 reports the average annual global losses. The highest average loss (≈ 322 million 2015US\$) is recorded if all agricultural sectors in the world experience an additional degree day. Large losses are also recorded if Sub-Saharan Africa, Eastern Europe, Eastern Asia or Latin America and the Caribbean suffer an additional degree day in extreme heat. These regions, if shocked, induce larger losses on average due to larger relative damages on local economic production. An alternative mechanism could be explained by a scale effect since these regions have the largest number of countries contemporaneously shocked.

I also compute average annual global losses if one single country experiences an additional degree day in extreme heat (right-hand side of Figure 9). The importance

Figure 8. Average annual per capita GVA losses (%) due to recent warming



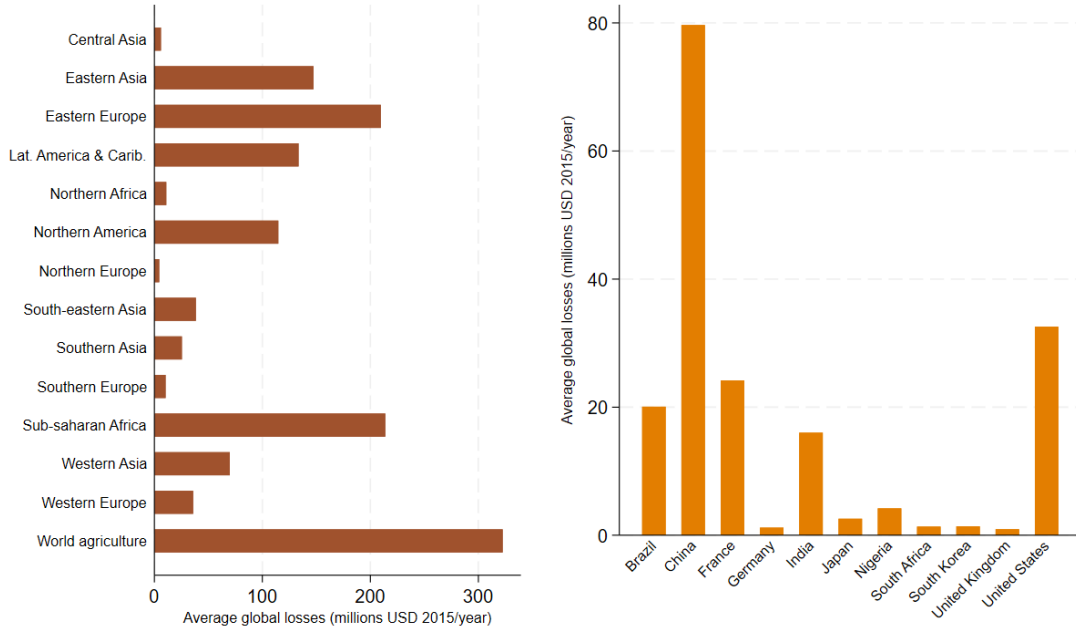
Notes: The figure shows the average annual losses (in red) and gains (in blue) in per capita GVA (%) compared to a counterfactual daily temperature evolved linearly from the trend estimated over the period 1970-2000. Sector-specific damages are weighted by the average sectoral share of total GVA between 1996 and 2000. The world map above only accounts for sector-specific local extreme heat conditions. The world map below accounts for indirect extreme heat in agriculture using sector-specific semi-elasticities from bootstrapping 1000 times the underlying panel estimates of Equation (16). Table B5 reports the sector-specific losses significant at 95% level estimated with 1000 bootstrap replications with replacement.

of the country in the production networks substantially matters for the magnitude of heat-induced losses. On average, global losses are at the highest for an additional degree day in China (≈ 80 million 2015US\$) and in other countries such as Brazil (≈ 20 million 2015US\$), France (≈ 24 million 2015US\$), India (≈ 16 million 2015US\$), and the United States (≈ 32 million 2015US\$).¹⁶ These losses are sizable since they are obtained for an increase by one in the extreme heat measure of degree days. Extreme heat has substantially increased over the time period considered. For example, the decadal average extreme heat in China in the 1970s was 16.4 degree days/year and reached 23.3 degree days/year in the 2010s. Similarly, extreme heat conditions in Brazil increased from 21.22 degree days/year to 40.6 degree days/year and from

¹⁶Together, these five countries make up more than 45% of world crop output (Costinot et al., 2016).

41.1 degree days/year to 55.7 days/year in the US.

Figure 9. Average annual global losses due to an additional degree day in extreme heat in agriculture in a specific sub-region (left) or country (right)



Notes: The figure shows the average annual global losses in 2015\$ million by perturbing the production network with an additional degree day in agricultural extreme heat conditions in the sub-region (resp. country) reported in the y-axis (x-axis), using sector-specific semi-elasticities from Equation (16), where indirect shocks are constructed with a time-varying production network that uses the first five-year average input-output interlinkages for each decade. Global averages only consider country-specific losses significant at the 95% level using 1000 bootstrap replications with replacement.

8 Conclusion

Recent studies have pushed forward the frontier for an accurate estimation of climate damages across sectors for an adequate quantification of the total economic impact of climate change. This paper contributes to this effort by shedding light on a new potential component of climate damages, arising from the propagation of weather shocks through production networks across sectors and countries, and over time. Complementing firm-level evidence on the spillover effects of natural disaster shocks, I build on prior research on production networks (Acemoglu et al., 2012) to quantify

the economic cost of global warming. The methodology is applied to global production networks constructed from input-output sectoral interlinkages for the past 50 years and sectoral value added data combined with high-resolution daily temperature and precipitation data.

The analysis reveals that the amplification mechanism of weather shocks persists at the sector level across the world and generates substantial fluctuations in sectoral production. Downstream sectors unresponsive to local weather suffer economic losses due to the interdependence of their production process with the domestic and foreign agricultural sectors that are hit by extreme heat conditions. In particular, sectors at later stages of the supply chain are negatively impacted by supply-side agricultural heat shocks that propagate downstream. In light of the negative impact of indirect extreme heat conditions in agriculture on other sectors, these findings suggest that climate damages may be larger than indicated by standard empirical approaches and integrated assessment models that do not account for trade interlinkages.

The findings point to the structure of sectoral production network linkages as a key driver of aggregate fluctuations induced by extreme heat. In particular, they indicate that even if most sectors with the exception of agriculture are sheltered from local weather fluctuations, the potential propagation of shocks over the economy's production network can impact them, thus resulting in movements in macroeconomic aggregates. Using the reduced-form estimates of my analysis to inform counterfactual simulations, I show that the omission of input-output linkages as a mechanism for the propagation and amplification of extreme heat conditions in agriculture may lead to approximately a threefold underestimation of the effect of recent warming around the world (0.1% vis-à-vis 0.33% of per capita GVA accounting for sectoral interlinkages) and global losses are sizable even for just a single country being shocked in isolation, suggesting that countries that are more central in the production network can induce larger global losses when experience more extreme heat conditions.

Several important issues remain open to future research. First, the analysis provides modest but suggestive evidence on the role of adaptation of countries, in particular, that the effect of local extreme heat condition depends on climate and income.

There is, however, little evidence of countries' ability to reduce their exposure to upstream extreme heat in agriculture. The analysis does not explicitly model adaptive investments, technological change, or other agriculture-specific adaptive responses (e.g. irrigation) that may heterogeneously affect the response functions and reduce climate damage. Moreover, crop-specific extreme heat conditions are computed over a time-invariant measure of agricultural land that does not allow for crop specialization adjustments, a crucial adaptive margin that can help mitigate climate damages (Costinot et al., 2016). Accounting for this and other adaptive margins may alter the propagation of extreme heat conditions in agriculture in countries that are more sheltered.

Second, the transmission of weather shocks is studied through the relative importance of trade partners in input-output interlinkages in a Cobb-Douglas economy. Productivity shocks in agriculture may impact the output of other sectors via two distinct channels. First, the resulting increase in the impacted sector's good price adversely affects sectors that rely on that good as intermediate input for production. Second, extreme heat conditions may also lead to reallocation of resources across sectors depending on the elasticities of substitution across inputs. The input specificity and different elasticities of substitution would lead to the impact of agricultural productivity shock to not remain confined to downstream sectors (Barrot and Sauvagnat, 2016). This channel has only been documented at the firm level, and although I find evidence consistent with the Cobb-Douglas model being a good approximation at the sector level, additional layers of production heterogeneity could shed light on the exact channel of transmission of agriculture extreme heat conditions through the economy.

Third, the analysis is mostly silent about agents' climate beliefs and expectation formation processes. Despite the use of implicit and explicit models of adaptation accounting for long-run climate, income and adjustments in sectoral interlinkages, adaptive behavior reflects agents' perceptions more than actual meteorological conditions, with inaccurate beliefs explaining substantial economic losses due to inadequate adaptation (Zappalà, 2024). Similarly, expectations also matter in accounting for adaptation costs and benefits (Shrader, 2021). Future research should focus on

accounting for heterogeneous beliefs and expectations in production networks and supply-chain relationships, modelling the learning process about underlying weather risk from weather shock realizations and adaptive responses.

References

- Acemoglu, D., U. Akcigit, and W. Kerr (2016). Networks and the macroeconomy: An empirical exploration. *NBER macroeconomics annual* 30(1), 273–335.
- Acemoglu, D., V. M. Carvalho, A. Ozdaglar, and A. Tahbaz-Salehi (2012). The network origins of aggregate fluctuations. *Econometrica* 80(5), 1977–2016.
- Acevedo, S., M. Mrkaic, N. Novta, E. Pugacheva, and P. Topalova (2020). The effects of weather shocks on economic activity: what are the channels of impact? *Journal of Macroeconomics* 65, 103207.
- Akyapi, B., M. Bellon, and E. Massetti (2024). Estimating macro-fiscal effects of climate shocks from billions of geospatial weather observations. *American Economic Journal: Macroeconomics*. *Forthcoming*.
- Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim, and T. W. Owen (2012). NOAA’s 1981–2010 US climate normals: an overview. *Bulletin of the American Meteorological Society* 93(11), 1687–1697.
- Balboni, C., J. Boehm, and M. Waseem (2023). Firm adaptation and production networks: Structural evidence from extreme weather events in Pakistan. Working Paper, Structural Transformation and Economic Growth (STEG).
- Baqaei, D. R. and E. Farhi (2024). Networks, barriers, and trade. *Econometrica* 92(2), 505–541.
- Barrage, L. (2020). Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy. *The Review of Economic Studies* 87(1), 1–39.
- Barrot, J.-N. and J. Sauvagnat (2016). Input specificity and the propagation of idiosyncratic shocks in production networks. *The Quarterly Journal of Economics* 131(3), 1543–1592.
- Berg, K. A., C. C. Curtis, and N. C. Mark (2024). GDP and temperature: Evidence on cross-country response heterogeneity. *European Economic Review*, 104833.

