On August 30, 2024, the U.S. Occupational Safety and Health Administration (OSHA) announced its intent to establish a federal rule for heat illness and injury prevention in work settings.[1] The standard would require employers to provide workers with rest breaks, water, heat safety trainings, and more—once temperatures reach pre-specified “trigger” levels.[1,2] While some stakeholders support this rule, others have voiced concerns—about inadequate empirical data to support its requirements, about a ‘one-size-fits-all’ approach that fails to account for industry and geographic differences, and about its implications for labor productivity.[3,4] Yet, the rule may be well-founded. A growing body of evidence suggests that workers laboring in high heat exposure industries—construction, manufacturing, and agriculture, and more—are vulnerable to illness, injury and death.[5–8] The Bureau of Labor Statistics (BLS) reports that, each year in the U.S., workplace heat exposures contribute to 3,500 injuries or illnesses and 34 deaths.[1,9] These figures are probably vast under-estimates due to under-reporting and misclassification of heat-related outcomes, which commonly present (and are recorded) as cardiovascular or respiratory conditions.[10–13] Thus, the true burden of heat-related injury, illness, and death among American workers remains unclear.[14] In the absence of a national standard, five states have enacted local workplace heat standards. These standards vary in requirements, workers covered, and the temperature thresholds that trigger action, leaving uncertainty about their impact on worker safety and labor productivity.[15–18] *There is a critical need to elucidate the true burden of occupational heat exposures, and to understand if and how local workplace heat standards support worker health and labor productivity.*

In the first-ever national study of adverse workplace heat-outcomes and heat safety policies in the U.S., we will fill these gaps. Using legal surveillance methods,[19] we will develop and publish an Open Source longitudinal database of state-level heat safety policies. We will link the policy database with occupational injury, illness, and fatality data from the BLS and per capita payroll data from the US Census Bureau to measure labor productivity. Using state-of-the-art time series methods, we will estimate total annual heat-injuries, -illnesses, and -deaths among workers, within each county and state of the U.S (years 2003 to 2022). We will then leverage geographic and temporal variation in the enactment of state-level workplace heat standards and use robust quasi-experimental methods to quantify impacts of these policies on occupational injury, illness, death and labor productivity. This proposal builds on our group’s previous work showing that high ambient temperatures are associated with adverse morbidity and mortality outcomes,[20–25] and our published quasi-experimental study showing that mandated ten-minute rest breaks for construction workers were associated with modest protection against injuries and illnesses.[26] *Our specific aims are to:*

Aim 1A. Estimate the total injury, illness, and mortality burden that workplace heat exposures represent to workers, for each U.S. county and state. <u>*Hypothesis*</u>*: The burden of workplace heat injuries, illness, and deaths is much higher than previously estimated.* We will link industry and county-stratified counts of all-cause, cardiovascular, respiratory, kidney, and heat-related workplace injury, illness, and fatality outcomes with daily temperature and humidity values. We will use a time series study design and distributed lag non-linear (DLNM) functions[27] to quantify excess heat-related adverse outcomes among workers in each U.S. county and state.

Aim 1B. Identify industry- and county- specific safe maximum threshold temperatures for workers, accounting for geographic differences in acclimatization and adaptation. <u>*Hypothesis:*</u> *Safe maximum thresholds vary across industry and geographic location.* We will use flexible spline terms to identify safe maximum temperatures.

Aim 2. Quantify associations of workplace heat safety standards (presence and level of requirement) with work-related heat injuries, illnesses, and deaths. <u>*Hypothesis:*</u> *Workplace heat standards are associated with lower rates of injury, illness, and death in workers, though level of protections varies from place to place.* We will use a quasi-experimental, staggered difference-in-difference design with synthetic controls to calculate changes in rates of heat-related injuries, illnesses, and deaths before vs. after the enactment of heat safety standards, comparing states with and without enacted heat standards.

Aim 3. Elucidate labor productivity impacts of heat safety standards. <u>*Hypothesis:*</u> *Heat standards are associated with improved labor productivity.* We will use a quasi-experimental design to estimate associations between heat anomalies or heat shocks and labor productivity (estimated using per capita payroll data), before versus after the enactment of heat safety standards, in areas with and without heat safety standards.

Impact. *Results from this work will provide critical empirical data about the total burden that heat represents to American workers, and about the implications of workplace heat safety standards for health, safety, and labor productivity. This work is critical for informing heat-standards that support safety and productivity.*

I. SIGNIFICANCE

A. The total burden of heat-related injury, illness, and deaths among American workers is unclear. The earth's temperatures are warming to unprecedented and dangerously high levels.[28] This represents a critical threat to laborers working in industries with high heat exposure—construction, manufacturing, landscaping, agriculture, forestry, food service, among others.[29–33] Because they engage in metabolically intense activities, with extremely high ambient or radiant temperature exposures, sometimes while wearing bulky clothing, workers are vulnerable to heat stress and heat-associated injury, illness, or death.[5,28,29,34–38] Indeed, OSHA estimates that, between years 2011 and 2020, American workers experienced 33,890 work-related injuries and illnesses attributable to heat exposures.[9]

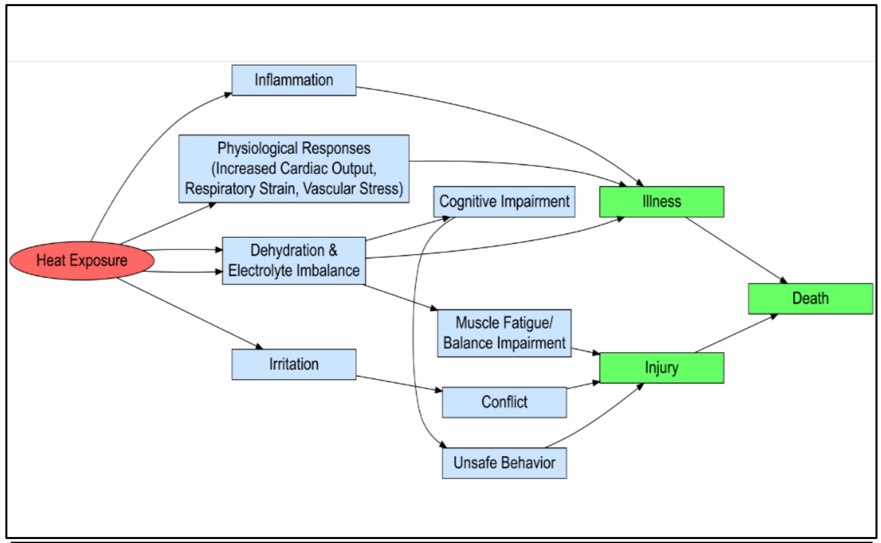

Figure 1. Conceptual diagram outlining key mechanisms underlying links between heat exposure, heat stress, and illness, injury, or mortality outcomes.

