Extreme Heat: The Economic & Social Consequences for the United States Methodology

Prepared for the Adrienne Arsht-Rockefeller Foundation Resilience Center at the Atlantic Council

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1 Introduction

This methodology document accompanies the August 2021 report "Extreme Heat: The Economic & Social Consequences for the United States," prepared for the Adrienne Arsht-Rockefeller Foundation Resilience Center at the Atlantic Council. The methodology document provides additional detail into the assumptions of the main report and the sources relied on to support and develop those assumptions. The contribution of the main report is to quantify some of the likely economic and social effects of heat in the US under current and possible future conditions. It provides new, quantitative evidence on the economic importance of heat for policymakers and investors and shows how they are disaggregated across regions, socioeconomic groups, and sectors of the economy. The paper considers only a subset of the ways in which extreme heat can impact the US economy and society and appraises impacts only in 'normal' – as opposed to unusually warm – years, meaning it provides a conservative view of the overall significance of the issue.

This methodology proceeds as follows:

- Section 2: Description of the underlying climate modelling used to produce the heat data for all subsequent analyses: days with maximum temperatures 90°F+, days with mean temperature 90F+, and Wet Bulb Globe Temperature (WBGT).
- Section 3: Explanation of the "workability" model which relates WBGT to effective labor losses due to heat stress.
- Section 4: Details for mapping the gridded heat and workability data to US county borders.
- Section 5: Outline of the economic production model used to estimate lost value added due to reduced worker productivity from WBGT-related heat stress, and core assumptions on sectoral exposure to heat stress.
- Section 6: Explanation of the agricultural yield model used to relate days with mean temperature 90°F+ to yield losses for key crops.
- Section 7: Description of the model that relates local excess mortality by age group to exposure to days with mean temperature 90°F+.
- Section 8: Details of the model relating occupational injuries to days with maximum temperature 90°F+, for indoor vs. outdoor work,
- Section 9: Description of the demographic data used to identify disparate impacts of productivity losses.
- Section 10: Bibliography of references and sources to support the methodology.
- Section 11: Presentation of technical appendix containing key mapping assumptions for the analyses in the report.

2 Climate modeling

Projections from climate models are the key input driving the results of the analysis. The modelling uses two different measures of heat as inputs:

- Wet Bulb Globe Temperature (WBGT). WBGT is a type of apparent temperature which usually takes into account the effect of temperature, humidity, wind speed, and visible and infrared radiation – these factors mediate the impact of temperatures on the human body. WBGT projections feed into the workability calculation (see Section 3).

- Days above 90°F. The 90°F (32.2°C) threshold is a common definition for a heatwave. The analysis draws on projections for the number of days each year where the maximum temperature is greater than 90°F and where the mean temperature is greater than 90°F. The former is reported at the 25km by 25km grid cell while the latter is at 5km by 5km grid cell.

Climate projections are based on the CMIP5 ensemble of climate models as well as the downscaled CORDEX ensemble. Climate models are complex computational models based on physics that simulate the atmosphere, ocean, land, biosphere, and cryosphere down to resolutions of roughly 100km-by-100km. This analysis draws from an ensemble of 60 climate models known as general circulation models (GCMs) or earth system models; they are developed, owned, and operated independently by 28 leading scientific research institutions across the world. The World Climate Research Programme brought these models together to run standardized experiments to determine the likely outcome of various rates of carbon emissions in an undertaking known as CMIP5: Coupled Model Intercomparison Project 5. The results of the CMIP5 ensemble are the most widely used source of climate projections in climate research today and have been evaluated in more than 1,500 papers. The analysis also draws on projections from an ensemble of regional climate models, which are dynamic models that take GCM input and refine it to simulate specific regions of the globe at a finer resolution. This allows scientists to more accurately investigate future climates in regions with complex terrain. The analysis draws on projections from the Coordinated Regional Downscaling Experiment (CORDEX) ensemble. The CORDEX ensemble consists of 80 regional climate models developed at 51 research institutions, using the CMIP5 ensemble or parts thereof as input data. The multimodel ensemble mean or median projection is taken as the central projection to feed into the impact modelling.

3 Workability data

The workability analysis captures how labor productivity declines as workers are subjected to greater human heat stress. The effect of heat stress on work comes through two channels: the need to take breaks to rest, hydrate, or seek cooling in a less exposed environment, and a natural self-limiting response of an overheated body reducing effort to maintain function. There is a well-established literature and experimental body of evidence relating productivity loss to the WBGT, the analysis for this report was developed with Woodwell Climate Research Center (WCRC) and external advisors to adapt existing models to reflect current understanding of human heat stress and workability. The model applied in this analysis adapts the formula of Dunne (2013). The revised formula allows increased work at higher WBGT, following the guidance of expert advisors, and so provides a more conservative estimate of productivity losses from heat stress. This adjustment is conceptually consistent with Foster (2021).

Labor productivity begins to decline at WBGT above 25°C, and is fixed at 0% when the WBGT is at or above 36.2°C. Beyond that temperature, heat stress is too great for meaningful work as the human body is not able to cool itself at rest without external measures. The formula for labor productivity in a given hour within a 100kmx100km grid cell is:

$$L_{h,g} = 100 - 20 * \max\left(0, \mathrm{WBGT}_{h,g} - 25\right)^{\frac{2}{3}}$$