- Bilal, A. and D. R. Känzig (2024). The macroeconomic impact of climate change: Global vs. local temperature. NBER Working Papers 32450, National Bureau of Economic Research.
- Boehm, C. E., A. Flaaen, and N. Pandalai-Nayar (2019). Input linkages and the transmission of shocks: Firm-level evidence from the 2011 Tōhoku earthquake. *Review of Economics and Statistics* 101(1), 60–75.
- Borusyak, K., P. Hull, and X. Jaravel (2022). Quasi-experimental shift-share research designs. *The Review of Economic Studies* 89(1), 181–213.
- Bright, E. and P. Coleman (2001). Landsat global 2000 [data set]. *Oak Ridge National Laboratory*. <https://doi.org/10.48690/1524196>.
- Burke, M., W. M. Davis, and N. S. Diffenbaugh (2018). Large potential reduction in economic damages under un mitigation targets. *Nature* 557(7706), 549–553.
- Burke, M., S. Hsiang, and E. Miguel (2015). Global non-linear effect of temperature on economic production. *Nature* 527(7577), 235–239.
- Burke, M. and V. Tanutama (2019). Climatic constraints on aggregate economic output. NBER Working Papers 25779, National Bureau of Economic Research.
- Carleton, T., A. Jina, M. Delgado, M. Greenstone, T. Houser, S. Hsiang, A. Hultgren, R. E. Kopp, K. E. McCusker, I. Nath, et al. (2022). Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *The Quarterly Journal of Economics* 137(4), 2037–2105.
- Carvalho, V. M., M. Nirei, Y. U. Saito, and A. Tahbaz-Salehi (2021). Supply chain disruptions: Evidence from the Great East Japan earthquake. *The Quarterly Journal of Economics* 136(2), 1255–1321.
- Carvalho, V. M. and A. Tahbaz-Salehi (2019). Production networks: A primer. *Annual Review of Economics* 11, 635–663.

- Caselli, F., M. Koren, M. Lisicky, and S. Tenreyro (2020). Diversification through trade. *The Quarterly Journal of Economics* 135(1), 449–502.
- Casey, G., S. Fried, and M. Gibson (2024). Understanding climate damages: Consumption versus investment. *European Economic Review*, 104799.
- Castro-Vincenzi, J., G. Khanna, N. Morales, and N. Pandalai-Nayar (2024). Weathering the storm: Supply chains and climate risk. NBER Working Papers 32218, National Bureau of Economic Research.
- Chaney, T. (2018). The gravity equation in international trade: An explanation. *Journal of Political Economy* 126(1), 150–177.
- Costinot, A., D. Donaldson, and C. Smith (2016). Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy* 124(1), 205–248.
- Dell, M., B. F. Jones, and B. A. Olken (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics* 4(3), 66–95.
- Dell, M., B. F. Jones, and B. A. Olken (2014). What do we learn from the weather? the new climate-economy literature. *Journal of Economic Literature* 52(3), 740–98.
- Deschênes, O. and K. Meng (2018). Quasi-experimental methods in environmental economics: Opportunities and challenges. In P. Dasgupta, S. K. Pattanayak, and K. Smith (Eds.), *Handbook of Environmental Economics*, Volume 4, pp. 285–332. Elsevier.
- di Giovanni, J. and A. A. Levchenko (2009). Trade openness and volatility. *The Review of Economics and Statistics* 91(3), 558–585.
- Dingel, J., K. Meng, and S. Hsiang (2023). Spatial correlation, trade, and inequality: Evidence from the global climate. NBER Working Papers 25447, National Bureau of Economic Research.

- Farrokhi, F. and H. S. Pellegrina (2023). Trade, technology, and agricultural productivity. *Journal of Political Economy* 131(9), 2509–2555.
- Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82(1), 41–88.
- Graff Zivin, J. and M. Neidell (2014). Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics* 32(1), 1–26.
- Hsiang, S. (2010). Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences* 107(35), 15367–15372.
- Hsiang, S. (2016). Climate econometrics. *Annual Review of Resource Economics* 8, 43–75.
- Hsiao, A., J. Moscona, and K. Sastry (2024). Food policy in a warming world. NBER Working Papers 32539, National Bureau of Economic Research.
- Hsieh, C.-T. and P. J. Klenow (2009). Misallocation and manufacturing tfp in china and india. *The Quarterly journal of economics* 124(4), 1403–1448.
- Hulten, C. R. (1978). Growth accounting with intermediate inputs. *The Review of Economic Studies* 45(3), 511–518.
- Hultgren, A., T. Carleton, M. Delgado, D. R. Gergel, M. Greenstone, T. Houser, S. Hsiang, A. Jina, R. E. Kopp, S. B. Malevich, et al. (2022). Estimating global impacts to agriculture from climate change accounting for adaptation. Available at SSRN: <https://ssrn.com/abstract=4222020>.
- Kahn, M. E., K. Mohaddes, R. N. Ng, M. H. Pesaran, M. Raissi, and J.-C. Yang (2021). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics* 104, 105624.

- Kalkuhl, M. and L. Wenz (2020). The impact of climate conditions on economic production. evidence from a global panel of regions. *Journal of Environmental Economics and Management* 103, 102360.
- Kanemoto, K., M. Lenzen, A. Geschke, and D. Moran (2011). Building Eora: a global multi-region input output model at high country and sector. In *19th International Input-Output Conference*.
- Kotz, M., A. Levermann, and L. Wenz (2024). The economic commitment of climate change. *Nature* 628(8008), 551–557.
- Kotz, M., L. Wenz, A. Stechemesser, M. Kalkuhl, and A. Levermann (2021). Day-to-day temperature variability reduces economic growth. *Nature Climate Change* 11(4), 319–325.
- Kunze, S. (2021). Unraveling the effects of tropical cyclones on economic sectors worldwide: direct and indirect impacts. *Environmental and Resource Economics* 78(4), 545–569.
- Lenzen, M., K. Kanemoto, D. Moran, and A. Geschke (2012). Mapping the structure of the world economy. *Environmental Science & Technology* 46(15), 8374–8381.
- Leontief, W. (1970). Environmental repercussions and the economic structure: an input-output approach. *The Review of Economics and Statistics*, 262–271.
- Letta, M. and R. S. Tol (2019). Weather, climate and total factor productivity. *Environmental and Resource Economics* 73(1), 283–305.
- Monfreda, C., N. Ramankutty, and J. A. Foley (2008). Farming the planet: 2. geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global biogeochemical cycles* 22(1).
- Moscona, J. and K. A. Sastry (2023). Does directed innovation mitigate climate damage? evidence from us agriculture. *The Quarterly Journal of Economics* 138(2), 637–701.

- Muñoz Sabater, J. (2019). ERA5 hourly data on single levels from 1950 to present. Accessed: 08-11-2023.
- Nath, I. (2020). Climate change, the food problem, and the challenge of adaptation through sectoral reallocation. NBER Working Papers 27297, National Bureau of Economic Research.
- Nath, I., V. A. Ramey, and P. J. Klenow (2024). How much will global warming cool global growth? NBER Working Papers 32761, National Bureau of Economic Research.
- Newell, R. G., B. C. Prest, and S. E. Sexton (2021). The GDP-temperature relationship: implications for climate change damages. *Journal of Environmental Economics and Management* 108, 102445.
- Ortiz-Bobea, A., T. R. Ault, C. M. Carrillo, R. G. Chambers, and D. B. Lobell (2021). Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change* 11(4), 306–312.
- Pankratz, N. M. and C. M. Schiller (2024). Climate change and adaptation in global supply-chain networks. *The Review of Financial Studies* 37(6), 1729–1777.
- Rode, A., R. E. Baker, T. Carleton, A. D’Agostino, M. Delgado, T. Foreman, D. R. Gergel, M. Greenstone, T. Houser, S. Hsiang, et al. (2022). Labor disutility in a warmer world: The impact of climate change on the global workforce. *Working Paper*.
- Rudik, I., G. Lyn, W. Tan, and A. Ortiz-Bobea (2024). The economic effects of climate change in dynamic spatial equilibrium. *Working Paper*.
- Schlenker, W. and M. J. Roberts (2009). Nonlinear temperature effects indicate severe damages to us crop yields under climate change. *Proceedings of the National Academy of Sciences* 106(37), 15594–15598.

- Shrader, J. (2021). Improving climate damage estimates by accounting for adaptation. *Working Paper*.
- Tol, R. S. (2022). A meta-analysis of the total economic impact of climate change. *arXiv preprint arXiv:2207.12199*.
- UNSD (2022). Gross Value Added by Kind of Economic Activity at constant (2015) prices - US dollars. ISIC Revision 3.1.
- Zappalà, G. (2024). Adapting to climate change accounting for individual beliefs. *Journal of Development Economics*, 103289.
- Zhang, P., O. Deschênes, K. Meng, and J. Zhang (2018). Temperature effects on productivity and factor reallocation: Evidence from a half million Chinese manufacturing plants. *Journal of Environmental Economics and Management* 88, 1–17.

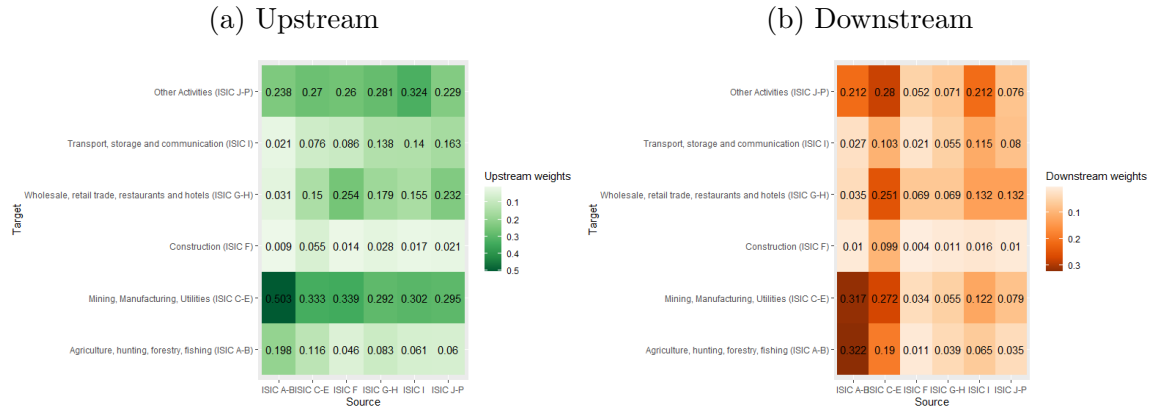
Appendix

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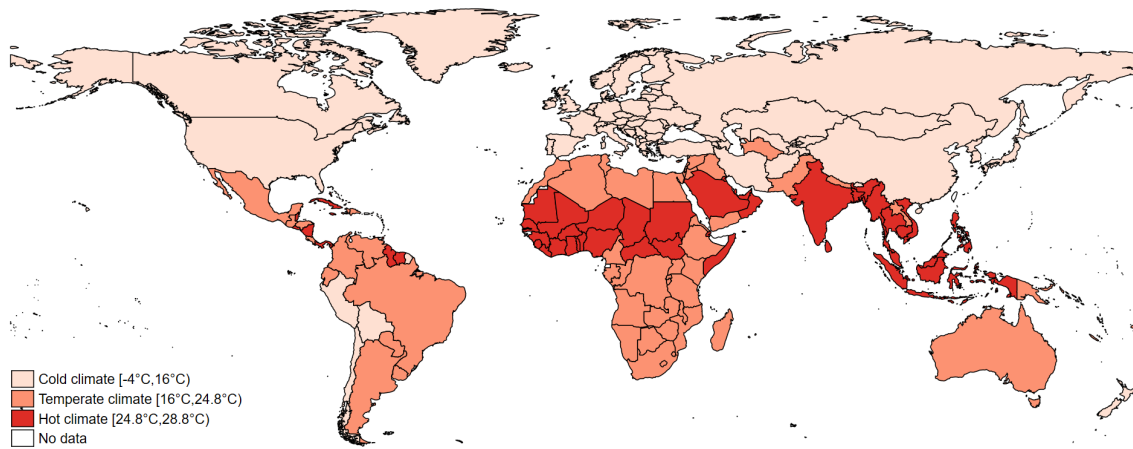
A Additional figures