Alarmingly, this is probably an undercount. This is because heat-related outcomes are generally identified using heat specific diagnostic or cause of injury codes (e.g., ICD-10 T67: Effects of heat and light, BLS Occupational Injury and Illness Classification System event/exposure code 321 and the nature code of 072).[10] However, heat-related events are often diagnosed and coded as other conditions, such as cardiovascular or respiratory exacerbations.[12,39] Indeed, heat can lead to illness, injury, and death through a variety of mechanisms including cardiovascular or respiratory strain,[37] reduced cognition,[35,40] by causing dizziness or exhaustion,[8] by increasing irritability or aggression[41,42] (which can lead to heat-related workplace violence/conflict), and more (**Figure 1**).[10–12] *Yet, to date, many of these heat-related outcomes have been missed because of reliance on heat-specific codes.* Advanced statistical methods are needed to improve our understanding of the total burden that heat represents to workers.

B. There is a lack of empirical data about the protections offered by workplace heat standards. Currently, the U.S. does not have a federal heat-specific standard for workers. Instead, OSHA relies on the General Duty Clause, which says that employers must provide employees with a hazard-free workplace.[43] In the absence of a federal workplace heat standard, California, Washington, Oregon, Colorado, and Minnesota have enacted their own standards (**Figure 2**).[15–17,44] These state-specific standards vary in terms of requirements, industries and workers covered, and the temperatures that trigger their enforcement. Even though some standards have been in place since year 2005, few empirical studies have assessed their effectiveness.[18,26,45] [26] ***There remains tremendous uncertainty about the effectiveness of state-level standards for worker protection.***

	California¹	Washington¹	Minnesota²	Oregon³	Colorado⁴
Observation/Supervision	✗	✗	✗	✗	✓
Heat Illness Prevention Plan	✓	✓	✗	✓	✗
Training	✓	✓	✓	✓	✓
Acclimatization	✓	✓	✗	✓	✓
Emergency Response	✓	✓	✗	✓	✓
Rest Breaks if Needed	✓	✓	✗	✗	✓
Shade or Cool Down Means	✓	✓	✗	✓	✓
Provision of Water	✓	✓	✗	✓	✓
86°F Trigger	✗	✗	✓	✗	✗
80°F Trigger	✓	✓	✓	✓	✓
77°F Trigger	✗	✗	✓	✗	✗

¹ Outdoor workers
² Indoor workers
³ Indoor and outdoor workers
⁴ Agricultural workers

Figure 2. Requirements of enacted state workplace heat policies. Green check marks indicate presence of the requirement, while red x marks indicate the state does not have that requirement.

On August 30, 2024, OSHA announced its plan to create a federal standard to protect for American workers against heat illness or injury.[1] While some stakeholders support the standard, others, and particularly business or industry representatives, have voiced criticisms—about inadequate empirical data to support its requirements, and about its failure to account for regional or industry differences. They have also expressed concerns that a federal standard would have negative financial implications for businesses. *There is a tremendous need to quantify and compare the effectiveness of currently enacted state-level heat standards, to address these concerns and to inform the creation of tailored and effective local or federal heat standards that support health, safety and business productivity.*[46,4]

We propose the first ever national study of associations of heat, heat safety standards, worker illness, injury, and death, and labor productivity in the U.S. We will use state-of-the-art statistical approaches, comprehensive national-scale databases, robust legal surveillance methods, and robust quasi-experimental designs to support inferences. Results will provide critical insights to inform the design and creation of a national heat safety standard for American workers.

II. INNOVATION.

To our knowledge, this will be the largest and most comprehensive study of workplace heat related injuries, illnesses and deaths, and safety protections ever to be conducted. This project innovates in several important ways. First, we will innovate over previously conducted studies of occupational heat illness, injury, and death by using state-of-the-art statistical methods to **quantify the total burden of heat-illness, -injury, and -death**. Unlike previous studies on workplace heat-related illness, injury, and death that relied solely on heat-specific codes, our approach will use advanced statistical methods to account for the fact that heat-related incidents may be classified under other causes, such as cardiovascular or respiratory conditions, rather than being explicitly coded as heat-related. This innovation will improve estimates of the total burden of workplace heat injury, illness, and death across the U.S. Second, this will be the first study, ever, to create a **comprehensive, national, longitudinal database** with detailed information about the presence and requirements of state-level workplace heat regulations. The database that we create will be used to develop and write a policy brief on the topic of heat safety regulations across the U.S. **We will make the database publicly available for all researchers to use.** Third, this will be the most comprehensive investigation of the impact of any heat safety standards, and the **impact of different requirements** of heat safety regulations in the U.S., and the first, to our knowledge, to make **comparisons across states**. We will use strong and robust quasi-experimental design to conduct this assessment, taking into account staggered enactment dates and differences in requirements. Fourth, to our knowledge, this will be the first study of its kind to identify safe thresholds temperatures for workers, across geography and industry. This information is critical for **informing the temperature thresholds (or triggers)** used to indicate when heat safety regulations should be implemented. This investigation will also inform if regulations and standards can be made to be standardized across geography and industry, or if they should be created to be specific to location and work situation. Finally, this will be the first ever study to quantify the **labor productivity implications** of workplace heat safety regulations. We will use a quasi-experimental design and granular industry, county, and business-firm specific per capita payroll data to quantify labor productivity. *This first-of-its-kind project will provide critical and robust empirical evidence needed to inform worker health and safety protections.*

III. APPROACH

A. Overview. In this robust, national level study, we will improve understanding of the total burden that heat illness, injury, and death represents to American workers and elucidate the implications of workplace heat safety standards for health, safety, and business productivity. We will use comprehensive, federally maintained databases and state-of-the-art methodological approaches to accomplish the study aims (**Table 1**). In Aim 1, we link rich micro-data from the BLS with county-level daily meteorological data and use a time series design with distributed lag nonlinear (DLNM) functions to estimate excess workplace injuries, illnesses, and deaths attributable to heat in each county and industry across the U.S. (Aim 1A). We will then use flexible DLNM functions to identify industry and county specific safe ambient temperature and heat index thresholds (Aim 1B). Next, we will use robust legal surveillance methods to develop a longitudinal database with detailed information on state-level workplace heat safety standards: industries/workers covered, requirements, and timing of enactment. We will link this rich, longitudinal policy database with year, county and industry specific estimates of heat-related outcomes (derived both from Aim 1, and from heat-specific codes in the BLS data). Using these data, we will conduct a quasi-experimental staggered difference-in-difference (DiD) study of impacts of heat safety regulations on workplace injuries, illnesses, and deaths from heat (**Aim 2**). We will then link the policy, meteorological and per capita payroll data and use a difference-in-difference-in-difference (DiDiD) design to calculate labor productivity implications of heat safety standards across the U.S. (**Aim 3**).