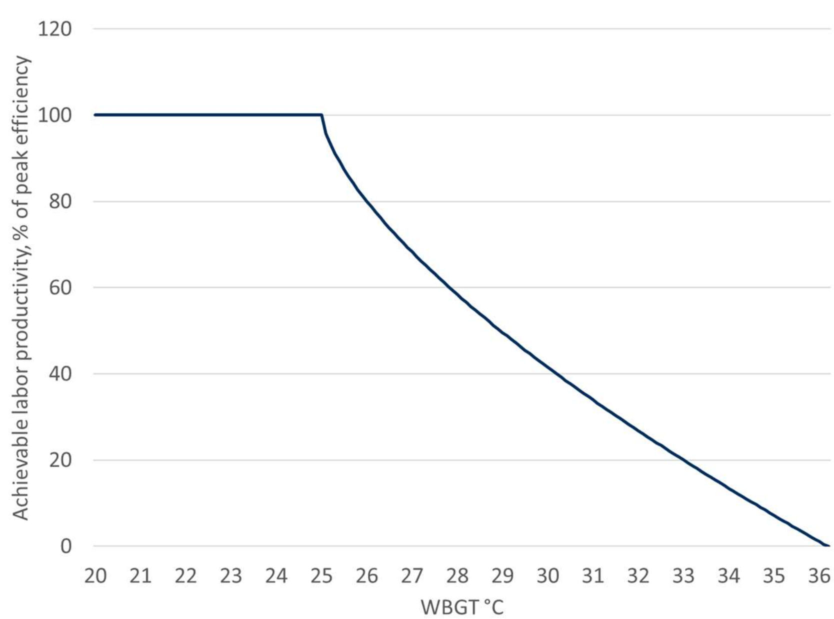
Where:

$g = grid\ cell$

$h = working\ hour$

$L_{h,g} = \%\ of\ potential\ labor\ productivity\ acheived\ in\ hour\ h\ and\ grid\ cell\ g$

Figure 1: Labor productivity at different WBGT (°C), as a percentage compared to peak efficiency



4 Scaling heat data to county borders

The chosen unit of analysis throughout this work is US counties, which is the most granular level at which many economic and demographic input data are accurate, up-to-date and readily available, such as from US Census and the Bureau of Economic Analysis Regional Economic Accounts. Analysis at the county level allows this work to capture greater variation in the exposure of people and economic activity to extreme heat. Due to the sometimes small numbers involved in such granular analysis, however, a given county estimate is subject to larger uncertainty than aggregate estimates. Accordingly, this work reports county-level results in indicative ranges rather than precise numbers.

The economic models take county-level number of heat days and workability impacts as inputs, which requires transforming the original raster data into a county-level dataset. The process of transformation is as follows:

- Define county borders using public Cartographic Boundary Shapefiles from the US Census Bureau
- Overlay heat rasters with county borders
- For each county, calculate area-weighted average heat outcomes based on the proportions of heat grids that overlap with county boundary
- Further overlay with Worldpop 1km*1km population data (2021) and for each county, calculate population-weighted average heat outcomes based on the population density of the heat grids that overlap with county boundary.

The area-weighted averages are applied in the agriculture models, where the area of land exposed to heat is of interest, while the population-weighted averages are applied to productivity and health models, where the number of people exposed is of interest.

Some summary statistics of the population-weighted heat data at the county level for the baseline period are as follows:

	Average annual % loss of working house (workability)		Number of days with max temp > 90F		Number of days with mean temp > 90F	
Max	11.9%	Duval County, TX	173.9	Yuma County, AZ	76.5	Yuma County, AZ
Mean	4.1%		34.5		1.1	

4.1 Mapping for counties with missing data

For four counties in the continental United States, temperature data from the climate models was unavailable. For these counties, temperature was proxied by that of its nearest geographical neighbor. The counties with missing data and their nearest neighbors are below.

Table 1: Mapping of counties with missing data to nearest neighbor

County missing data	Nearest neighbor
Matthews, VA	Gloucester, VA
Dukes, MA	Bristol, MA
San Juan, WA	Skagit, WA
Nantucket, MA	Barnstable, MA

5 GVA losses

5.1 Exposure to heat – outdoor and non-climate controlled work

Heat stress affects labor productivity only when workers are exposed to the heat. Workers who enjoy fully air-conditioned commutes and workplaces will not experience any loss of productivity. Modelling the effects of human heat stress on labor productivity requires determining how much work in each sector is done outdoors or in non-climate controlled buildings. A county where all work is done in climate-controlled environments would have zero workability loss regardless of the incidence of heat stress in that county. However, there are no direct sources of data on the exposure of different sectors to outdoor and non-climate controlled heat, so expert judgment determines the levels of exposure applied based on the best data available. The sector classification is based on NAICS codes, which are the standard for reporting in US data sources.

Two sources inform the estimation of economic activity's exposure to human heat stress. O*NET OnLine is a resource developed by the US Department of Labor to catalogue the working conditions and skill requirements of detailed occupations.[1] The data report how frequently work is done outdoors, inside in non-climate controlled buildings, and inside in climate-controlled buildings. The second source is USA Energy Information Administration (EIA) data on commercial building cooling. The EIA data reports the percent of floorspace cooled for commercial buildings across major sectors but does not capture how much time is spent outdoors, and so is most accurate for occupations where outdoor work is infrequent (U.S. EIA, 2016).

Work in the Agriculture and Construction sectors is primarily conducted outdoors. The general approach in the literature estimating the impact of heat is to assume full exposure of these sectors (agriculture, forestry, fishing and hunting; mining, quarrying, oil and gas extraction; utilities; and construction[2]). O*NET data broadly support the assumption that occupations in these sectors are largely working outdoors every day.[3] The O*NET data likewise report that the limited indoor work is frequently in non-climate controlled facilities. The EIA data cover only commercial buildings which in expert judgment are not relevant to occupations in the sectors. Between the high degree of outdoor work and the predominance of non-air conditioned indoor work in these sectors, this analysis models Agriculture and Construction as fully exposed to heat.