Figure A1. Average upstream and downstream weights across countries



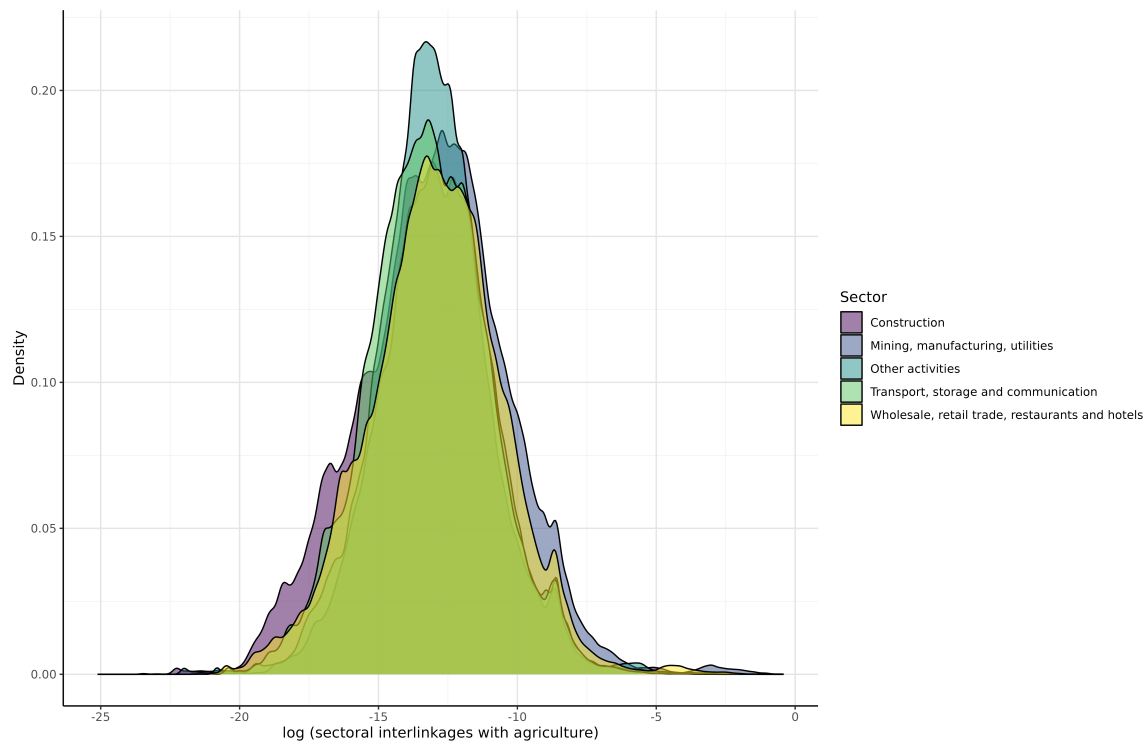
Notes: The figure shows the average upstream and downstream weights across countries by sector. Upstream and downstream weights are constructed from the perspective of Source sectors on the x-axis.

Figure A2. Countries in the sample by climatic zone



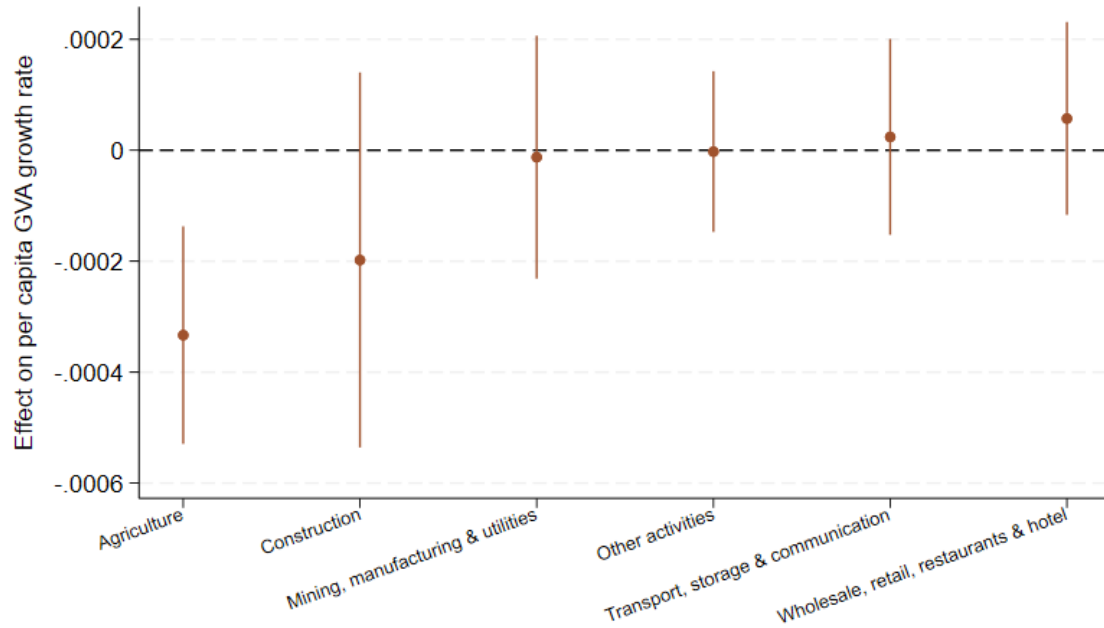
Notes: The map represents the countries in the sample divided by climatic zones, defined as terciles of the average annual temperature from 1975 through 2020. The classification is implemented in order to compute heterogeneous treatment effects as reported in Figure F1.

Figure A3. Sectoral density function of intermediate input interlinkages with agriculture



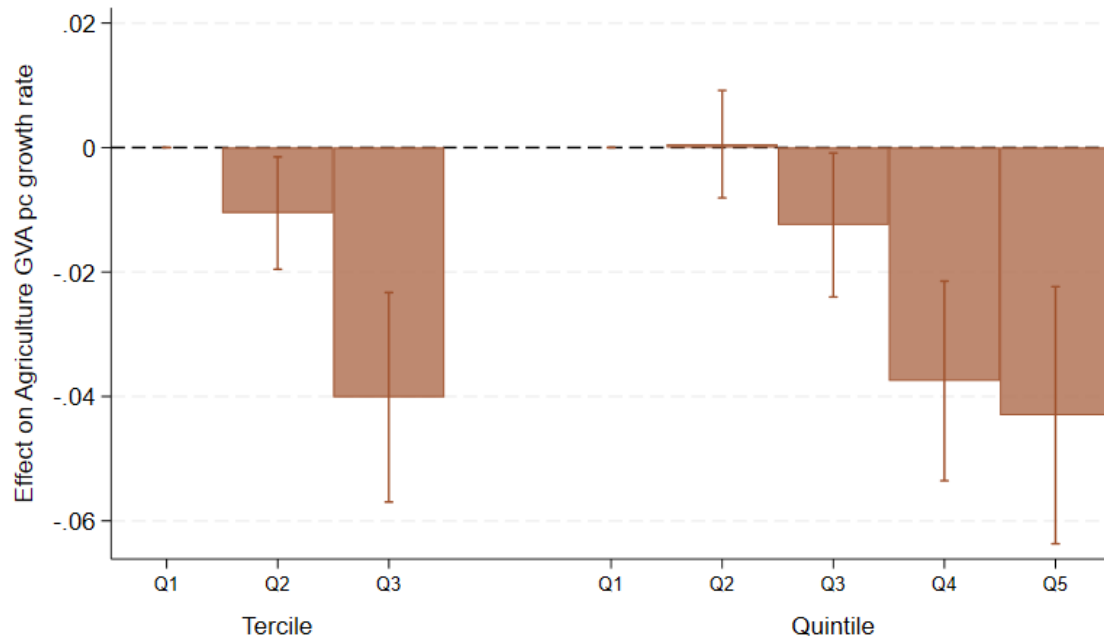
Notes: The figure plots the sector-specific density distribution of the (log) of interlinkages with agriculture used as outcome variable in the regression equation (10).

Figure A4. Effect on local abnormal hot days on sectoral per capita value added growth rate



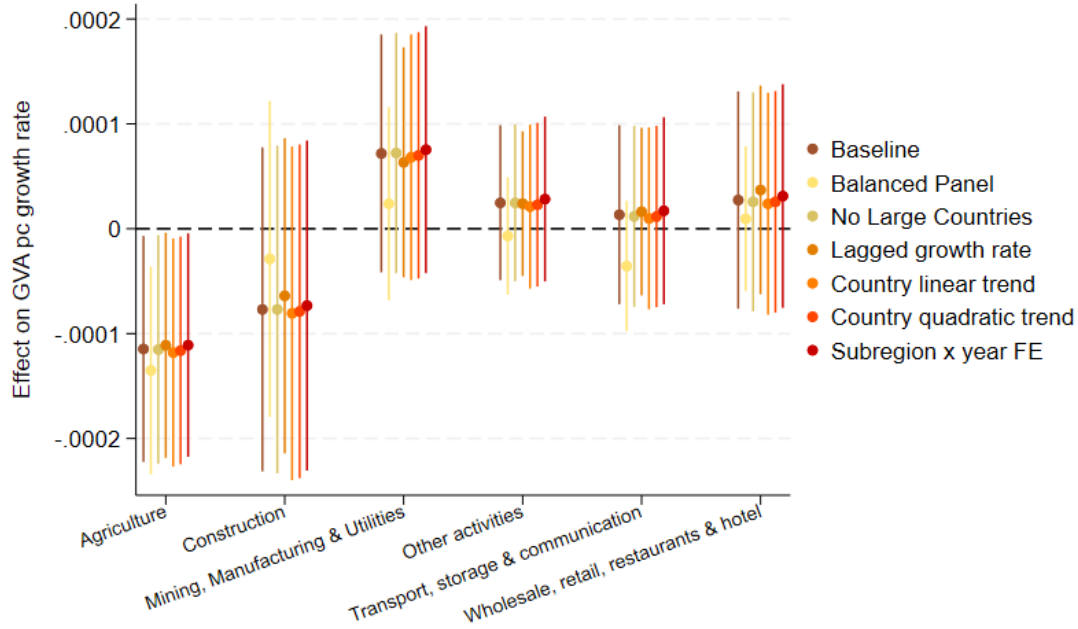
Notes: The figure shows the regression estimates for the country-average number of days above the 95th percentile of the daily distribution in temperature (Panel (a)). All sector-specific coefficients are estimated jointly in a stacked regression model fully saturated with country-sector and sector-year fixed effects and controlling for a sector-specific second order polynomial in total precipitation. Bins represent the 95% confidence intervals around point estimates. Standard errors are clustered at the country level.