Table 1. Overview of study aims, approach, and outcomes.			
Aims	**Data sources**	**Study design and analysis**	**Output**
Aim 1A: Estimate total burden of heat	**BLS SOII and CFOI micro-data linked with meteorological data**	**Time series with distributed lag nonlinear model functions for temperature/humidity**	**Excess injuries, illnesses, deaths from heat in American workers**
Aim 1B: Identify geography and industry specific safe temperature thresholds			**County, state and industry-specific safe temperature/heat index thresholds**
Aim 2: Quantify health impacts of state-level heat standards	**Legal surveillance data linked with heat-related outcome estimates**	**Quasi-experimental staggered difference-in-difference (DiD)**	**Impacts of workplace heat safety standards on heat-related outcomes in workers**
Aim 3: Quantify of heat standards on labor productivity	**Heat shock/anomaly estimates and legal surveillance data linked with per capita payroll data from the US Census Bureau**	**Quasi-experimental difference-in-difference-in-difference (DiDiD)**	**Impacts of workplace heat safety standards on labor productivity**

Abbreviation: BLS: Bureau of Labor Statistics; SOII: Survey of Occupational Injury and Illness, CFOI: Census of Fatal Occupational Injuries

Aim 1A. Estimate the total injury, illness, and mortality burden that workplace heat exposures represent, for each county and state across the U.S.

B. Rationale. To date, most research on associations of occupational heat-injuries and illnesses has relied on heat-specific diagnostic or cause of injury codes.[14,47] However, it is well known that heat-related injuries, illnesses, and deaths are often diagnosed and coded as other conditions, such as cardiovascular, respiratory exacerbations, among others.[12,39,48] As a result, current work-related heat injuries, illnesses, and deaths counts are likely under-counted,[47,49] thus masking the true burden that heat represents to workers. Improving understanding of the burden that heat represents to workers, as well as geographic and industry variability in this burden, is critical, as this information illustrates the extent to which environmental heat exposure is a health hazard. *We will use daily meteorological data linked with daily counts of occupational injury, illness, and death and a well-accepted two-stage time series analysis approach*[21,50,51] *to derive estimates of the total burden of heat related injuries, illnesses, or deaths attributable to heat – across each county and industry.*

C. Time period: The study time period will be years 2003 to 2022. These years were selected to capture years before and after the enactment of California's occupational heat safety standard (year 2005); this is the first state to enact a workplace heat safety standard.[15,18] This is relevant for the analyses that we will conduct in Aim 2. In addition, year 2003 was selected as a starting year because prior to this year, the BLS applied Standard Industrial Classification Industry Group codes to classify industries, rather than the North American Industrial Classification System (NAICS) system, which it uses today. Also, the twenty-year time period provides the opportunity to assess long-term trends and capture variability in climate patterns, regulatory changes, and socioeconomic conditions that influence heat exposure and related health outcomes.

D. DATA

Di. Bureau of Labor Statistics data on occupational injury, illness, and deaths. We will use restricted microdata from the Survey of Occupational Injuries and Illnesses (SOII) and the Census of Fata Occupational Injuries (CFOI).[52,53] We have received approval from the BLS to use these data (see attached approval letter). We will conduct analyses using the BLS's virtual data enclave. Access to these data requires special sworn status. The PI of this study already has special sworn status and is thus well positioned to conduct the work.

Dii. Survey of occupational injuries and illnesses (years 2003-2022): The SOII[52] provides estimates of nonfatal workplace injuries and illnesses in the U.S. Every January of each calendar year, the BLS uses a two-stage sampling process to sample employer respondents. First, units are sampled with consideration of industry, ownership, and firm size. Second, cases are sampled from firms according to take days away from work or work restrictions. The resulting survey data provide detailed information on the frequency, type, and severity of workplace injuries and illnesses across all types of employment setting in the U.S. Nonfatal outcomes are defined as those that result in loss of consciousness, days away from work, restricted work activity, job transfer, or medical treatment beyond first aid. Injuries are defined as cuts, fractures, sprains, amputations, etc. Illnesses are defined as abnormal acute or chronic conditions or disorders caused by work related factors. *Using these data, we will calculate daily counts of injuries/illnesses and numbers of days away from work, stratified by industry, occupation, nature of injury/illness/death, city/state, sex, and age.*

Diii. Census of fatal occupational injuries (years 2003-2022). The CFOI includes data on workers across all industries and occupations, including employees, self-employed individuals, and military personnel in the U.S. The CFOI reports worker demographics (age, gender, race), injury details (nature of the injury, body part affected), incident specifics (location, time, and day of the fatality), and contextual factors (industry, occupation, and circumstances leading to the incident). *For this study, we will use daily counts of fatal occupational injuries, stratified by industry, nature of injury/illness/death, county/state, sex, and age.*

Div. Industry codes. We will classify industries according to NAICS aggregated group codes. Prior work has found that the following three sectors have the highest rates of heat related deaths: Agriculture, Forestry, Fishing, Hunting (NAICS code 11); Construction (NAICS code 23); Administrative and Support and Waste Management and Remediation Services (NAICS code 56).[14] In initial analyses, we will consider associations with all industry codes because of potential mis- and under-reporting of heat related outcomes in other industries. NAICS is revised on a five-year cycle to reflect economic changes; thus, there were changes made in 2007, 2012, 2017 and 2022. We will harmonize the data using Concordance, from the US Census Bureau.[54]

Dv. Codes to identify disease and injury specific outcomes. We will estimate associations with all causes of injury, illness, and death. This is because heat-related outcomes are often misclassified (and not always coded as heat-related).[9] In addition, we will identify cardiovascular, respiratory, heat exposure, kidney-, injury, and headache-related outcomes using the Occupational Injury and Illness Classification System (OIICS) codes that are used in the SOII and CFOI data (**Table 2**). These specific outcomes were selected based on a priori evidence that heat may associated with these conditions (**Figure 1**).[35,37,40,8,10–12,41,42,55] OIICS was developed by the BLS and provides detailed classifications for injury and illness events based on nature of injury/illness, body part, source, and event/exposure. OIICs has undergone multiple revisions. To ensure consistency across study years, we will develop a crosswalk, to allow mapping of codes from earlier OICCS versions (v1.0 and v2.0) with corresponding codes in the later version (v2.01).

Table 2. Key outcomes and Occupational Injury and Illness Classification System codes that we will use to ascertain heat related cases.