Manufacturing and service sectors have greater variability in human heat stress exposure. The approach to estimating exposure to human heat stress in these sectors is consequently more granular. The methodology begins by identifying representative occupations in the O*NET database. Manufacturing captures a wide range of economic activity, from producing computer chips in cleanrooms to steel forging to textile processing to non-primary food manufacturing. 10 occupations represent the manufacturing sector for this analysis, selected to represent different subsectors of manufacturing and different occupations within manufacturing. Services have even greater variability in their exposure to heat. Services include white-collar office jobs which are almost entirely done in air-conditioned offices as well as work in the transportation industry which can be significantly more exposed to heat. Accordingly, the analysis considers 15 separate subsectors within the "Service" sector,

[1] Outdoor work: (O*NET OnLine, 2021c), Indoor, not environmentally controlled work: (O*NET OnLine, 2021b), Indoor, environmentally controlled work: (O*NET OnLine, 2021a)

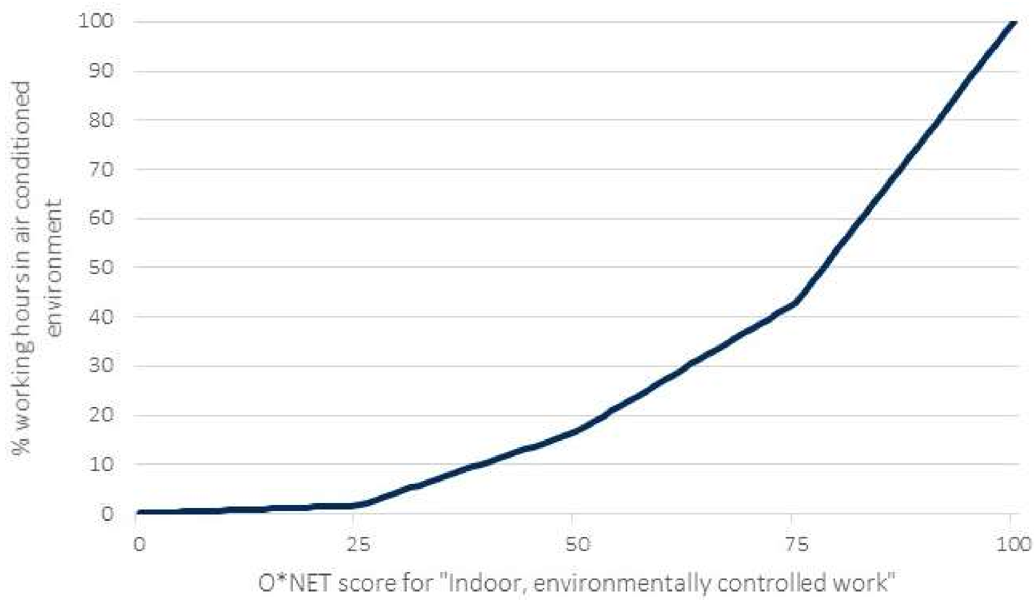
[2] "Agriculture" in this methodology refers to NAICS code 11, Agriculture, forestry, fishing, and hunting. "Construction and other outdoor occupations" includes NAICS 21, Mining, quarrying, oil and gas extraction; 22, Utilities; and NAICS 23, Construction.

[3] Such as 11-9013.00 Farmers, Ranchers, and Other Agricultural Managers, 45-3031.00 Fishing and Hunting Workers, 43-5041.00 Meter Readers, Utilities, 49-9052.00 Telecommunications Line Installers and Repairers, 49-9051.00 Electrical Power-Line Installers and Repairers, 11-9021.00 Construction Managers, 47-2073.00 Operating Engineers and Other Construction Equipment Operators, 47-2021.00 Brickmasons and Blockmasons, 47-2181.00 Roofers, 47-5071.00 Roustabouts, Oil and Gas, 47-5013.00 Service Unit Operators, Oil and Gas, 47-5011.00 Derrick Operators, Oil and Gas.

and 3-10 representative occupations for each. Occupations selected and their O*NET scores are available in the appendix.

O*NET scores report frequency of exposure to air-conditioning and must be converted into percentages of time exposed. The percentage of time spent without AC for given jobs is based on the "Indoor, environmentally controlled work" page of O*NET OnLine. The formula relating O*NET scores to percentage exposure is as follows: a score of 25 corresponds to having AC one day every other month ("Once a year or more but not every month"), 50 to having AC two months in a year ("Once a month or more but not every week"), 75 to having AC 3 times per week ("Once a week or more but not every day"). Linear interpolation completes the mapping of O*NET scores to percentage exposure between these inflection points. Figure 2 illustrates the function relating the O*NET score from 0-100 to a percentage from 0-100. The percentage of time exposed to heat stress equals 100 minus the percentage of time working in AC.

Figure 2: Mapping O*NET score to percentage of time spent working in environmentally-controlled spaces



EIA data provide a second reference point for estimating exposure to heat. The EIA data report the total square footage of floorspace in different types of commercial buildings and the square footage which is air-conditioned. By omitting time spent outdoors, the EIA data provides a lower bound on heat exposure. Expert judgment selected the most relevant commercial building type for Manufacturing and each two digit NAICS code within the Services and Other sector of this analysis. Whenever there is uncertainty, the more conservative (higher % of uncooled floorspace) estimate applies. For example, some governmental duties take place in buildings used for "Public Order and Safety"—police stations, fire stations, prisons, and courthouses—which have twice the uncooled floorspace of office buildings. For floorspace between 1-50% and 51-99% cooled, the midpoint applies to all floorspace. Square footage that falls into the 1-50% cooled category is assigned 25% cooling, and footage in the 51-99% cooled category is assigned 75% cooling. The qualitative comparison to O*NET-based estimates remains consistent if instead the 2/3 point applies (33% for 1-50%, and 83% for 51-99%).[4]

[4] Data that was suppressed due to low sample size are inferred based on the sum of reported categories and the total reported square footage. Ignoring missing data does not significantly reduce the estimates of uncooled floorspace. The largest differences are in Other (41% vs. 35%), Food sales + food service + lodging (17% vs. 13%), and Healthcare (8% vs. 6%).