Figure A5. Quantiles of Extreme Heat on Agriculture Value Added



Notes: The figure shows the regression estimates for the measure of extreme heat (degree days) constructed as in Equation (1) on the agricultural GVA per capita growth rate and categorized by terciles or quintiles. Each set of bars corresponds to the estimates from a single regression which accounts for linear and quadratic terms of precipitation, and country and year fixed effects. Bins represent the 95% confidence intervals around point estimates. Standard errors are clustered at the country level.

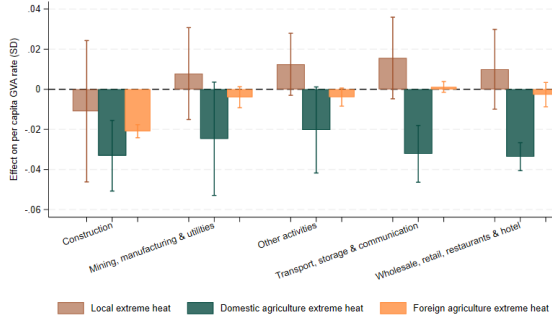
Figure A6. Robustness: Response to local extreme heat



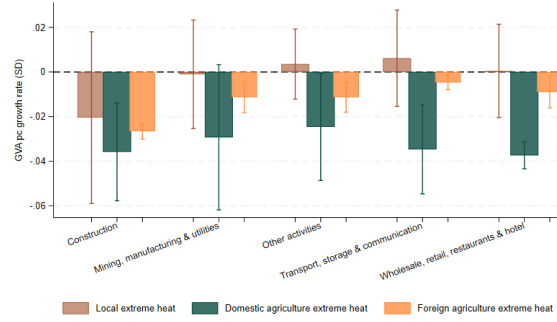
Notes: The figure shows the regression estimates for the country-average number of degree days of extreme heat using a sector-country balanced panel; excluding large countries (Brazil, China, India, Russia, US); including lagged growth rate; including country-specific linear trends; including linear and quadratic country-specific trends; including subregion-by-year fixed effects. All sector-specific coefficients are estimated jointly in a stacked regression model fully saturated with country-sector and sector-year fixed effects. Bins represent the 95% confidence intervals around point estimates. Subregions divide the world into 17 zones: Australia and New Zealand, Central Asia, Eastern Asia, Eastern Europe, Latin America and the Caribbean, Melanesia, Northern Africa, Northern America, Northern Europe, Polynesia, South-eastern Asia, Southern Asia, Southern Europe, Sub-Saharan Africa, Western Asia, Western Europe.

Figure A7. Robustness: Alternative specifications

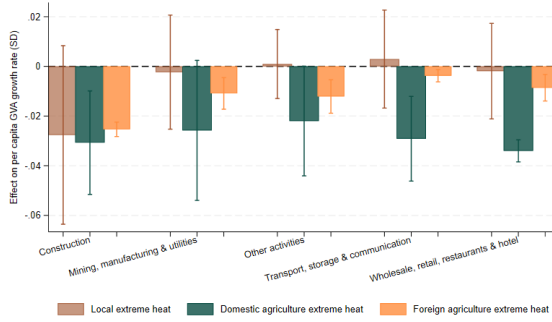
(a) Subregion-by-year FE



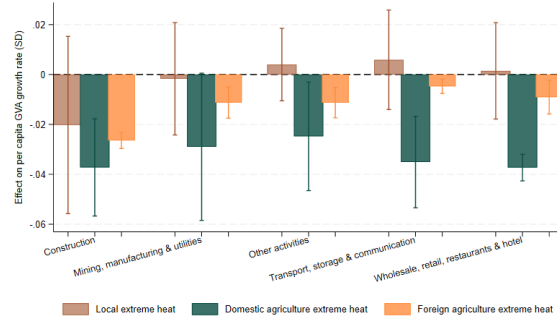
(b) Country-specific linear trend



(c) Balanced panel

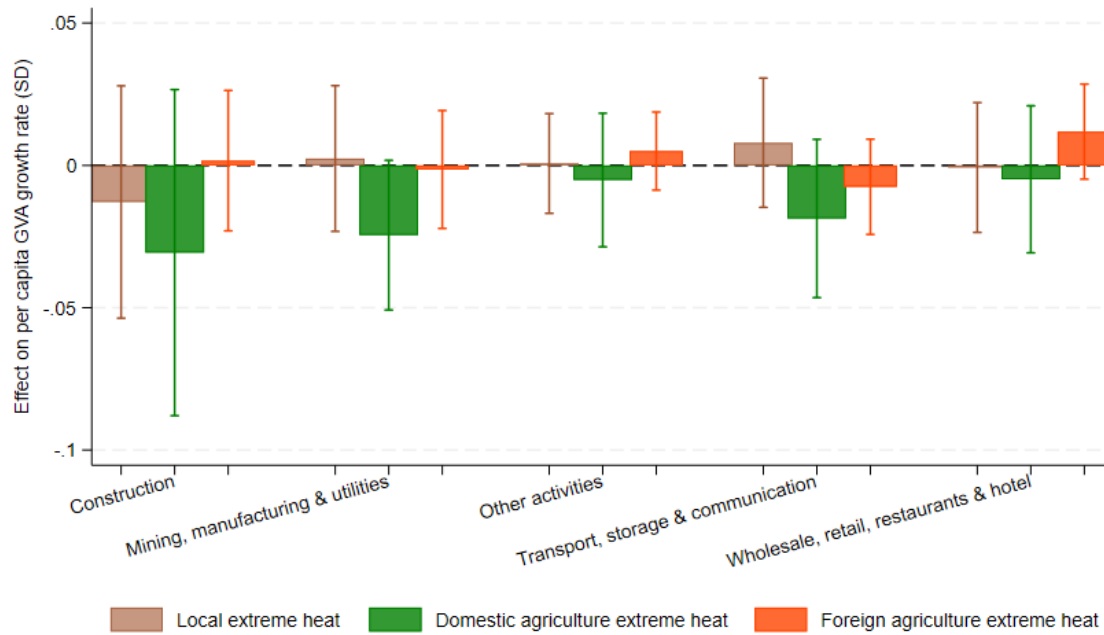


(d) Excluding “large” countries



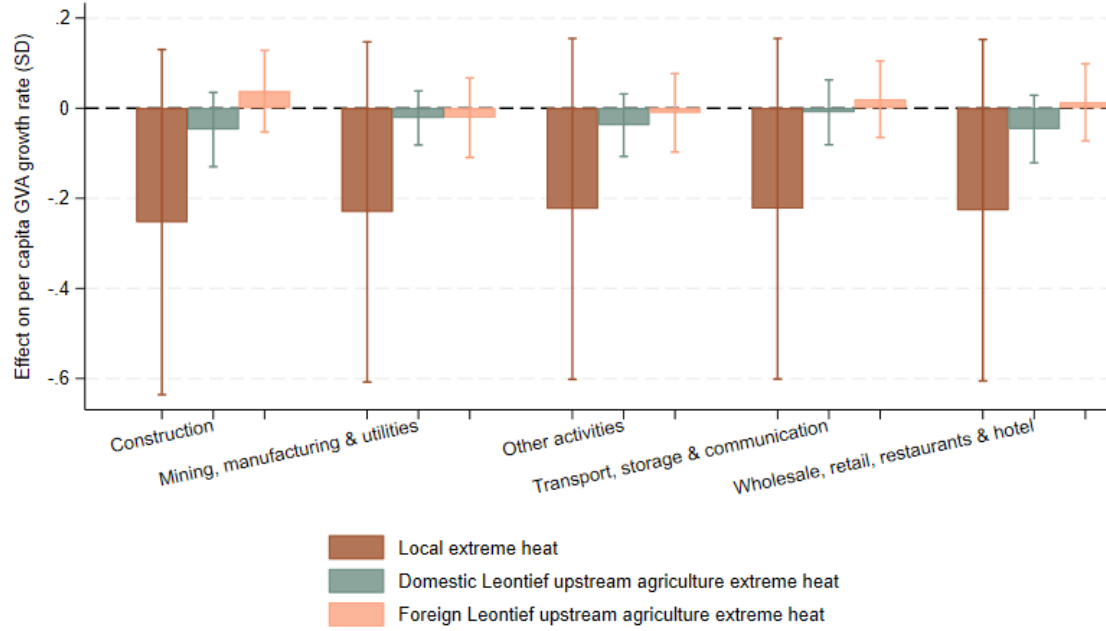
Notes: The figure shows the (standardized) sector-specific coefficients associated with local extreme heat and domestic and foreign downstream agricultural heat shocks, Panel (a) shows the estimates accounting for subregion-year FE; Panel (b) accounts for country-specific linear trends; Panel (c) uses sector-country balanced panel; Panel (d) excludes large countries (Brazil, China, India, Russia, US). Bins represent the 95% confidence intervals around point estimates. Subregions divide the world into 17 zones: Australia and New Zealand, Central Asia, Eastern Asia, Eastern Europe, Latin America and the Caribbean, Melanesia, Northern Africa, Northern America, Northern Europe, Polynesia, South-eastern Asia, Southern Asia, Southern Europe, Sub-Saharan Africa, Western Asia, Western Europe.

Figure A8. Local and upstream agricultural extreme heat on sectoral production



Notes: Bars represent the (standardized) sector-specific coefficients associated with local shocks and domestic and foreign downstream shocks, using the extreme heat exposure measure constructed as in Equation (1). Domestic and foreign downstream shocks are constructed respectively as in Equations (5) and (7). The specification jointly estimates all sector-specific coefficients in a stacked regression model fully saturated with country-sector and sector-year fixed effects and sector-specific responses to a second-order polynomial of total precipitation. Bins represent the 95% confidence intervals with standard errors clustered at the country level.

Figure A9. Local and upstream agricultural extreme heat on sectoral production in a Leontief matrix



Notes: Bars represent the (standardized) sector-specific coefficients associated with direct shocks and domestic and foreign upstream shocks, using the average number of days above the 95th percentile of the daily temperature distribution. Domestic upstream shocks are constructed as the average weather shock in agriculture in the same country as the sector of interest weighted by the upstream interdependence with each sector. Symmetrically, foreign upstream shocks are constructed as the average weather shock in the agriculture sector abroad weighted by the upstream interdependence with each sector. The specification jointly estimates all sector-specific coefficients in a stacked regression model fully saturated with country-sector and sector-year fixed effects and accounting for sector-specific responses to temperature realizations below the 5th percentile and sector-specific responses to precipitation realizations below the 5th and above the 95th percentile. Bins represent the 95% confidence intervals with standard errors clustered at the country level.