Outcome	OIICS v2.01 codes
Traumatic injuries and disorders	10XXXX
Heat Exposure	172XXX
Circulatory (cardiovascular)	23XXXX, 515XXX, 516XXX
Respiratory system	24XXXX, 5168XX
Kidney related outcomes	517XXX,262XXX
Headache, migraine	5141XX, 2232XX

Dvi. Meteorological data. We will use validated, high spatial resolution (800 m) gridded meteorological data for the conterminous U.S., produced by the PRISM Climate group at Oregon State University,[75] to assign county level temperature, humidity, and precipitation variables. PRISM data are the official spatial meteorological data set used by the U.S. Department of Agriculture. In analyses, mean daily temperature will serve as the primary exposure variable. In addition, to maintain consistency with some state and federal policies on heat, we will derive a measure of the average daily heat index. The heat index is a metric that combines temperature and humidity and is developed to represent human thermal comfort.[56] We will calculate the heat index using the weathermetrics package in R, which relies on the formula published by the National Weather Service.[56]

Dvii. Spatial resolution of analyses. It is well accepted that associations between high ambient temperature and mortality or morbidity outcomes vary geographically.[57–59] For instance, past research has shown that populations living in areas closer to the equator are better able to survive high temperature exposures, compared to populations living further from the equator.[58] The reasons for this phenomenon are unclear, but probably include better adaptive capacity in areas that have been hotter, historically. For these reasons, in this two stage-analysis, we will first conduct county-level analyses to allow temperature-outcome associations to vary geographically. We will use the resulting estimates to derive county-specific estimates of excess numbers of injuries, illnesses, and deaths resulting from heat. We will then aggregate the county level estimates to the state level. We will report county and state level estimates in publications.

E. Stratification of analyses by sociodemographics, industry, and geography. Because associations between temperature and adverse events may vary according to industry and worker sociodemographics,[47,60] we will stratify Aim 1 analyses by industry and worker demographics, including age (e.g., < 50 vs 50+), sex, and race/ethnicity. In addition, we will stratify results by county and state, and by severity of injury/illness (definitions for injury severity are described in section F). Reasons for individual variation in heat vulnerability may include differences in underlying biology – allowing one's body to better respond to hot temperatures, or may be explained by structural factors that enhance or reduce vulnerability (e.g., racialized deprivation resulting in less access to cooling opportunities, outside of work).[60–64]

F. Time series design to estimate county-specific associations. In the first stage of this two-stage analysis, we will use a time series design to estimate county- industry-specific associations (double stratifying by county and industry).[20,23,26,65] We will assume a *Poisson* or *Quasi-Poisson* distribution, depending upon whether we identify evidence of overdispersion.[66]

The *dependent variable* will be daily counts of deaths, injuries or illnesses (all-cause or cause-specific, **Table 2**), stratified by industry, county, and nature of the injury/illness/death. We will also run models stratified by **severity of the illness/injury** (for non-fatal outcomes). Severity will be defined using the BLS's definitions, based on whether the injury resulted in days away from work (most severe), job transfer or restriction (moderately severe), or were able to continue working in their same position following treatment (most mild).[52]

The *independent variable* will be daily average county-level mean daily temperature or heat index. We will implement distributed lag nonlinear models (DLNM) [27,67,68] which allow simultaneous estimation of non-linear exposure-response associations and the non-linear effects across lags (lag-response associations). To adjust for potential harvesting (the phenomenon where extreme temperatures lead to the premature death/injury of vulnerable individuals who were already close to death/injury),[69] we will specify a maximum lag of 10 days, which is consistent with previous analyses of heat-mortality associations.[50] *Our group has extensive experience applying these methods in a variety of settings and contexts.*[20–22,22,23,25,70,71]

G. Weighting to account for survey sampling. In analyses that use SOII data, we will apply BLS supplied sampling weights to ensure estimates are representative of the American workforce.[52] These weights account for the complex sampling design and non-responses in the SOII, and allow generalization to the national level. The CFOI data do not require weighting, because they include all known fatal work-related injuries**.**

H. Confounders. We will control for seasonality and long-term time trends using a natural cubic B-spline with eight degrees of freedom per year, as well as other time-varying covariates, such as precipitation. The full confounder set will be identified by developing directed acyclic graphs,[72] informed by a review of the peer-review literature. As we have done previously, we will also control for day-of-the-week using indicator terms.[20,22,71] Because it might be on the causal pathway between temperature and the outcomes, we will not adjust for air pollutants, such as ozone; doing so could obscure the total effect of temperature on the outcome.[73]

I. Meta-analysis to derive state and national pooled estimates of association. At the second stage, we will pool county-level estimates of association using meta-analytic methods. To reduce the number of parameters to be pooled, we will create a cumulative estimate of the risk over the lag period. We will then use multivariable meta-regression models to pool county-specific cumulative risk estimates to derive state and national estimates.[21,68] The meta-regression models will include indicators for county, allowing county-specific exposure- and lag-response relationships. We will quantify and test residual heterogeneity by the multivariate extension of the Cochran Q test and I^2 statistic.

J. Best linear unbiased predictor of mortality, injury or illness for each county. We will use the fitted multivariable meta-regression models to derive the best linear unbiased prediction of the overall cumulative exposure-response associations in each county. [21,68] This approach allows areas with small counts of injury, illness, or mortality, which would otherwise have imprecise estimates, to borrow information from larger populations that share similar characteristics. Thus, the best linear unbiased predictors represent a trade-off between county-specific associations, derived from the first stage of the analysis, and the pooled estimates.

K. County-specific optimal temperature and heat index. For each county, we will use the county-specific best linear unbiased predictor to identify the temperature or heat index (humidity and temperature combined) value[51] at which risk of mortality, or injury/illness, was minimal.[21,68] We will discuss and use this further in Aim **1B**, described below.

L. Calculating excess workplace injuries, illnesses, and deaths from heat. We will calculate the total and proportion of deaths, in each county of every year of the study, associated with hot daily temperatures or heat index by calculating the proportion of work-related injury, illness, and death that occurred on non-optimal temperature/heat index days. We will calculate empirical Confidence Intervals (CIs) using Monte Carlo simulations, assuming a multivariate normal distribution of the best linear unbiased predictions of the reduced coefficients. [21,68]

Aim 1B. Identify optimal maximum upper thresholds for implementing state level heat safety regulations to protect worker health.

M. Rationale. Some requirements for state-level heat safety standards are enforceable only once temperatures reach a certain threshold or 'trigger' value. These thresholds vary across states (**Figure 2**), and there remains knowledge gaps about whether these thresholds are sufficient to prevent heat-related injury, illness, or death. Further, it remains unclear if the thresholds should vary according to region, industry, or person. Empirical research is needed to inform the trigger temperatures that are used to indicate the need to follow certain requirement protocols.

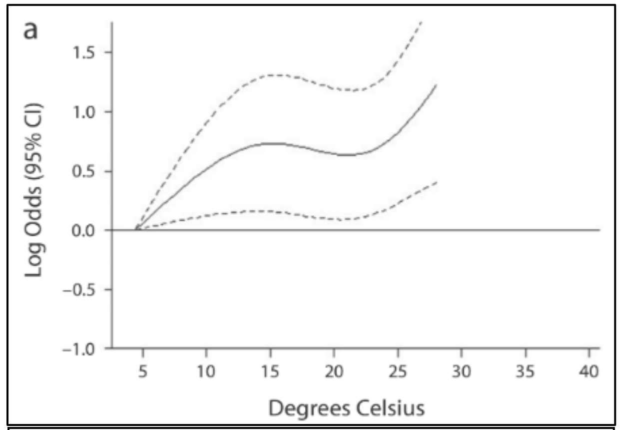

Figure 3. This plot shows that the log odds of infant death increased incrementally with high temperatures, and particularly after a threshold value of 23.9° C.