Table 2 below reports the exposure estimates from O*NET, the EIA, and the exposure applied in this analysis for the Manufacturing and Services and Other sectors. As discussed above, Agriculture (NAICS 11) and Construction and other outdoor occupations (NAICS 21-23) are 100% exposed. Details on the O*NET estimates are provided in the appendix.

Table 2: EIA Air-conditioning data, O*NET exposure data, and selection of "Manufacturing" and "Services and other" sectors' exposure for labor productivity analysis

Major sector for analysis	NAICS code	NAICS sector	Approximate EIA building activity (U.S. EIA, n.d.)	Estimated O*NET Non-AC %	Estimated EIA uncooled floorspace % (midpoint / 2/3)	% exposure applied
Manufacturing	31-33	Manufacturing	Other	50%	41% / 36%	50%
Services and other	42	Wholesale trade	Warehouse and storage	20%	69% / 64%	50%
Services and other	44-45	Retail trade	Mercantile and service	30%	33% / 28%	30%
Services and other	48-49	Transportation and warehousing	Warehouse and storage	80%	69% / 64%	80%
Services and other	51	Information	Office	40%	16% / 12%	15%
Services and other	52	Finance and insurance	Office	40%	16% / 12%	15%
Services and other	53	Real estate rental and leasing	Office	40%	16% / 12%	15%
Services and other	54	Professional scientific and technical services	Office	30%	16% / 12%	15%
Services and other	55	Management of companies and enterprises	Office	20%	16% / 12%	15%
Services and other	56	Administrative and support and waste management and remediation services	Office	35%	16% / 12%	15%
Services and other	61	Educational services	Education	20%	22% / 18%	20%
Services and other	62	Health care and social assistance	Healthcare	15%	8% / 6%	10%

Major sector for analysis	NAICS code	NAICS sector	Approximate EIA building activity (U.S. EIA, n.d.)	Estimated O*NET Non-AC %	Estimated EIA uncooled floorspace % (midpoint / 2/3)	% exposure applied
Services and other	71	Arts, entertainment, and recreation	Public assembly	25%	26% / 22%	25%
Services and other	72	Accommodation and food services	Food sales + food service + lodging	50%	17% / 14%	25%
Services and other	81	Other services except government and government enterprises	Office	30%	16% / 12%	15%
Services and other	92	Government and government enterprises	Office	40%	16% / 12%	15%

5.2 Output losses – production function

The analysis uses a simple economic model to estimate the impact of worker heat stress on economic production. Production within each sector follows a Cobb-Douglas production function with constant returns to scale, where Y represents output, A total factor productivity, L labor input, K capital input, and β is the labor share in production. Exposure to extreme heat reduces the productivity of labor, reducing the effective size of the labor force.

$$Y = AL^{\beta}K^{(1-\beta)}$$

$$Marginal\ product\ of\ labor\ (MPL): \frac{\partial Y}{\partial L} = \beta \frac{Y}{L}$$

Given the nature of the production function, estimating economic losses associated with extreme heat for the baseline, 2030 and 2050 require four inputs:

- the labor share in production (β), which the analysis assumes remains constant over time;
- sector output at the county level, which is projected forward to 2050;
- labor input to the sector at the county level, which is projected forward to 2050;
- effective reduced labor supply due to heat stress, which is projected forward to 2050.

5.2.1 Labor share in production

The component β can be approximated by the relative earnings to labor for each sector.[5] The analysis assumes that β is sector specific but does not vary across counties or over time. The sectoral share of labor in the production function is estimated from the Global Trade Analysis Project (GTAP) 2014 Social Accounting Matrix (SAM) for the US. The relative earnings are calculated as: $\frac{Rent\ pai\ \ to\ labor}{Rent\ paid\ to\ capital+\ Rent\ paid\ to\ labor}$. Table 3 summarizes the coefficients used. A concordance table between the sectors can be found in the technical appendix.

Table 3: Estimates for β in the production function

Sector	Labor share
Agriculture	65.3%
Construction and other outdoor occupations	49.6%
Manufacturing	48.8%
Services and other	51.0%

Source: Vivid Economics

5.2.2 County-level sector output

The gross value added (GVA) for each sector and county is extracted from the latest Bureau of Economic Analysis Regional Economic Accounts and projected forward in line with GDP forecasts.[6] The Shared Socioeconomic Pathways (SSP) dataset, which feeds into the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report, includes national level GDP forecasts under five different scenarios (IIASA, 2018). The analysis takes the GDP forecast for the SSP5 scenario (closest to a 'business as usual' scenario) and assumes that county-sector GVA grows proportionally with national GDP growth. That is, if total GDP doubles from 2020 to 2050, GVA in each sector and each county also doubles. This assumes there is no structural economic transformation, which is discussed in Box 1.

5.2.3 County-sector labor supply

The US Bureau of Economic Analysis Regional Economic Accounts provides the baseline number of jobs in each sector and each county, which is projected forward using population forecasts. Hauer (2019) has developed SSP-consistent forecasts of population in different age brackets by gender and race for all counties.

[5] This relies on the assumption of perfect competition in the economy. Under perfect competition, profit-maximizing behavior means that the factors of production are paid a return equal to their respective marginal products.

[6] A concordance table between the NAICS sector classification used in the census and the sector list in this analysis can be found in the technical appendix.