B Additional tables

Table B1. Summary statistics on sectoral GVA growth rate

	N	mean	SD	min	max
Log GVA per capita	47,289	6.166	1.789	-2.880	11.534
GVA per capita growth rate	47,289	0.014	0.121	-3.299	2.572
Sector					
Agriculture, hunting, forestry, fishing (ISIC A-B)	7,860	0.002	0.104	-1.691	0.745
Mining, Manufacturing, Utilities (ISIC C-E)	7,900	0.013	0.170	-3.299	2.572
Construction (ISIC F)	7,906	0.010	0.128	-3.169	2.430
Wholesale, retail trade, restaurants and hotels (ISIC G-H)	7,906	0.018	0.087	-1.513	1.261
Transport, storage and communication (ISIC I)	7,857	0.026	0.112	-2.514	2.030
Other Activities (ISIC J-P)	7,860	0.015	0.110	-1.639	1.502
Number of countries	183				
Number of sectors	6				
Number of years per country-sector		44.220	5.235	12	46

Table B2. Countries and year-sectors in final sample

Country	Number of years-sectors	Country	Number of years-sectors	Country	Number of years-sectors
Afghanistan	276	French Polynesia	276	Nigeria	276
Albania	276	Gabon	276	North Korea	184
Algeria	276	Gambia	276	North Macedonia	180
Andorra	276	Georgia	180	Norway	276
Angola	276	Germany	276	Oman	276
Antigua and Barbuda	276	Ghana	276	Pakistan	276
Argentina	276	Greece	276	Palestine	180
Armenia	180	Greenland	276	Panama	276
Aruba	276	Grenada	276	Papua New Guinea	276
Australia	276	Guatemala	276	Paraguay	276
Austria	276	Guinea	276	Peru	276
Azerbaijan	180	Guyana	276	Philippines	276
Bahamas	296	Haiti	276	Poland	276
Bahrain	276	Honduras	276	Portugal	276
Bangladesh	276	Hungary	276	Qatar	276
Barbados	276	Iceland	276	Republic of the Congo	276
Belarus	180	India	276	Romania	276
Belgium	276	Indonesia	276	Russia	180
Belize	276	Iran	276	Rwanda	276
Benin	276	Iraq	276	Samoa	276
Bermuda	276	Ireland	276	San Marino	276
Bhutan	276	Israel	276	Saudi Arabia	276
Bolivia	276	Italy	276	Senegal	276
Bosnia and Herzegovina	180	Jamaica	276	Serbia	180
Botswana	276	Japan	276	Seychelles	276
Brazil	276	Jordan	276	Sierra Leone	276
British Virgin Islands	276	Kazakhstan	180	Singapore	276
Brunei	276	Kenya	276	Slovakia	180
Bulgaria	276	Kuwait	276	Slovenia	180
Burkina Faso	276	Kyrgyzstan	180	Somalia	276
Burundi	276	Laos	276	South Africa	276
Cabo Verde	276	Latvia	180	South Korea	276
Cambodia	276	Lebanon	276	South Sudan	72
Cameroon	276	Lesotho	276	Spain	276
Canada	276	Liberia	276	Sri Lanka	276
Cayman Islands	276	Libya	276	Sudan	72
Central African Republic	276	Liechtenstein	276	Suriname	276
Chad	276	Lithuania	180	Swaziland	276
Chile	276	Luxembourg	276	Sweden	276
China	276	Madagascar	276	Switzerland	276
Colombia	276	Malawi	276	Syria	276
Comoros	276	Malaysia	276	São Tomé and Príncipe	276
Costa Rica	276	Maldives	297	Tajikistan	178
Croatia	180	Mali	276	Tanzania	276
Cuba	276	Malta	276	Thailand	276
Cyprus	276	Mauritania	276	Togo	276
Czechia	180	Mauritius	276	Trinidad and Tobago	276
Côte d'Ivoire	276	Moldova	180	Tunisia	276
Democratic Republic of the Congo	276	Monaco	230	Turkey	276
Denmark	276	Mongolia	276	Turkmenistan	180
Djibouti	276	Montenegro	180	Uganda	276
Dominican Republic	276	Morocco	276	Ukraine	180
Ecuador	276	Mozambique	276	United Arab Emirates	276
Egypt	276	Myanmar	276	United Kingdom	276
El Salvador	276	México	276	United States	276
Equatorial Guinea	276	Namibia	276	Uruguay	276
Eritrea	126	Nepal	276	Uzbekistan	180
Estonia	180	Netherlands	276	Vanuatu	276
Ethiopia	180	New Caledonia	276	Venezuela	276
Fiji	276	New Zealand	276	Vietnam	276
Finland	276	Nicaragua	276	Yemen	186
France	276	Niger	276	Zambia	276
				Zimbabwe	276
Total	47,289				

Table B3. Mapping between EORA26 sectors and UNSD industries

EORA26 Sector	UNSD industry
Agriculture	Agriculture, hunting, forestry, fishing (ISIC A-B)
Fishing	Agriculture, hunting, forestry, fishing (ISIC A-B)
Mining and Quarrying	Mining, Manufacturing, Utilities (ISIC C-E)
Electricity, Gas and Water	Mining, Manufacturing, Utilities (ISIC C-E)
Food & Beverages	Mining, Manufacturing, Utilities (ISIC C-E)
Textiles and Wearing Apparel	Mining, Manufacturing, Utilities (ISIC C-E)
Wood and Paper	Mining, Manufacturing, Utilities (ISIC C-E)
Petroleum, Chemical and Non-Metallic Mineral Products	Mining, Manufacturing, Utilities (ISIC C-E)
Metal Products	Mining, Manufacturing, Utilities (ISIC C-E)
Electrical and Machinery	Mining, Manufacturing, Utilities (ISIC C-E)
Transport Equipment	Mining, Manufacturing, Utilities (ISIC C-E)
Other Manufacturing	Mining, Manufacturing, Utilities (ISIC C-E)
Recycling	Mining, Manufacturing, Utilities (ISIC C-E)
Construction	Construction (ISIC F)
Maintenance and Repair	Construction (ISIC F)
Wholesale Trade	Wholesale, retail trade, restaurants and hotels (ISIC G-H)
Retail Trade	Wholesale, retail trade, restaurants and hotels (ISIC G-H)
Hotels and Restaurants	Wholesale, retail trade, restaurants and hotels (ISIC G-H)
Transport	Transport, storage and communication (ISIC I)
Post and Telecommunications	Transport, storage and communication (ISIC I)
Financial Intermediation and Business Activities	Other Activities (ISIC J-P)
Public Administration	Other Activities (ISIC J-P)
Education, Health and Other Services	Other Activities (ISIC J-P)
Private Households	Other Activities (ISIC J-P)
Others	Other Activities (ISIC J-P)
Re-export & Re-import	Other Activities (ISIC J-P)

Notes: Author's classification based on Kunze (2021) and adapted to six UNSD sectors.

Table B4. Effect of extreme heat on crop prices

	Crop Price (USD/Tonne)		(log) Crop Price (USD/Tonne)	
	(1)	(2)	(3)	(4)
Degree Days	0.4114** (0.2078)	0.2875*** (0.0825)	0.0007*** (0.0002)	0.0002* (0.0001)
Total Precipitation	1,196.6 (992.6)	435.0 (838.0)	0.4562 (1.207)	-0.7051 (0.5697)
Total Precipitation ²	-412,342.2 (328,287.8)	-156,285.3 (248,919.6)	-853.8 (1,026.4)	233.7 (269.8)
Observations	96,266	96,266	96,265	96,265
Outcome mean	834.15	834.15	6.1182	6.1182
Crop-Country fixed effects	✓	✓	✓	✓
Crop-Year fixed effects	✓	✓	✓	✓
Country-specific linear trends		✓		✓

Notes: Degree Days is a crop-specific extreme heat exposure in $^{\circ}\text{C} \times \text{days/year}$ for each country-crop combination around the world computed as the average exposure to extreme temperatures in degree-days (using maximum optimal growing temperature thresholds from FAO EcoCrop) on land cultivating a given crop (from Monfreda et al. (2008)). Total Precipitation is measured in metres.

Table B5. Sector-country damages (% loss GVA per capita) significant at 95% level