N. Approach. As described in **section K,** we will use county-specific best linear unbiased predictors to identify the temperature[51] at which risk of mortality, or injury/illness, was minimal.[21,68] In addition to calculating this for each county, we will calculate the optimal temperature for the cross-classification of a county and industry. We will identify this as the ideal threshold temperature, after which rates of heat-related outcomes increase.

O. Presentation of results. We will report results in tables and figures. In addition, we will create maps that demonstrate the geographic variability in rates of heat-related outcomes, as well as in the optimal temperature thresholds.

P. Preliminary data. In previous work, we have applied similar methods to identify threshold temperatures at which mortality responses begin to increase. We have also used these methods to estimate associations between temperatures and mortality outcomes. For example, in a study of associations between temperature and infant mortality in Philadelphia, PA, we identified a threshold of 23.9°C as the relevant value after which higher odds of death increased (**Figure 3**).[22] In another study, we demonstrated that the relationship between ambient temperature and mortality, and that relevant upper temperature thresholds, vary across places (**Figure 4**).[21]

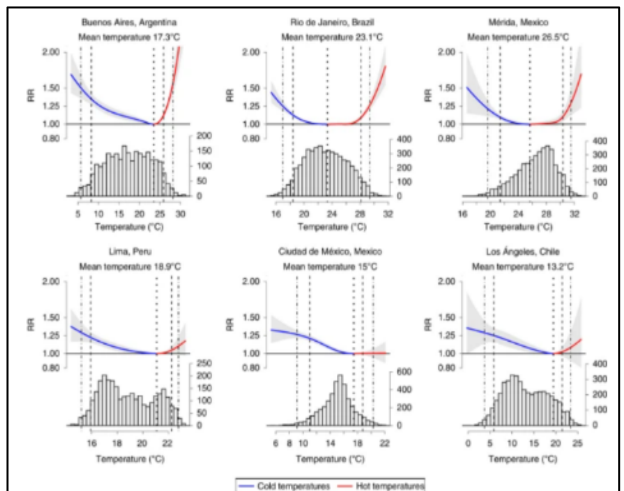

Figure 4. Associations between daily temperature and relative rates of mortality in select Latin American cities. The figure demonstrates that there are different 'optimal' temperatures (indicated by the dashed lines) depending on the location.

Q. Sensitivity analyses. We will conduct a variety of sensitivity analyses, to test the robustness of our results to different modeling decisions, such as covariates that are included in the models, or ways that the variables are parameterized. For example, in **Aim 1A** analyses, we will explore a variety of methods for parameterizing the lag structure and temperature metrics—polynomial, linear, spline—with different degrees of freedom and, in the case of the splines, different knot locations. We will choose the optimal parameterization by examining model fit statistics, such as qAIC or AIC statistic, while also considering etiologically appropriate categories We will report results from the sensitivity analyses along with our main analysis results.

R. Power calculation Assuming a baseline rate of occupational injuries and illnesses that ranges from 3 to 6 per 100 workers (consistent with rates that we see in select states, **Table 3**) and a probability of heat exposure of 45% (consistent with findings from prior U.S. analyses)[74] we will have more than 90% power to detect an effect size

of 5% or greater. If the probability of heat exposure is 10% (a conservatively low estimate), we will have more than 80% power to detect an effect of 5% when the baseline rate is 5 or greater.

Table 3. State level rates of injury and illness, total recordable cases per 100 workers, year 2019. Source: BLS SOII data			
Industry	**CA**	**WA**	**OR**
Agriculture, forestry, fishing, hunting	**6.0**	**7.8**	**5.3**
Construction	**3.7**	**5.7**	**4.4**
Manufacturing	**3.0**	**4.6**	**4.4**

Aim 2. Quantify associations of workplace heat safety standards (presence and level of requirements) with work-related heat injuries, illnesses, and deaths.

S. Rationale. In the absence of a federal standard, California, Oregon, Washington, Minnesota, Colorado have enacted their own standards. The state-specific standards vary in terms of requirements, workers covered, and dates of enactment (ranging from 2005 in California to 2022 in Colorado). Little is known about the effectiveness of these standards. Such information is critical for informing the creation of a federal standard, or for informing the creation or modification of state-specific standards with respect to requirements. We will fill these gaps by leveraging between-state heterogeneity in presence/absence, enactment timing and requirements of heat-safety standards to conduct the first-every multi-state, quasi-experimental study of associations of these standards with heat associated adverse outcomes in workers.

T. Overview. Because it is not possible to conduct a randomized control trial to estimate the effect of state-level heat safety policies on rates of injury, illness and death in workers, we will estimate effects using a quasi-experimental difference-in-difference (DiD) design.[75,76] Under this framework, we will compare before vs. after enactment changes in rates of occupational heat-injury, illness, and death in states that became “treated” (i.e., adopted heat safety policies) with changes in rates in untreated comparison states (i.e., states that did not adopt a policy). To strengthen causal inferences, and to account for the fact that only a small number of U.S. states enacted heat safety policies, we will estimate associations using a synthetic DiD approach.[75] *Results from this analysis will provide strong empirical evidence about the impacts of state-level heat safety policies on adverse heat outcomes in workers.*

U. Setting and time-period. The following states enacted heat safety policies at staggered time points between years 2005 and 2022: California, Colorado, Minnesota, Oregon, and Washington. We will leverage heterogeneity in the timing of and geography of enactment of the heat safety standards to conduct this quasi-experimental study. A few states (e.g., Oregon and Washington) first enacted emergency standards before creating permanent standards. We will include the emergency standard enactment, as well as the permanent standard enactment, thus providing additional years’ of treatment exposure in these states. At the time of writing this proposal, BLS micro-data are only available through year 2022. This means that the state of CO, which enacted their policy in 2022,[77] will not be included as a treated state in Aim 2 analyses. However, if additional BLS data are available by the time of conducting this analysis, we will expand the study period and include CO.