Box 1: Structural economic transformation in the model

In this analysis, the structure and spatial distribution of economic activity in 2030 and 2050 does not change from 2020. Key features of the economy remain fixed within each county at baseline levels:

- sectoral composition of economic activity
- the share of capital and labor in each sector
- employment rates

These are inherently unrealistic assumptions, as the economy should undergo some adaptation to the extreme heat modelled in the future:

- Heavily exposed areas should reduce their economic activity in outdoor work (sectoral shift)
- Heavily exposed sectors should increase their capital intensity (capital/labor shift)
- Employment rates may change due to transition effects (exposed occupations shrinking and requiring a smaller workforce)

However, they are useful assumptions to illustrate the effect of climate change without adaptation. Likewise, the emissions pathway under RCP 8.5 contains certain assumptions on economic activity that may be inconsistent with any adaptation pathway modelled as a response to extreme heat. As such, the results indicate how the impact of extreme heat will evolve if current ways and places of living and working are maintained.

5.2.4 Effective reduction in labor supply due to heat stress

The effective reduction in labor supply due to heat stress is a combination of the workability data (section 3) and the exposure analysis (section 5.1). For example, if the workability modelling estimates a 20% loss for exposed workers in a given county, 100% of agricultural workers and construction workers are exposed, and therefore the effective reduction in labor supply is 20%. In contrast, 50% of manufacturing workers are exposed, meaning the effective reduction in labor supply is 10%.

The analysis assumes that losses are already embodied in reported GDP data and forecasts. That is, if actual GDP in an area in 2020 is $95mn, and the workability-related losses are 5%, the GDP without exposure to heat stress would have been $100mn.

6 Agricultural yield losses

The approach to estimating agricultural yields in the United States follows Schlenker and Roberts (2009). Prof. Schlenker has provided updated results using data through 2020 (Schlenker, 2021). Crops' exposure to temperatures beyond critical thresholds during their growing seasons[7] will experience yield losses. This analysis focuses on corn, soy, cotton and wheat. Corn, soy and wheat cover approximately 62% of US harvested area in 2010, while cotton is an important cash crop for heat-exposed areas of the American south (Schauberger et al., 2017). Based on the typical distribution of heat days across the year in the United States, corn, soy, and cotton are expected to be exposed to every day of extreme heat in the data. The model uses degree days above the temperature thresholds to estimate reductions in log yield. The effects are:

Crop	Temperature threshold	Hot degree day coefficient	t-statistic
Corn	29°C	-0.0068174	-11.46
Soy	30°C	-0.0064135	-16.68
Cotton	32°C	-0.0036863	-6.56

The heat input data reports the number of "hot days" where the mean temperature is greater than or equal to 90°F (32°2C), so degree days are calculated as 3.2 x "hot days" for corn, 2.2 x "hot days" for soy, and 0.2 x "hot days" for cotton. This approach is very conservative, as it does not capture any degree days where the day's mean temperature is between the threshold temperature and 32.2°C, or extra degree days where the mean temperature exceeds 32.2°C.

Schlenker and Roberts apply the corn and soy estimates only to counties east of the 100 degree meridian, due to the extensive use of capital intensive subsidised irrigation for those crops in the west. Eastern areas rely more on groundwater irrigation. This analysis conservatively applies estimates for all four crops to all states straddling or east of the 100 degree meridian.[8] While this includes some counties Schlenker and Roberts consider likely to be more irrigated, the approach is reasonable considering the uncertainty around exact irrigation methods and the highly conservative approach adopted with respect to degree days. Schauberger et al. (2017) Figure 2, maps d-f show that these areas are only partially irrigated, and counties with at least 75% irrigation of the relevant crop are not dominant compared to rainfed counties (Figure 1, maps d-f).

Schauberger et al. do not find significant impact for wheat in current climate conditions, due to the earlier growing season, but model expected yield declines in future climate scenarios. While most extreme heat days are currently in late July and August, missing wheat's vulnerable growing season, climate models suggest the heat season will begin earlier over time. Table 1 of Schauberger et al. (2017) suggests that future wheat yield losses will be about 45% of future corn yield losses (22%/49%), so the relationship between heat and wheat yield equals 45% of the yield losses estimated for corn from Schlenker and Roberts in 2030 and 2050.

[7] March–August for corn and soybeans (also Schauberger et al. 2017) and April–October for cotton, Schlenker and Roberts (2009). October 15 to July 15 for wheat, Schauberger et al. (2017).
[8] While Schlenker and Roberts do not find significantly different impacts for cotton, relatively little cotton is grown in the western half of the United States, so the impact of excluding those states from the analysis is minimal.

Production and pricing data for this analysis come from the USDA. Data for US area planted and average yields are 2010-2020 average production by county from the USDA CropScape (USDA, 2021a). Production is valued at the simple average of monthly prices from 2020, again from the USDA (USDA, 2021b).

Future production and prices in 2030 and 2050 remain at present values. As with the workability analysis, the assumption that farmers do not adapt in response to the changing climate is unrealistic. Again, this approach illustrates the expected losses if nothing changes except for the climate, highlighting the need for action. Further, prices should be expected to increase in level and variability as yields decline. However, estimating general equilibrium effects of US yield declines on global prices is beyond the scope of this project.

7 Mortality

The mortality analysis adopts the estimates of Deschênes and Greenstone (2011), Table 2, by age category. Coefficients from Deschênes and Greenstone Table 2 (1d) are applied to the data on population and heat to estimate the effect of the number of days with mean temperature above 90°F on mortality rates. The additional deaths due to extreme heat are calculated by multiplying the age-specific change in mortality rate by the local population in each county aged 0-1, 1-44, 45-64, and 65+. The analysis assumes that the age-specific mortality rates reported by Barreca et al. (2013) estimated for 1960-2004 are equal across all counties in the United States, at 15.0 (0-1), 1.2 (1-44), 8.9 (45-64), and 52.8 (65+) per 1,000. Deschênes and Greenstone and Barreca et al. (2016)are both heavily relied on in the literature estimating heat-related mortality.[9] Census data report ages in five year ranges (0-4, 5-9, etc.)., so the number of children aged 0-1 was computed using the average national infant mortality rate and assuming uniform birth rates across the past five years in every county.