Country	Sector	Average loss	95% CI	Country	Sector	Average loss	95% CI	Country	Sector	Average loss	95% CI
Afghanistan	Agriculture	1.25	[0.74 ; 1.78]	Japan	Agriculture	0.82	[0.40 ; 1.26]	Ukraine	Agriculture	1.21	[0.58 ; 1.86]
Albania	Agriculture	1.39	[0.81 ; 1.97]	Jordan	Agriculture	1.12	[0.53 ; 1.73]	Uruguay	Agriculture	1.39	[0.77 ; 2.02]
Algeria	Agriculture	1.37	[0.81 ; 1.96]	Kenya	Agriculture	0.99	[0.41 ; 1.58]	Uzbekistan	Agriculture	1.81	[0.71 ; 2.84]
Andorra	Agriculture	1.35	[0.80 ; 1.94]	Kuwait	Agriculture	1.11	[0.53 ; 1.71]	Vanuatu	Agriculture	1.35	[0.81 ; 1.93]
Angola	Agriculture	1.74	[0.99 ; 2.50]	Kyrgyzstan	Agriculture	0.91	[0.43 ; 1.41]	Venezuela	Agriculture	1.85	[0.94 ; 2.75]
Antigua	Agriculture	1.62	[0.93 ; 2.32]	Laos	Agriculture	1.12	[0.54 ; 1.72]	Viet Nam	Agriculture	2.03	[0.93 ; 3.12]
Argentina	Agriculture	1.30	[0.76 ; 1.88]	Latvia	Agriculture	1.03	[0.49 ; 1.59]	Yemen	Agriculture	1.53	[0.81 ; 2.24]
Armenia	Agriculture	1.19	[0.67 ; 1.72]	Lebanon	Agriculture	1.13	[0.54 ; 1.73]	Zambia	Agriculture	1.34	[0.79 ; 1.91]
Aruba	Agriculture	1.31	[0.68 ; 1.95]	Lesotho	Agriculture	1.09	[0.52 ; 1.68]	Zimbabwe	Agriculture	1.17	[0.68 ; 1.68]
Australia	Agriculture	1.27	[0.75 ; 1.82]	Liberia	Agriculture	1.03	[0.49 ; 1.59]	Afghanistan	Construction	1.65	[0.26 ; 2.97]
Austria	Agriculture	1.33	[0.79 ; 1.92]	Libya	Agriculture	1.07	[0.51 ; 1.63]	Albania	Construction	1.59	[0.07 ; 3.04]
Azerbaijan	Agriculture	1.11	[0.61 ; 1.61]	Liechtenstein	Agriculture	1.08	[0.52 ; 1.66]	Angola	Construction	2.30	[0.61 ; 3.77]
Bahamas	Agriculture	1.70	[1.00 ; 2.45]	Lithuania	Agriculture	1.06	[0.50 ; 1.64]	Antigua	Construction	1.49	[0.13 ; 2.74]
Bahrain	Agriculture	1.45	[0.85 ; 2.09]	Luxembourg	Agriculture	1.00	[0.47 ; 1.55]	Armenia	Construction	2.08	[0.53 ; 3.52]
Bangladesh	Agriculture	1.28	[0.74 ; 1.84]	Madagascar	Agriculture	1.26	[0.56 ; 1.94]	Aruba	Construction	3.69	[1.44 ; 5.73]
Barbados	Agriculture	1.71	[0.96 ; 2.46]	Malawi	Agriculture	1.06	[0.52 ; 1.62]	Austria	Construction	1.70	[0.26 ; 3.07]
Belarus	Agriculture	1.20	[0.64 ; 1.78]	Malaysia	Agriculture	1.16	[0.47 ; 1.86]	Azerbaijan	Construction	1.32	[0.08 ; 2.51]
Belgium	Agriculture	1.20	[0.71 ; 1.71]	Maldives	Agriculture	1.01	[0.43 ; 1.60]	Bahrain	Construction	1.98	[0.46 ; 3.39]
Belize	Agriculture	1.69	[1.00 ; 2.41]	Mali	Agriculture	1.09	[0.52 ; 1.68]	Bangladesh	Construction	1.49	[0.09 ; 2.83]
Benin	Agriculture	1.34	[0.78 ; 1.91]	Malta	Agriculture	-0.11	[-0.18 ; -0.04]	Barbados	Construction	1.92	[0.38 ; 3.25]
Bermuda	Agriculture	1.58	[0.91 ; 2.28]	Mauritania	Agriculture	1.03	[0.50 ; 1.58]	Belgium	Construction	1.25	[0.02 ; 2.41]
Bhutan	Agriculture	1.63	[0.94 ; 2.34]	Mauritius	Agriculture	0.96	[0.36 ; 1.55]	Benin	Construction	1.77	[0.43 ; 2.94]
Bolivia	Agriculture	1.78	[1.01 ; 2.56]	Mexico	Agriculture	1.17	[0.56 ; 1.80]	Bhutan	Construction	2.67	[0.79 ; 4.41]
Bosnia and Herzegovina	Agriculture	1.43	[0.85 ; 2.05]	Moldova	Agriculture	1.23	[0.59 ; 1.88]	Bosnia and Herzegovina	Construction	1.38	[0.04 ; 2.67]
Botswana	Agriculture	1.30	[0.77 ; 1.87]	Mongolia	Agriculture	1.21	[0.57 ; 1.86]	Brazil	Construction	1.39	[0.07 ; 2.63]
Brazil	Agriculture	1.66	[0.95 ; 2.39]	Montenegro	Agriculture	1.22	[0.58 ; 1.86]	Brunei	Construction	2.16	[0.62 ; 3.50]
British Virgin Islands	Agriculture	1.62	[0.95 ; 2.31]	Morocco	Agriculture	1.01	[0.48 ; 1.55]	Bulgaria	Construction	1.43	[0.02 ; 2.77]
Brunei	Agriculture	1.57	[0.90 ; 2.26]	Mozambique	Agriculture	1.04	[0.50 ; 1.61]	Burundi	Construction	1.47	[0.22 ; 2.58]
Bulgaria	Agriculture	1.27	[0.69 ; 1.88]	Myanmar	Agriculture	0.62	[0.29 ; 0.96]	Cambodia	Construction	1.61	[0.33 ; 2.74]
Burkina Faso	Agriculture	1.25	[0.70 ; 1.80]	Namibia	Agriculture	1.16	[0.55 ; 1.79]	Cameroon	Construction	2.02	[0.51 ; 3.32]
Burundi	Agriculture	1.39	[0.80 ; 2.00]	Nepal	Agriculture	0.98	[0.46 ; 1.52]	Cape Verde	Construction	1.44	[0.07 ; 2.73]
Cambodia	Agriculture	1.21	[0.71 ; 1.72]	Netherlands	Agriculture	1.00	[0.48 ; 1.53]	Cayman Islands	Construction	1.76	[0.19 ; 3.25]
Cameroon	Agriculture	1.39	[0.79 ; 2.00]	New Caledonia	Agriculture	1.03	[0.50 ; 1.58]	Central African Republic	Construction	1.54	[0.24 ; 2.66]
Canada	Agriculture	1.00	[0.58 ; 1.45]	New Zealand	Agriculture	0.89	[0.41 ; 1.38]	Chad	Construction	1.45	[0.03 ; 2.81]
Cape Verde	Agriculture	1.65	[0.94 ; 2.37]	Nicaragua	Agriculture	0.91	[0.40 ; 1.41]	Colombia	Construction	1.60	[0.16 ; 2.88]
Cayman Islands	Agriculture	1.75	[1.01 ; 2.51]	Niger	Agriculture	1.12	[0.54 ; 1.72]	Congo	Construction	2.14	[0.56 ; 3.52]
Central African Republic	Agriculture	1.45	[0.86 ; 2.06]	Nigeria	Agriculture	1.18	[0.56 ; 1.81]	Costa Rica	Construction	1.31	[0.17 ; 2.38]
Chad	Agriculture	1.52	[0.87 ; 2.20]	North Korea	Agriculture	0.53	[0.19 ; 0.87]	France	Construction	1.28	[0.01 ; 2.50]
Chile	Agriculture	1.30	[0.76 ; 1.86]	Norway	Agriculture	0.91	[0.43 ; 1.39]	French Polynesia	Construction	1.61	[0.29 ; 2.81]
China	Agriculture	0.84	[0.44 ; 1.26]	Oman	Agriculture	1.23	[0.56 ; 1.90]	Gabon	Construction	2.17	[0.64 ; 3.55]
Colombia	Agriculture	1.60	[0.87 ; 2.34]	Pakistan	Agriculture	0.86	[0.40 ; 1.32]	Gambia	Construction	1.37	[0.10 ; 2.60]
Congo	Agriculture	1.50	[0.85 ; 2.17]	Panama	Agriculture	1.00	[0.43 ; 1.59]	Russia	Construction	1.40	[0.07 ; 2.67]
Costa Rica	Agriculture	0.89	[0.45 ; 1.32]	Papua New Guinea	Agriculture	1.35	[0.57 ; 2.12]	Rwanda	Construction	2.20	[0.60 ; 3.58]
Cote d'Ivoire	Agriculture	1.01	[0.43 ; 1.58]	Paraguay	Agriculture	1.07	[0.50 ; 1.64]	Saudi Arabia	Construction	2.15	[0.44 ; 3.65]
Croatia	Agriculture	1.15	[0.55 ; 1.76]	Peru	Agriculture	0.92	[0.39 ; 1.45]	Senegal	Construction	1.17	[0.03 ; 2.27]
Cuba	Agriculture	1.24	[0.60 ; 1.90]	Philippines	Agriculture	1.14	[0.48 ; 1.81]	Serbia	Construction	1.42	[0.06 ; 2.72]
Cyprus	Agriculture	1.09	[0.52 ; 1.68]	Poland	Agriculture	1.13	[0.54 ; 1.73]	Slovakia	Construction	1.45	[0.07 ; 2.77]
Czech Republic	Agriculture	1.09	[0.52 ; 1.67]	Portugal	Agriculture	1.00	[0.47 ; 1.55]	Slovenia	Construction	2.01	[0.43 ; 3.48]
DR Congo	Agriculture	1.18	[0.50 ; 1.88]	Qatar	Agriculture	1.19	[0.56 ; 1.84]	Somalia	Construction	1.57	[0.17 ; 2.92]
Denmark	Agriculture	1.01	[0.48 ; 1.54]	Romania	Agriculture	1.44	[0.86 ; 2.07]	Spain	Construction	2.00	[0.14 ; 3.72]
Djibouti	Agriculture	1.14	[0.54 ; 1.74]	Russia	Agriculture	1.38	[0.82 ; 1.99]	Venezuela	Construction	2.02	[0.46 ; 3.37]
Dominican Republic	Agriculture	1.22	[0.54 ; 1.88]	Rwanda	Agriculture	1.75	[0.95 ; 2.53]	Aruba	Mining, manufacturing, utilities	1.62	[0.55 ; 3.38]
Ecuador	Agriculture	1.29	[0.56 ; 2.01]	San Marino	Agriculture	1.41	[0.83 ; 2.03]	Colombia	Mining, manufacturing, utilities	2.30	[0.89 ; 4.62]
Egypt	Agriculture	1.21	[0.55 ; 1.86]	Sao Tome and Principe	Agriculture	1.10	[0.66 ; 1.58]	Spain	Mining, manufacturing, utilities	1.09	[0.09 ; 2.34]
El Salvador	Agriculture	1.17	[0.56 ; 1.80]	Saudi Arabia	Agriculture	1.82	[1.04 ; 2.63]	Aruba	Other activities	1.32	[0.27 ; 2.48]
Eritrea	Agriculture	1.15	[0.55 ; 1.76]	Senegal	Agriculture	1.16	[0.69 ; 1.67]	Australia	Other activities	0.57	[0.05 ; 1.09]
Estonia	Agriculture	0.99	[0.47 ; 1.52]	Serbia	Agriculture	1.25	[0.71 ; 1.80]	Bermuda	Other activities	0.72	[0.10 ; 1.37]
Ethiopia	Agriculture	1.09	[0.46 ; 1.72]	Seychelles	Agriculture	1.43	[0.82 ; 2.06]	Cayman Islands	Other activities	0.73	[0.07 ; 1.42]
Fiji	Agriculture	1.16	[0.56 ; 1.78]	Sierra Leone	Agriculture	1.17	[0.69 ; 1.68]	Colombia	Other activities	1.36	[0.22 ; 2.60]
Finland	Agriculture	0.94	[0.44 ; 1.45]	Singapore	Agriculture	1.23	[0.55 ; 1.90]	France	Other activities	0.56	[0.04 ; 1.06]
France	Agriculture	1.31	[0.77 ; 1.87]	Slovakia	Agriculture	1.33	[0.77 ; 1.89]	Germany	Other activities	0.57	[0.08 ; 1.14]
French Polynesia	Agriculture	1.38	[0.81 ; 1.97]	Slovenia	Agriculture	1.40	[0.83 ; 2.01]	Spain	Other activities	1.48	[0.77 ; 2.65]
Gabon	Agriculture	1.28	[0.60 ; 1.95]	Somalia	Agriculture	1.47	[0.82 ; 2.13]	Aruba	Transport, storage, communications	2.02	[0.58 ; 3.42]
Gambia	Agriculture	1.41	[0.80 ; 2.04]	South Africa	Agriculture	1.39	[0.83 ; 2.00]	Australia	Transport, storage, communications	0.69	[0.00 ; 1.35]
Gaza Strip	Agriculture	1.22	[0.56 ; 1.88]	South Korea	Agriculture	0.80	[0.37 ; 1.24]	Bolivia	Transport, storage, communications	0.96	[0.03 ; 1.86]
Georgia	Agriculture	1.14	[0.56 ; 1.74]	Spain	Agriculture	1.21	[0.41 ; 1.94]	Russia	Transport, storage, communications	0.77	[0.01 ; 1.49]
Germany	Agriculture	1.05	[0.51 ; 1.61]	Sri Lanka	Agriculture	0.90	[0.43 ; 1.38]	Singapore	Transport, storage, communications	1.71	[0.48 ; 2.94]
Ghana	Agriculture	1.05	[0.45 ; 1.65]	Suriname	Agriculture	1.05	[0.44 ; 1.66]	Uzbekistan	Transport, storage, communications	1.06	[0.22 ; 1.86]
Greece	Agriculture	1.22	[0.59 ; 1.87]	Swaziland	Agriculture	0.91	[0.43 ; 1.40]	Viet Nam	Transport, storage, communications	0.91	[0.07 ; 1.73]
Greenland	Agriculture	1.09	[0.47 ; 1.70]	Sweden	Agriculture	0.96	[0.46 ; 1.47]	Yemen	Transport, storage, communications	0.98	[0.03 ; 1.90]
Guatemala	Agriculture	1.19	[0.55 ; 1.83]	Switzerland	Agriculture	1.10	[0.52 ; 1.68]	Aruba	Wholesale, retail, hotel, restaurant	4.51	[2.23 ; 6.90]
Guinea	Agriculture	0.92	[0.43 ; 1.42]	Syria	Agriculture	1.16	[0.55 ; 1.79]	Australia	Wholesale, retail, hotel, restaurant	1.37	[0.57 ; 2.17]
Guyana	Agriculture	1.10	[0.47 ; 1.75]	TFYR Macedonia	Agriculture	1.15	[0.55 ; 1.76]	Bahamas	Wholesale, retail, hotel, restaurant	1.19	[0.30 ; 2.07]
Haiti	Agriculture	1.13	[0.51 ; 1.74]	Tajikistan	Agriculture	0.98	[0.47 ; 1.52]	Bahrain	Wholesale, retail, hotel, restaurant	0.79	[0.09 ; 1.47]
Honduras	Agriculture	1.09	[0.52 ; 1.66]	Tanzania	Agriculture	1.29	[0.56 ; 2.01]	Belgium	Wholesale, retail, hotel, restaurant	0.83	[0.16 ; 1.49]
Hungary	Agriculture	1.08	[0.51 ; 1.66]	Thailand	Agriculture	0.90	[0.43 ; 1.38]	Bermuda	Wholesale, retail, hotel, restaurant	0.85	[0.10 ; 1.58]
Iceland	Agriculture	1.08	[0.47 ; 1.69]	Togo	Agriculture	0.99	[0.43 ; 1.55]	Brazil	Wholesale, retail, hotel, restaurant	0.81	[0.09 ; 1.51]
India	Agriculture	0.93	[0.45 ; 1.42]	Trinidad and Tobago	Agriculture	1.24	[0.50 ; 1.98]	Burkina Faso	Wholesale, retail, hotel, restaurant	0.76	[0.07 ; 1.42]
Indonesia	Agriculture	1.22	[0.44 ; 2.00]	Tunisia	Agriculture	1.12	[0.54 ; 1.72]	Russia	Wholesale, retail, hotel, restaurant	1.08	[0.33 ; 1.84]
Iran	Agriculture	1.01	[0.46 ; 1.55]	Turkey	Agriculture	1.19	[0.57 ; 1.83]	Saudi Arabia	Wholesale, retail, hotel, restaurant	0.84	[0.01 ; 1.61]
Iraq	Agriculture	0.91	[0.44 ; 1.40]	Turkmenistan	Agriculture	0.91	[0.43 ; 1.40]	Sierra Leone	Wholesale, retail, hotel, restaurant	1.92	[0.93 ; 2.92]
Ireland	Agriculture	0.87	[0.40 ; 1.34]	UAE	Agriculture	1.24	[0.62 ; 1.88]	Singapore	Wholesale, retail, hotel, restaurant	1.33	[0.51 ; 2.14]
Israel	Agriculture	1.22	[0.56 ; 1.88]	UK	Agriculture	1.01	[0.51 ; 1.52]	Spain	Wholesale, retail, hotel, restaurant	1.21	[0.29 ; 2.80]
Italy	Agriculture	1.21	[0.58 ; 1.85]	USA	Agriculture	1.04	[0.50 ; 1.58]	Viet Nam	Wholesale, retail, hotel, restaurant	0.93	[0.17 ; 1.66]
Jamaica	Agriculture	1.23	[0.53 ; 1.94]	Uganda	Agriculture	1.04	[0.44 ; 1.64]				