V. Legal surveillance to develop a longitudinal database on state workplace heat policies. To date, there is no comprehensive national database with details on the scope and requirements of workplace heat safety regulations in states across the U.S., the timing of their enactment, or changes over time. While high-level information on these state level standards has been summarized (**Figure 2**), a detailed and comprehensive assessment, which captures exemptions, shifts from emergency to permanent standards, and changes in requirements over time, is needed to conduct a robust and comprehensive analysis. *Here, we will employ rigorous, longitudinal policy surveillance and legal mapping approaches to develop a comprehensive database of workplace heat safety regulations and protections across the U.S.*[19,78] Not only will the database describe dates of enactment of emergency and permanent standards across the U.S., but it will also compare the level of comprehensiveness of the standard to OSHA’s proposed federal standard. To create the database, we will develop and use standardized coding protocols for consistent, comparable and reproducible analyses. The resulting rich, longitudinal database will be used to conduct the analyses. It will also be published as publicly available in Law Atlas (http://www.lawatlas.org), maintained by the Center for Public Health Law research at Temple University’s Beasley School of Law.[79] The publicly available data set will represent a valuable new tool for research and analysis. In addition, we will publish a policy brief describing the longitudinal database on workplace heat policies. The Center for Public Health Law Research is a leader in these approaches and methods. The group hosts workshops on these methods, maintains an open-source website with longitudinal policy data, and has published extensively on policies and on legal surveillance methods.[78,79]

W. The synthetic DiD design. The synthetic DiD approach is a recent innovation in quasi-experimental design methods.[75] It attractive for our context for several reasons. First, it accommodates the fairly small numbers of treated groups (N=4 for this analysis). Second, it relaxes the parallel trends assumption by reweighting control states and matching them to treated states based on pre-enactment outcome trends. Third, it controls for pre-enactment differences comparing treated and untreated states through these optimized weights. Finally, the synthetic DiD method accounts for staggered timing of policy enactment by allowing for estimation of distinct treatment effects for each enactment period, and then computing a final effect estimate as a weighted average of the period-specific estimates.

X.Analysis. We will conduct analyses using the sdid command in Stata.[80] We will run industry- or industry-group-stratified analyses, restricted to the industries to which a state's policy applied (e.g., agricultural workers). For each industry (or industry group), we will construct a panel data set in which each row will contain counts and rates of heat-related illness, injury, or death stratified by state, worker sex, and age category. Treated states will be defined as those that enacted heat safety policies during the study period. Synthetic control groups will be constructed from states that never enacted a policy, using unit weights to ensure that the pre-treatment trends in the treated states are closely matched by a weighted combination of control states. Because of the staggered timing of policy enactment, the synthetic control groups will be constructed for each treated state from those states that have not yet enacted a policy at the time of treatment. Additionally, time weights will be created to best align the pre- and post-treatment periods between treated and control states, improving the validity of the comparison across time.

We will estimate the average treatment effect using two-way fixed effects ordinary least squares regression models. The <u>dependent variable</u> will be defined as the natural logarithm of year-, state-, and industry- (or industry-group)-stratified rates of occupational heat injuries, illnesses, or deaths (counts of the heat-related outcome divided by the numbers of people employed in the industry of interest). We will also calculate sex- and age- or race/ethnicity stratified rates. The primary <u>independent variable</u> will be an indicator term representing if the state was subject to enactment of a workplace heat safety standard during that year. Models will include fixed terms for both state and year. These fixed effects control for time-invariant differences across states and for common shocks that affect all states over time. We will use multiplier bootstrap methods to calculate robust standard errors and corresponding 95% confidence intervals.[81] To evaluate lag and lead effects of policy enactment, we will rerun analyses, including lag (and lead) effects of the policy enactment, allowing us to capturing any delayed or anticipatory impacts of the policies.

After conducting the initial analyses to estimate associations between the presence of any state-level workplace heat safety regulation and heat-related outcomes, we will repeat the analyses, accounting for variation in the comprehensiveness of state-level policies, considering impacts of requirements such as acclimatization programs, rest breaks, provision of water, and training requirements. We will include these covariates as interaction terms with the treatment indicators to estimate heterogeneity of associations according to the level of comprehensiveness and specific requirements.

Y. Sensitivity analyses. We will implement a number of sensitivity analyses to test the robustness of our results. These are outlined **in Table 4**.

Table 4. Sensitivity analyses.

Issue	Solution
Validation of control groups	We will rerun analyses using a traditional difference-in-difference analysis and using negative controls, defined as industry groups unaffected by the policy but exposed to similar state level factors (e.g. construction workers, if the heat safety standard only applies to agricultural workers). We will additionally adjust for time varying covariates such as temperature and precipitation.
Study design inappropriate, biased estimator, pre-treatment fit is not feasible	Employ an instrumental variable specification,[82] the augmented synthetic control[83] method or the group time estimator approach as proposed by Callaway and

	Sant'Anna.[84] We will also rerun analyses using the synthetic control method.[83,85]
Cities in comparison (untreated) states have implemented local standards (like Dallas and Houston, TX)**[26]**	We will repeat analyses (including construction of synthetic controls), removing states with these cities from analyses.

Z. Preliminary data. Our group conducted a quasi-experimental study and quantified associations of a rest break ordinance, implemented for construction workers in Dallas, Texas in 2016, with workplace injuries and illnesses. We compared before vs. after rates in among construction workers in Dallas County to before vs. after rates among construction workers in Tarrant County.[26] Results from this analysis showed little change in rates of injury/illness among Dallas construction workers, before vs. after the enactment of the rest break mandate (**Figure 5**). These results suggest that a ten-minute rest break for every four hours worked is insufficient for preventing illnesses and injuries.

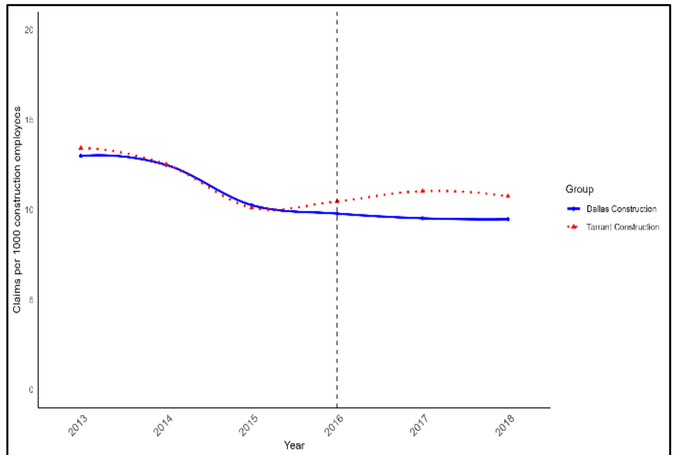

Figure 5. After the enactment of a rest break mandate in 2016 for Dallas, TX construction workers, rates of workers' compensation claims in Dallas, TX, were only modestly – after vs. before the mandate, even when compared to after vs. before differences in Tarrant County, TX, where there was never a mandate.

We have also conducted several prior analyses using DiD and quasi-experimental methods, including models for staggered policy adoption and the synthetic DiD method, to estimate the effects of policies on population health.[76,86–89]

AA. Statistical power. To calculate statistical power, we conducted a series of simulations using a DiD design with staggered policy enactment. We simulated the rates of heat-related illness, injury, and death across four treated states and 10 control states, for years 2003 to 2022. We explored power across a range of expected treatment effects (10%, 20%, and 30% reductions in the outcome rate) and baseline outcome rates (5, 10, and 15 adverse heat events per 100 workers per state per year). If we assume a baseline rate of 5 per 100 workers we will have nearly 80% power to detect a 20% reduction in the outcome rate. We will have approximately 90% power to detect 20% reduction in the rate assuming a baseline rate was 10 per 100 workers. Power reached nearly 100% for a 30% reduction in outcomes and a baseline rate of 15 injuries/illnesses/deaths per 100 workers.