[9] See for example (Hsiang et al., 2015)

8 Occupational injury

High temperatures increase the rate of occupational injury, creating dangerous conditions for workers as well as further reducing labor productivity. Park et al (2021) demonstrate that hotter temperatures increases the rate of workplace injuries and that 14,000 workplace injuries each year are attributable to heat. The analysis draws on claims-level injury data from the California Worker's Compensation System over the 2001 to 2018 period, which the authors link to spatially and temporally granular weather data at the zipcode-day level, as well as information on occupation and industry characteristics.

Park et al. 2021 estimate sector-specific coefficients relating temperature to occupational injuries. Figure 6 shows they consider agriculture, construction, and utilities as "outdoor" sectors. Indoor sectors analysed are manufacturing, wholesale trade, and transportation and warehousing. While this report's analysis of workability, described in Section 3, identifies these "indoor" sectors as somewhat heat exposed, the occupational injury analysis follows Park et al.'s approach and applies the "indoor" coefficient to the manufacturing and service sectors, as estimated from Figure 6 of their report for the 90-95°F range.

Park et al. report coefficients estimating the additional injuries in indoor vs. outdoor occupations a heat day causes in a typical California zip code. To estimate the effect in any given US county, results need to be scaled by the number of indoor and outdoor jobs in a typical California zip code compared to the number of indoor and outdoor jobs in each county. That is, this analysis first estimates the number of additional injuries a heat day causes per *job* in California. For indoor jobs and equivalently for outdoor jobs:

$$Additional\ heat\ day\ injuries\ per\ indoor\ job$$
$$= \frac{(0.084\ injuries\ per\ heat\ day/CA\ zip\ code * \ 1{,}741\ zip\ codes)}{\#CAindoorjobs}$$

An additional day with a maximum temperature in the 90-95°F bin is thus associated with an additional 13.85 occupational injuries per 100k outdoor jobs, and only 0.65 additional occupational injuries per 100k indoor jobs. These estimates are applied to the number of heat days and jobs in each county to estimate the additional occupational injuries associated with extreme heat in each county.

The coefficients require an hyperbolic sine transformation to estimate the number of excess injuries associated with a 90°F+ max temperature day. However, Bellemare and Wichman (2020) show that for an arcsinh–linear specification, converting the coefficients estimated under the inverse hyperbolic sine transformed data is not necessary if the independent variable (in the current analysis, the number of occupational injuries in a sector and county in a year) is sufficiently large. All of the sector-county combinations which will experience extreme heat days in 2020, 2030, and 2050 have sufficiently large injury rates to apply the coefficient directly.

9 Demographic characteristics

Demographic data come from the American Community Survey (ACS) five year Public Use Microdata Sample (PUMS) 2019, available on the Census Bureau website. The lowest level of granularity is at the Public Use Microdata Areas (PUMA) level. Each PUMA is an area containing roughly 100,000 people or more. A mapping was applied to convert this data from PUMA-level to county-level.

Demographic variables were recoded into more aggregated and mutually exclusive categories. Race was recoded into a single mutually exclusive race variable (that is, someone originally coded as Hispanic and white is recoded as Hispanic because they identified as Hispanic).

The demographic data was aggregated to PUMA level by applying the weights (PWGTP), where PWGTP represents the number of people represented by each observation. A breakdown of the number of people by race-gender-education-income-sector was produced for each PUMA. To convert this aggregated data from PUMA-level to county-level, A PUMA-to-county crosswalk[10] based on PUMA 2000 definition was used. Where some PUMAs were not matched in the crosswalk due to a change in PUMA code in 2010, a conversion from PUMA 2010 to PUMA 2000 based on simple averages was applied before mapping to county using the crosswalk. This process successfully captures the transformation from PUMA to the complete set of counties.

[10] Note: select all states when downloading the crosswalk; the data will take a few minutes to process.

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11 Technical appendix

Table 4: GTAP sector aggregation to Vivid sector

GTAP Sector	GTAP Sector Code	GTAP Sector Description	Vivid Sector
1	pdr	Paddy Rice: rice, husked and unhusked	Agriculture
2	wht	Wheat: wheat and meslin	Agriculture
3	gro	Other Grains: maize (corn), barley, rye, oats, other cereals	Agriculture
4	v_f	Veg & Fruit: vegetables, fruitvegetables, fruit and nuts, potatoes, cassava, truffles,	Agriculture
5	osd	Oil Seeds: oil seeds and oleaginous fruit; soy beans, copra	Agriculture
6	c_b	Cane & Beet: sugar cane and sugar beet	Agriculture
7	pfb	Plant Fibres: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles	Agriculture
8	ocr	Other Crops: live plants; cut flowers and flower buds; flower seeds and fruit seeds; vegetable seeds, beverage and spice crops, unmanufactured tobacco, cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets; swedes, mangolds, fodder roots, hay, lucerne (alfalfa), clover, sainfoin, forage kale, lupines, vetches and similar forage products, whether or not in the form of pellets, plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes, sugar beet seed and seeds of forage plants, other raw vegetable materials	Agriculture
9	ctl	Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof	Agriculture
10	oap	Other Animal Products: swine, poultry and other live animals; eggs, in shell (fresh or cooked), natural honey, snails (fresh or preserved) except sea snails; frogs' legs, edible products of animal origin n.e.c., hides, skins and furskins, raw , insect waxes and spermaceti, whether or not refined or coloured	Agriculture
11	rmk	Raw milk	Agriculture
12	wol	Wool: wool, silk, and other raw animal materials used in textile	Agriculture
13	frs	Forestry: forestry, logging and related service activities	Agriculture
14	fsh	Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing	Agriculture
15	coa	Coal: mining and agglomeration of hard coal, lignite and peat	Construction and other outdoor occupations