Notes: The table reports the average loss for each sector as a % loss in GVA per capita relative to the observed production between 2001 and 2020, accounting for own, domestic and foreign heat and cold shocks. 95% confidence intervals are obtained from 1000 estimates from bootstrapping Equation (16), where indirect shocks are constructed with a time-varying production network that uses the first five-year average input-output interlinkages for each decade.

C Additional data sources

Sub-national sectoral activity. To obtain geographic variation in sectoral exposure to weather conditions within a country, I rely on the geographic distribution of sectoral activities. This information is available for 41 countries around the world, including Europe, Brazil, Canada, China, and United States. For each country, I consider the first available five years of sectoral production to construct a measure of sub-national geographic distribution of sectoral activities. I use these measure as a weight to aggregate nationally sub-national measures of weather exposure. Below, I describe each data source in detail.

I rely on Eurostat data on GVA by industry (NACE Rev. 2) at the sub-national level for 34 European countries. I use NUTS-3 level information from 31 countries (Albania, Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Malta, Netherland, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Sweden, Türkiye, Serbia, Spain) and NUTS-2 level for three other countries (Cyprus, Luxembourg, Montenegro).

State-level sectoral data for Brazil are taken from the Brazilian Institute of Geography and Statistics, which displays information since 2003 for 15 economic services: agriculture, industry (extraction industries; transformation industries; and electricity and gas), construction, trade and transportation (trade; transport, storage and communications; hotels and restaurants; and information and communication), finance (financial activities; real estate; and professional activities) and government and other services (public administration and defense; education and health; and other services).

Sectoral value added data across provinces for Canada is obtained from the Statistics of Canada, which provides information since 2001 according to the NAICS standard in chained 2012 U.S. dollar.

Value added data across states for China are taken from the Macro Economy Statistics Yearbook. As for value added, the dataset comprises nine sectors, including agriculture, wholesale and retail, hotels and catering and transport, storage and post.

For the United States, data at the state level come from the Bureau of Economic Analysis. Information is reported since 1997 according to the NAICS standard.

Crop prices. Data on domestic crop prices come from the UN FAOSTAT domain on Agricultural Producer Prices and Producer Price Index (expressed in USD/Tonne), which reports official national level data received from FAO Members on annual prices their farmers obtain from 1991 to 2020 for 160 countries and for about 262 products. Agriculture Producer Prices are prices received by farmers for primary crops, live animals and livestock primary products as collected at the point of initial sale (prices paid at the farm-gate). I match crop names to *DegreeDays* measures at the crop level computed using the UN FAO EcoCrop database and the agricultural land where each crop is grown in each country as explained in Section 2.

D Local economic response to local weather shocks

The majority of the reduced-form climate impact studies motivates econometric specifications with a partial equilibrium model of production where the economy consists of N regions (Burke et al., 2015; Dell et al., 2012). To match the theoretical framework with the empirical approach, I describe here an economy consisting of N regions indexed by $n \in \{1, \dots, N\}$ (or m), each populated with J sectors indexed by $j \in \{1, \dots, J\}$ (or k). Production possibilities for sector j in region n are described by a constant returns-to-scale Cobb-Douglas technology whose inputs are capital and labor:

$$Y_{nt}^j = \mathcal{Z}_{nt}^j (K_n^j)^\lambda (L_{nt}^j)^{1-\lambda} \quad (\text{D.17})$$

where total factor productivity \mathcal{Z}_{nt}^j is a product of three components: (i) a region-sector specific component \bar{z}_n^j , (ii) a sector-year specific component \tilde{z}_t^j (capturing for instance sector-specific global technological innovations), (iii) an exponential vector of temperature effects T_{nt}^j with sector-specific elasticities β_j . Taking the log and rearranging in terms of output per worker, one obtains:

$$\log \frac{Y_{nt}^j}{L_{nt}^j} = \frac{1}{1-\lambda} [\log \bar{z}_n^j + \log \tilde{z}_t^j + f(T_{nt}^j, \beta_j)] + \frac{\lambda}{1-\lambda} \log \left(\frac{K_n^j}{Y_{nt}^j} \right) \quad (\text{D.18})$$

Traditionally, the reduced-form effect of temperature $\hat{\beta}$ on output per capita is estimated under the assumption that the residual variation in temperature is not correlated with the error term once absorbed unit- and time-specific unobserved heterogeneity.¹⁷

¹⁷Identifying $\hat{\beta}$ also requires that the unit-specific capital-to-output ratio is constant.

E Reduced-form approach to the climate-output relationship

Kahn et al. (2021) review the three main approaches that study the climate-output relationship in reduced form in the literature (Dell et al., 2012; Burke et al., 2015; Kalkuhl and Wenz, 2020), highlighting the restrictive assumptions that each of these models requires to study the effect of temperature. In an attempt to deal with the non-stationarity issue of trended temperatures, a recently often implemented alternative is to use changes in temperature levels (Akyapi et al., 2024; Newell et al., 2021; Letta and Tol, 2019). Nevertheless, this measure does not inform how atypical the weather realization is with respect to individual expectations since it neglects any information provided by the levels and assumes that individuals rationally update their beliefs annually, under an implicit instantaneous model of adaptation.

In this Appendix section, I report an extension of these approaches discussed in Newell et al. (2021) and discuss the assumptions that it relies on. To allow for the non-linear effect of temperature changes while dealing with the non-stationarity issue of trended temperatures, one could include higher-order polynomials of first-differenced temperature as main regressors (as in Ortiz-Bobea et al. (2021)). Without loss of generality, the estimating equation considering only a second-order polynomial of differenced temperature is written as

$$\Delta y_{nt} = \alpha_n + \delta_t + \lambda \Delta T_{nt} + \psi \Delta [T_{nt}^2] + \varepsilon_{nt} \quad (\text{E.19})$$

which uses the growth rate of log-differences of real GDP per capita of country n in year t as the dependent variable, the main regressors are the linear and quadratic differenced temperature, where the latter term is the change in temperature-squared (different from the squared change in temperature), α_n is the country-specific fixed effect and δ_t is the time-specific fixed effect. Motivated by empirical evidence on the temperatures being trended, I assume that

$$T_{nt} = a_{T_n} + b_{T_n}t + \nu_{T_{nt}} \quad (\text{E.20})$$

where, in line with historical evidence, $b_{T_n} > 0$, and $\mathbb{E}(\nu_{T_{n;t}}) = 0$ and $\mathbb{E}(\nu_{T_{n;t}}^2) = \sigma_{T_n}^2$. Substituting Equation (E.20) in Equation (E.19) and taking expectations yields

$$\mathbb{E}(\Delta y_{nt}) = \mathbb{E}(\delta_t) + \alpha_n + b_{T_n}[\lambda + 2\psi a_{T_n}] + 2\psi b_{T_n}^2 t \quad (\text{E.21})$$

To ensure that $\mathbb{E}(\Delta y_{nt})$ is not trended, there are some restrictions to impose. First, since δ_t is unobserved, one can set $\mathbb{E}(\delta_t) = 0$ (Kahn et al., 2021), and then require that $2\psi b_{T_n}^2 t = 0$ for all n . Therefore, this approach does not resolve the trend problem around the output growth-climate specifications, introducing a trend in the mean output growth, which is not supported empirically. An alternative approach would be to include region-year rt fixed effects in Equation (E.19), such that it becomes

$$\Delta y_{nrt} = \alpha_{nr} + \delta_{rt} + \lambda \Delta T_{nrt} + \psi \Delta [T_{nrt}^2] + \varepsilon_{nrt} \quad (\text{E.22})$$

with $T_{nrt} = a_{T_{n,r}} + b_{T_{n,r}}t + \nu_{T_{n,rt}}$, where the shock $\nu_{T_{n,rt}}$ for country n in region r in year t has zero mean and finite variance. Taking expectations as above, to have that $\mathbb{E}(\Delta y_{nrt})$ is stationary, one would require no trend in temperature $b_{T_{n,r}} = 0$, or exact cancellation of quadratic trends in temperature at the regional level with the region-year fixed effects, i.e. $\delta_{rt} + \psi \bar{b}_{T_r}^2 t = 0$, for all r , where $\bar{b}_{T_r}^2 = \frac{1}{n} \sum_{n=1}^{n_r} b_{T_{n,r}}^2$.