Aim 3. Elucidate impacts of workplace heat safety regulations on labor productivity.

BB. Rationale. Some stakeholders have expressed concern about the financial and operational implications of workplace heat safety rules, arguing that compliance with the rule's requirements (e.g., provision of shade, breaks, adjusted work schedules) will be costly—particularly for businesses and industries, like agriculture and constructure, which are already working at narrow profit margins.[46,4] Yet, empirical research has shown that better well-being among workers is associated with improved productivity,[90] that environmental regulations are associated with reduced costs and improved financial performance,[91] and that organizational investments in worker safety are associated with financial gains.[92] Indeed, workplace accidents may lead to interrupted or reduced quality of production, high costs for society (e.g., healthcare costs), and cause workers or the public to question the safety of the organization, thus threating its long-term survival.[93] Yet, no studies, to our knowledge, have investigated the labor productivity impacts of workplace standards that are heat-specific. This is an important gap to fill, to inform the enactment of workplace heat safety standards. *Here, we will fill this gap by conducting a national scale quasi-experimental study of associations between state-level workplace heat safety policies and per capita payroll data, which we will use to measure labor productivity.*

CC. Overview. Previous work has shown heat shocks (acute periods of extreme hot temperatures) are associated with reduced labor activity.[74] For example, Park et al. found that, across the U.S., in years with ten additional days that were extremely hot (defined as 90 degrees or hotter), there was 0.26% reduction in per capita payroll, suggesting that heat shocks are associated with reduced labor productivity.[74]

Here, we will test the hypothesis that enactment of workplace heat safety standards attenuates the negative labor productivity impacts of heat-shocks.[58] To do so, we will first estimate associations between heat shocks or heat anomalies with business- and county-stratified per capita payroll data. We will then estimate the extent to which presence of a heat safety standards within a state/county modifies these associations.

DD. Study area and time period. The time-period for the study will be 2003 to 2024. Treated states will be defined as California, Colorado, Minnesota, and Oregon, Washington, selected to capture the periods before enactment of the first heat safety standard (in California, 2005) and after the enactment of the last heat safety standard, to date (Colorado, 2022).

EE. Per capita payroll data to estimate labor productivity. We will use the U.S. Census Bureau's annual County Business Patterns (CBP) data to estimate per capita payroll, stratified by business firm, industry and county.[94] The CBP data contain information on annual payroll at the zip code, county, and state levels, broken down by industry and establishment size. Per capita payroll will be calculated by dividing the total payroll in each county by annual county-level population data obtained from the U.S. Census Bureau. As in previous studies, we use per capita payroll as a measure of labor productivity. This approach assumes that increases in payroll per person reflect increases in the value of the workers' output (marginal labor productivity), without being influenced by other factors such as business expenditures or operational costs. By focusing on payroll, we capture the compensation workers receive, which can serve as a proxy for the value they are generating in the production process.[74]

FF. Anomalously hot temperatures and heat shocks. Here, we use the term temperature anomaly to refer to deviations of the county and year specific temperatures from typical normal temperature, based on long-term averages, for that county. We refer to heat shocks as acute periods of extreme temperature, defined using thresholds that are selected *a priori*. The use of these shock and anomaly variables offers several advantages. These include that they indicate area-specific deviations from expected conditions, making them interpretable. Also, because these variables are uncorrelated with historical meteorological conditions, shocks and anomalies can be treated as randomized exposures.[95,96] Finally, a population's ability to be unaffected by these anomalies or shocks may be an important indicator of adaptive capacity; in the proposed analyses, we are testing the hypothesis that heat safety standards improve adaptive capacity in the workplace.

Calculation of variables. We will calculate the temperature anomaly and heat shock variables, for each county and year, using Oregon State University's PRISM estimates of daily temperatures, as well as measures of derived heat index.[97] Detailed descriptions of the derivation of these variables is given in **Table 5.** We will use PRISM's long-term average normal dataset to derive the measure of deviations from long-term averages. The normal dataset describes monthly and annual conditions over the past 30 years (years 1991 to 2020). The data set is extensively peer reviewed and validated.[98,99]

Table 5. Heat shocks or temperature anomaly variable definitions and derivation.

Metric	Calculation	Example Calculation (Philadelphia County, 2010)
Anomaly: Deviations from 30-year summer/winter average temperature	Subtract the season-specific average daily temperature for each year from the season-specific 30-year average (1991-2020).	If the 2010 summer average was 85°F and the long-term average was 78°F: 85 - 78 = 7.
Heat shock: Counts of days in a year that exceeded critical temperature thresholds	Count the number of days each year where temperatures exceed a defined threshold (e.g., 80°F, 90°F) or percentile-specific values. Includes cold temperatures as covariates.	If 10 days in 2010 exceeded 80°F, the value for that year = 10.
Heat shock: Days across temperature distribution categories	Categorize daily temperatures into ranges (e.g., -5 to 0°F, 0 to 5°F) or percentiles of the temperature distribution. Count the days in each category.	If there were 2 days at -5 to 0°F and 3 days at 1 to 5°F, those categories are coded as 2 and 3, respectively.

Figure 6 presents counts of days within each year between 2010 and 2020 that exceeded 90 degrees F in Philadelphia, PA. These would be defined as 'heat shocks,' using a threshold temperature of 90 degrees F. From the figure, we see that there were particularly high numbers of heat shock days in years 2010, 2016 and 2018. Based on this, we hypothesize that labor productivity would be lower in years 2010, 2016, and 2018 –

would be lower, relative to other years. The figure also demonstrates that counts of days within a year when temperatures were extremely high vary from year to year.

GG. Design. We will employ a quasi-experimental DiDiD design with staggered treatment adoption,[100] leveraging temporal and geographical variation in enactment of heat safety standards, as well as random heat shock/temperature anomalies, over the study period. We will account for staggered timing of policy enactment, which varies across states by using a time-varying treatment indicator that captures the year that each county was 'treated' with an enacted heat standard. This will allow us to estimate the impact of the heat safety standards while accounting for differences in adoption timing across regions. Any county*industry*business firm category that was subject to an enacted heat safety policy will be defined as treated. To achieve exchangeability between the treated and non-treated groups, we will use propensity score matching, with propensity scores developed using covariates such as long term meteorological conditions, sociodemographic compositional characteristics, and proportion of the area residents employed in high heat exposure industries.[101]

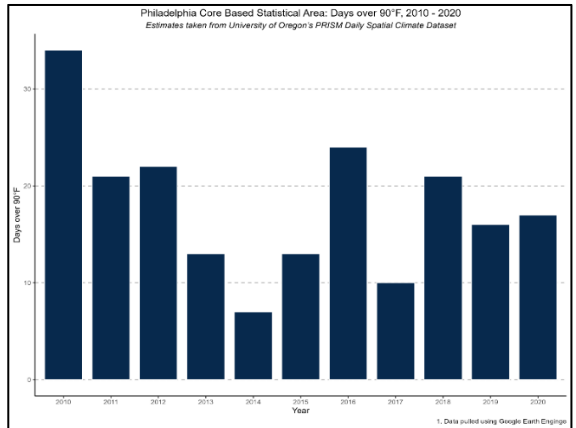

Figure 6. Counts of days within each year, spanning the period between 2010 and 2010, that minimum daily temperatures exceeded 90 degrees F.