GTAP Sector	GTAP Sector Code	GTAP Sector Description	Vivid Sector
16	oil	Oil: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)	Construction and other outdoor occupations
17	gas	Gas: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)	Construction and other outdoor occupations
18	omn	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying	Construction and other outdoor occupations
19	cmt	Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules, and hinnies. raw fats or grease from any animal or bird.	Manufacturing
20	omt	Other Meat: pig meat and offal. preserves and preparations of meat, meat offal or blood, flours, meals and pellets of meat or inedible meat offal; greaves	Manufacturing
21	vol	Vegetable Oils: crude and refined oils of soya-bean, maize (corn),olive, sesame, ground-nut, olive, sunflower-seed, safflower, cotton-seed, rape, colza and canola, mustard, coconut palm, palm kernel, castor, tung jojoba, babassu and linseed, perhaps partly or wholly hydrogenated,inter-esterified, re-esterified or elaidinised. Also margarine and similar preparations, animal or vegetable waxes, fats and oils and their fractions, cotton linters, oil-cake and other solid residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; degras and other residues resulting from the treatment of fatty substances or animal or vegetable waxes.	Manufacturing
22	mil	Milk: dairy products	Manufacturing
23	pcr	Processed Rice: rice, semi- or wholly milled	Manufacturing
24	sgr	Sugar	Manufacturing
25	ofd	Other Food: prepared and preserved fish or vegetables, fruit juices and vegetable juices, prepared and preserved fruit and nuts, all cereal flours, groats, meal and pellets of wheat, cereal groats, meal and pellets n.e.c., other cereal grain products (including corn flakes), other vegetable flours and meals, mixes and doughs for the preparation of bakers' wares, starches and starch products; sugars and sugar syrups n.e.c., preparations used in animal feeding, bakery products, cocoa, chocolate and sugar confectionery, macaroni, noodles, couscous and similar farinaceous products, food products n.e.c.	Manufacturing
26	b_t	Beverages and Tobacco products	Manufacturing

GTAP Sector	GTAP Sector Code	GTAP Sector Description	Vivid Sector
27	tex	Textiles: textiles and man-made fibres	Manufacturing
28	wap	Wearing Apparel: Clothing, dressing and dyeing of fur	Manufacturing
29	lea	Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear	Manufacturing
30	lum	Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials	Manufacturing
31	ppp	Paper & Paper Products: includes publishing, printing and reproduction of recorded media	Manufacturing
32	p_c	Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel	Manufacturing
33	crp	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products	Manufacturing
34	nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete	Manufacturing
35	i_s	Iron & Steel: basic production and casting	Manufacturing
36	nfm	Non-Ferrous Metals: production and casting of copper, aluminium, zinc, lead, gold, and silver	Manufacturing
37	fmp	Fabricated Metal Products: Sheet metal products, but not machinery and equipment	Manufacturing
38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers	Manufacturing
39	otn	Other Transport Equipment: Manufacture of other transport equipment	Manufacturing
40	ele	Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus	Manufacturing
41	ome	Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks	Manufacturing
42	omf	Other Manufacturing: includes recycling	Manufacturing
43	ely	Electricity: production, collection and distribution	Manufacturing
44	gdt	Gas Distribution: distribution of gaseous fuels through mains; steam and hot water supply	Manufacturing
45	wtr	Water: collection, purification and distribution	Manufacturing
46	cns	Construction: building houses factories offices and roads	Manufacturing

GTAP Sector	GTAP Sector Code	GTAP Sector Description	Vivid Sector
47	trd	Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel	Manufacturing
48	otp	Other Transport: road, rail ; pipelines, auxiliary transport activities; travel agencies	Manufacturing
49	wtp	Water transport	Construction and other outdoor occupations
50	atp	Air transport	Services and other
51	cmn	Communications: post and telecommunications	Services and other
52	ofi	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding (see next)	Services and other
53	isr	Insurance: includes pension funding, except compulsory social security	Services and other
54	obs	Other Business Services: real estate, renting and business activities	Services and other
55	ros	Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons (servants)	Services and other
56	osg	Other Services (Government): public administration and defense; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and similar activities, activities of membership organizations n.e.c., extra-territorial organizations and bodies	Services and other
57	dwe	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)	Services and other

Source: Vivid Economics

Table 5: NAICS mapping to Vivid sector

NAICS sector	NAICS sector description	Vivid sector
11	Agriculture, Forestry, Fishing and Hunting	Agriculture
21	Mining, Quarrying, and Oil and Gas Extraction	Construction and other outdoor occupations
22	Utilities	Construction and other outdoor occupations

NAICS sector	NAICS sector description	Vivid sector
23	Construction	Construction and other outdoor occupations
31-33	Manufacturing	Manufacturing
42	Wholesale Trade	Services and other
44-45	Retail Trade	Services and other
48-49	Transportation and Warehousing	Services and other
51	Information	Services and other
52	Finance and Insurance	Services and other
53	Real Estate and Rental and Leasing	Services and other
54	Professional, Scientific, and Technical Services	Services and other
55	Management of Companies and Enterprises	Services and other
56	Administrative and Support and Waste Management and Remediation Services	Services and other
61	Educational Services	Services and other
62	Health Care and Social Assistance	Services and other
71	Arts, Entertainment, and Recreation	Services and other
72	Accommodation and Food Services	Services and other
81	Other Services (except Public Administration)	Services and other
92	Public Administration	Services and other