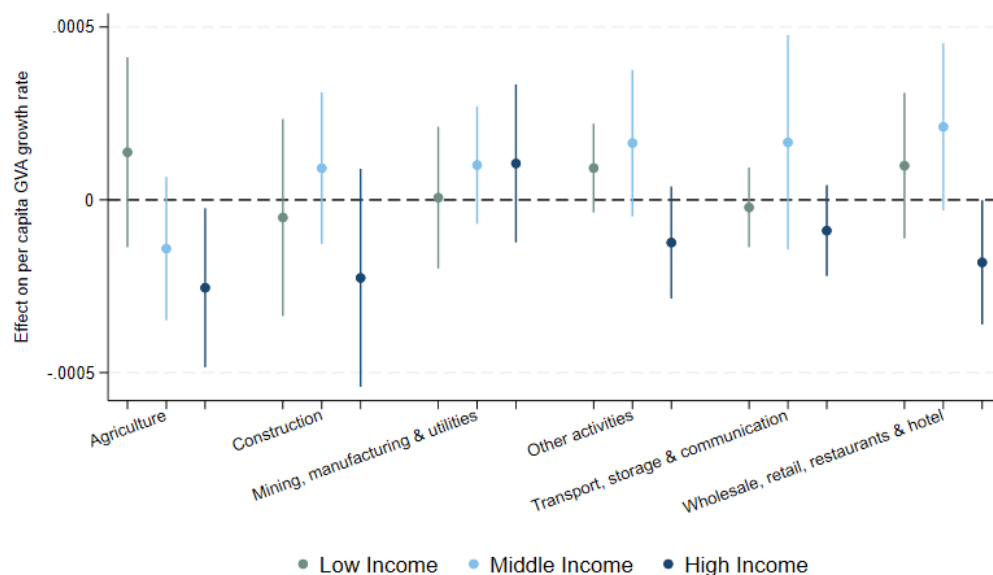
F Heterogeneous effects of local extreme heat across adaptation potential

The impact of extreme heat may differ as a function of factors that influence the adaptation potential of countries, including income and climate. First, richer countries have less binding budget constraints and wider adaptation capacity to cope with weather fluctuations. Second, a hotter climate may differentially incentivize adaptive investments as returns to adaptation would be relatively higher for more frequent temperature changes. I estimate heterogeneous temperature-value added relationships by interacting the vector of temperature and precipitation coefficients with income and climate terciles from long-run average income and temperature (Appendix Figure A2 shows the sample composition) (Carleton et al., 2022).

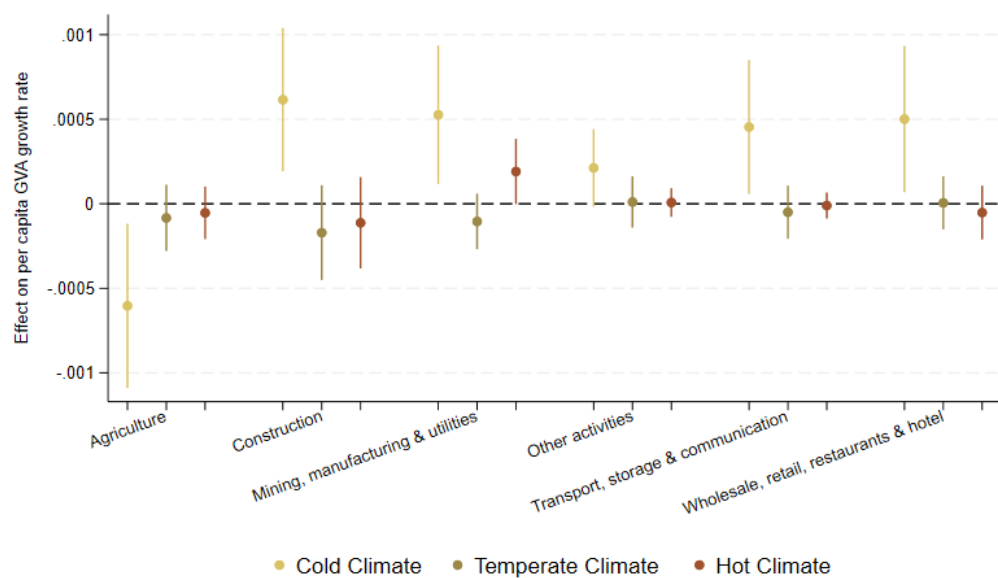
Appendix Figure F1 graphically presents the coefficient associated with heat shocks interacted with income and climate terciles. Starting from heterogeneity by income, agricultural value added becomes more sensitive to extreme heat as income rises. This result, perhaps surprising at first, could be explained by differences in improved technologies, infrastructure, or insurance that influence producer strategies (Hultgren et al., 2022). There is not substantial heterogeneity in the response of other sectors to extreme heat conditions by income, with the estimate coefficients that are never statistically distinguishable from zero. Similarly, I document that countries adapt to higher temperatures across crops such that agricultural value added is sheltered from the impact of extreme heat in temperate and hot countries and negatively affected in cold countries. Conversely, there is considerable heterogeneity in the sectoral response to extreme heat by climate. In particular, the manufacturing and service sectors benefit from hotter conditions in cold countries, whereas these sectors do not respond in hot and temperate countries.

Figure F1. Income and climate heterogeneity in GVA response to extreme heat

(a) Income terciles



(b) Climate terciles



Notes: The figure shows the coefficients associated with the response of sectoral GVA per capita growth rate to extreme heat by income using long-run average per capita GDP and average temperature. All sector-specific coefficients are estimated jointly in a stacked regression model fully saturated with country-sector and sector-year fixed effects and controlling for a second order polynomial in precipitation. Bins represent the 95% confidence intervals with standard errors clustered at the country-level.

G Quantifying the cost of the propagation of recent warming

To understand the differential cost of propagation of recent warming, I use the estimates of the effect of local abnormal days and domestic and foreign agriculture extreme heat to simulate how much slower or faster each sector would have grown annually over the 2001-2020 period, compared to a scenario under which daily temperature evolves linearly based on its historical trend of 1970-2000. To do so, I estimate country-specific regressions of the type $T_{dmnt} = \alpha_n + \lambda_{dm} + \beta_n t + \varepsilon_{dnct}$ on the 1970-2000 sample, where T_{dmct} is the average temperature in day d in month m in year t in country n . I obtain country-specific historical trends in daily temperature exploiting within day-month variation between 1970 and 2000 and use $\hat{\beta}_n$ to construct a counterfactual daily temperature \tilde{T}_{dmnt} between 2001 and 2020 that is then used to compute the counterfactual extreme heat measure. I assume that the trend is linear and that such a trend does not affect the volatility of temperature shocks, which most likely results in an underestimation of the adverse effects of abnormal temperatures.

I average these effects over the 2001-2020 period to obtain a sector-specific relative measure of estimated losses in value added. I finally compare the estimated losses in value added omitting and accounting for the transmission of shocks across countries through trade interlinkages. This computation does not necessarily represent the differential impact of recent anthropogenic warming accounting for network shocks and is instead agnostic to the cause of recent warming.

First, I compute the annual cost/benefit of annual warming in 2001-2020 compared to a counterfactual temperature which evolves linearly from the estimated trend over the period 1970-2000, and distinguish between omitting and accounting for extreme heat in agriculture both domestic and abroad:

$$g_{jnt}^{local} = \hat{\beta}_j(\text{ExtremeHeat}_{nt} - \widetilde{\text{ExtremeHeat}}_{nt}) \quad (\text{G.23})$$

$$\begin{aligned}
g_{jnt}^{global} = & (\hat{\beta}_j ExtremeHeat_{nt} + \sum_{\ell \in \{D;F\}} \hat{\gamma}_{j,\ell} NetworkShock_{jnt}^{Dn,\ell}) \\
& - (\hat{\beta}_j \widetilde{ExtremeHeat}_{nt} + \sum_{\ell \in \{D;F\}} \hat{\gamma}_{j,\ell} \widetilde{NetworkShock}_{jnt}^{Dn,\ell})
\end{aligned} \tag{G.24}$$

where $ExtremeHeat_{nt}$ is the observed extreme heat measure constructed in Equation (1), $\widetilde{ExtremeHeat}_{nt}$ is the counterfactual predicted extreme heat measure had the 1970-2000 temperature mean evolved linearly, and similarly for $NetworkShock$, which is constructed as detailed in Equations (4) and (6), and the counterfactual predicted $\widetilde{NetworkShock}$ is constructed using the extreme heat measures using counterfactual temperatures that evolved linearly from the 1970-2000 trend. $\hat{\beta}_j$'s are the sector-specific estimates for the effect of local extreme heat, and $\hat{\gamma}_{j,\ell}$ are the sector-specific domestic and foreign semi-elasticities to downstream agricultural extreme heat exposure on the sectoral growth rate obtained from bootstrapping 1000 times the underlying panel estimates from Equation (16). I compute sector j 's counterfactual value added levels in year t omitting and accounting for indirect shocks

$$\hat{Y}_{jnt}^p = Y_{ict-1} + y_{jnt} + g_{jnt}^p \tag{G.25}$$

where hatted term indicates a counterfactual, Y is the (log) GVA per capita, y is the observed growth rate and $p \in \{local, global\}$. I can then compute the average relative loss in GVA for sector j in country n over the 2001-2020 period as

$$\% \overline{LOSS}_{jn}^p = \frac{1}{T} \sum_{t=2001}^{2020} \frac{e^{\hat{Y}_{jnt}^p} - e^{Y_{jnt}}}{e^{Y_{jnt}}} \tag{G.26}$$

to obtain a measure of the average cost of recent warming at the sector level omitting and accounting for the propagation of heat shocks (reported in Figure ??).

The aggregated average loss in GVA across sectors for country n is

$$\% \overline{LOSS}_n^p = \sum_j^J \% \lambda_{jn} \overline{LOSS}_{jn}^p \tag{G.27}$$

where λ_{jn} is the baseline five-year average share of total GVA of sector j in country n between 1996 and 2000. The country-level losses omitting and accounting for

indirect heat shocks are reported in Figure 8.