HH. Analysis. We will develop ordinary least square regression models. The key dependent variable will be defined as county, year, industry, and firm size stratified per capita payroll. The primary independent variables will be year- and county-specific temperature anomaly or heat shock variables (**Table 5**), an indicator term representing whether the county adopted a workplace heat safety standard for the relevant industry and firm size, and a time-varying indicator term representing if the observation is before or after the standard was enacted. The treatment effect will be identified by comparing changes in heat shock/temperature anomaly and per capita payroll associations, before and after the policy enactment in treated counties to changes in counties that did not yet adopt the standard. We will include interaction terms between the temperature shock/anomaly variables, the variables representing if this was a pre- or post-implementation period, and whether the county was treated with a heat safety standard. We will adjust the models for time varying covariates that might confound associations, such as measures of extreme precipitation within a year, or cold shocks. We will also implement an event study approach, allowing for the estimation of dynamic treatment effects at various time points before and after the policy enactment. This will help capture potential anticipatory (i.e., effects that occur before the policy is fully implemented) and delayed effects (i.e., lagged responses to the policy).

II. Sensitivity analyses. To test the robustness of our findings, we will rerun analyses using different definitions for anomalously hot temperatures and heat shocks (e.g., adjusting the threshold used to define extreme temperature days). We will rerun analyses with adjustment for additional covariates.

JJ. Preliminary data. In previous work, we have found that anomalously warm temperatures have implications for social dynamics. Specifically, in previous work, we found that anomalously warm daily temperatures were associated with higher rates of violent crime in Philadelphia, PA (**Figure 7**).[23]

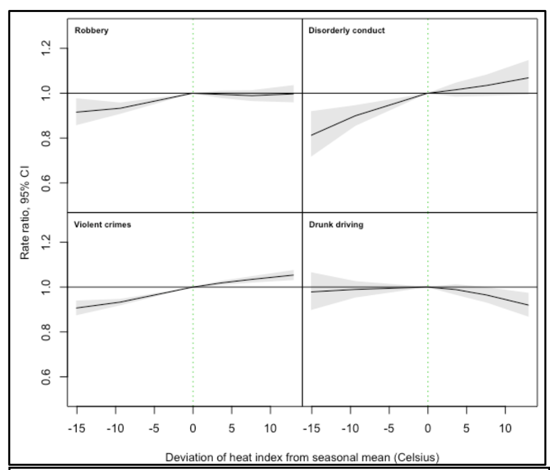

Figure 7. In this figure, we see that as mean daily heat index values deviate more substantially from the seasonal average temperatures, rates of violent crime and disorderly conduct increase.

KK. Anticipated results, potential pitfalls and alternative approaches. In this nationally representative study, we will fill critical gaps in knowledge about relationships between heat, heat policies, worker safety, and labor productivity. Specifically, through this work, we will: *(1) improve understanding of the total burden that heat represents to the American workforce, (2) identify geography and industry specific safe maximum* *temperature thresholds for workers, (3) elucidate impacts of heat safety policies on rates of injury, illness, and death attributable to heat among workers, and (4) quantify the impacts of heat safety policies and standards on labor productivity*. This work has the tremendous potential to have important impacts with respect to workplace safety and health. These questions are particularly relevant and timely as we face globally rising temperatures.[28]

We acknowledge several potential concerns and propose a series of approaches for addressing these. The SOII is the only database that provides national estimates of work-related injury or illness in the U.S. Nevertheless, a criticism of the database is that injuries or illnesses may be under-reported. This concern has been raised as a concern in previous publications[102–106] and it is thought to be most relevant for workers in the agriculture industry.[53] In particular, within the context of the current research question, a major concern may be that the SOII does not include out-of-scope workers, such as those who are employed in public sector jobs, those who are self-employed, and those who work on small farms. To account for potential under-reporting, we will apply a correction factor based on findings from previous studies that have quantified the extent of underreporting for different types of industries.[53] By adjusting the injury rates upward, we can better capture the full scope of heat-related injuries that occur but may not be officially recorded. Another obstacle may be small numbers of deaths, or injuries and illnesses. This may be a particular concern–for cause specific outcomes, or when exploring whether associations vary according to worker demographics. To address this issue, we will collapse categories, using informed decisions when we do so. For example, we may combine counties when they are geographically close to one another. The quasi-experimental DiD design that we will implement in aims 2 and 3 is inherently ecologic. While in some contexts this is a concern, here, the ecologic design is appropriate because it avoids the "aggregation fallacy" or the incorrect assumption that individual-level observations provide meaningful inferences about population-level interventions.[107] Another concern related to Aims 2 and 3 is that other policies that would be associated with heat-related injury, illness, and death in workers were enacted in similar time periods as the heat safety mandates, and that these will confound estimates. To address this concern, we will conduct sensitivity analyses, including the use of negative controls (e.g., workers from within the same geographic area, but who are working in an industry that were not impacted by the heat specific policy but who would have been impacted by other policies that could confound associations). More generally, we will implement a number of sensitivity analyses to test the robustness of results.

LL. Future directions. The proposed work will provide the foundation for continued research elucidating the impacts of heat on the workforce, and the best ways to support health, safety and financial well-being within the context of global climate change. We may expand upon this work by exploring impacts of chronic (rather than acute) heat exposures on disease incidence among workers, impacts of heat safety policies on reducing these associations, and by investigating impacts of combined exposures to air pollution and heat in an occupational context. A third way we might build upon the proposed study is to explore interaction of different broader social/labor policies, such as paid sick leave or workers' compensation, with heat-specific standards for workplaces. Finally, we might conduct qualitative work to provide additional context and understanding to results from the quantitative analyses that we propose here.

MM. Impact. Results from this work will provide critical information about the burden of work-related injuries, illnesses, and deaths attributable to heat exposure, identify industry- and region-specific safe upper temperature or heat index thresholds for workers, and elucidate the health, safety and labor productivity implications of workplace heat safety standards. This work represents a critically important step in improving understanding of the burden of heat-related outcomes among workers, and in promoting goals for health, safety, and business financial viability within the context of globally rising temperatures.

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