Source: Vivid Economics

Table 6: Representative Manufacturing Occupations and Exposure from O*NET

O*NET sector code	Occupation title	AC exposure score	Non – AC and outdoors %
11	Industrial Production Managers	71	61%
17	Manufacturing Engineers	85	35%
17	Industrial Engineers	87	30%
51	Jewelers and Precious Stone and Metal Workers	80	45%
51	Machinists	77	52%
51	Aircraft Structure, Surfaces, Rigging, and Systems Assemblers	77	52%
51	Textile Knitting and Weaving Machine Setters, Operators, and Tenders	94	13%
51	Sewing Machine Operators	64	68%
51	Foundry Mold and Coremakers	24	98%
51	Food and Tobacco Roasting, Baking, and Drying Machine Operators and Tenders	57	76%

Table 7: Representative Service and Other Occupations and Exposure from O*NET

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
Wholesale Trade	13	Wholesale and Retail Buyers, Except Farm Products	100	0%	20%
	41	Sales Representatives, Wholesale and	91	20%	

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
		Manufacturing, Except Technical and Scientific Products			
	41	Sales Representatives, Wholesale and Manufacturing, Technical and Scientific Products	69	63%	
Retail trade	41	Cashier	83	39%	30%
	41	Retail Salespersons	79	48%	
	41	Door-to-Door Sales Workers, News and Street Vendors, and Related Workers	46	86%	
	41	Counter and Rental Clerks	91	20%	
	41	Sales Representatives, Wholesale and Manufacturing, Except Technical and Scientific Products	91	20%	
	41	First-Line Supervisors of Retail Sales Workers	92	18%	
Transportation and warehousing	53	Traffic Technicians	82	41%	80%
	53	Ship Engineers	48	84%	
	53	Bus Drivers, Transit and Intercity	43	87%	
	53	Light Truck Drivers	31	95%	
	53	Locomotive Engineers	11	99%	
Information	27	Film and video editors	100	0%	40%
	27	Broadcast technicians	99	2%	

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
	27	Audio and video technicians	96	9%	
	27	Sound Engineering Technicians	96	9%	
	27	Media Technical Directors/Managers	95	11%	
	27	News Analysts, Reporters, and Journalists	86	32%	
	27	Broadcast Announcers and Radio Disc Jockeys	78	50%	
	27	Camera Operators, Television, Video, and Film	80	45%	
	27	Technical Writers	79	48%	
	27	Producers and Directors	89	25%	
Finance and Insurance	13	Credit Analysts	100	0%	40%
	13	Loan Officers	100	0%	
	13	Human Resources Specialists	97	6%	
	11	Financial managers	93	16%	
	13	Financial Examiners	89	25%	
	13	Accountants and Auditors	91	20%	
	13	Insurance Underwriters	89	25%	
	13	Tax Preparers	82	41%	
	13	Market Research Analysts and Marketing Specialists	76	54%	
	13	Management Analysts	74	58%	

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
Real estate rental and leasing	11	Property, Real Estate, and Community Association Managers	73	59%	40%
	13	Appraisers and Assessors of Real Estate	79	48%	
	41	Real Estate Brokers	94	13%	
	41	Real Estate Sales Agents	59	73%	
Professional scientific and technical services	15	Statisticians	90	22%	30%
	15	Database administrators	99	2%	
	15	Geographic Information Systems Technologists and Technicians	96	11%	
	17	Landscape Architects	85	34%	
	17	Robotics Technicians	79	48%	
	19	Economists	94	14%	
	19	Hydrologists	75	57%	
Management of companies and enterprises	11	Chief Executives	98	4%	20%
	11	Financial Managers	93	16%	
	11	Human Resources Managers	90	22%	
	11	Supply Chain Managers	81	43%	
	11	Sales Managers	63	69%	
Administrative and support and waste management and remediation services	17	Water/Wastewater Engineers	84	36%	35%
	19	Environmental Science and Protection Technicians, Including Health	83	38%	

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
	19	Environmental Restoration Planners	72	60%	
	51	Water and Wastewater Treatment Plant and System Operators	83	38%	
Educational services	25	Archivists	98	4%	20%
	25	Mathematical Science Teachers, Postsecondary	93	13%	
	25	Tutors	91	20%	
	25	Recreation and Fitness Studies Teachers, Postsecondary	85	34%	
	25	Secondary School Teachers, Except Special and Career/Technical Education	78	50%	
Health care and social assistance	29	Pharmacists	100	0%	15%
	29	Dentists, General	94	13%	
	29	Dietitians and Nutritionists	90	22%	
	31	Veterinary Assistants and Laboratory Animal Caretakers	98	4%	
	31	Medical Assistants	87	30%	
Arts, entertainment and recreation	27	Editors	98	4%	25%
	27	Dancers	94	14%	
	27	Actors	89	25%	
	27	Musicians and singers	80	46%	
	27	Photographers	73	60%	
Accommodation and food services	35	Cooks, Institution and Cafeteria	91	20%	50%

NAICS sector	O*NET Sector Code	Occupation title	AC exposure score	Non- AC and outdoors %	Chosen percentage exposed to heat stress
	35	Waiters and Waitresses	81	43%	
	35	Bartenders	74	58%	
	35	Chefs and Head Cooks	70	62%	
	35	Cooks, Fast Food	49	83%	
Other services except government and government enterprises	39	Hairdressers, Hairstylists, and Cosmetologists	85	34%	30%
	39	Travel guides	78	50%	
	23	Paralegals and Legal Assistants	97	7%	
	43	Postal Service Mail Carriers	78	50%	
	43	Tellers	92	18%	
Government and government enterprises	33	Police and Sheriff's Patrol Officers	56	77%	40%
	33	Firefighters	56	77%	
	11	Administrative Services Managers	82	41%	
	23	Administrative Law Judges, Adjudicators, and Hearing Officers	99	2%	

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