Quantifying the impact of future extreme heat on the outdoor work sector in the United States

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Abstract

Outdoor workers perform critical societal functions, often despite higher-than-average on-the-job risks and below-average pay. Climate change is expected to increase the frequency of days when it is too hot to safely work outdoors, compounding risks to workers and placing new stressors on the personal, local, state, and federal economies that depend on them. After quantifying the number of outdoor workers in the contiguous United States and their median earnings, we couple heat-based work reduction recommendations from the US Centers for Disease Control and Prevention with an analysis of hourly weather station data to develop novel algorithms for calculating the annual number of unsafe workdays due to extreme heat. We apply these algorithms to projections of the frequency of extreme heat days to quantify the exposure of the outdoor workforce to extreme heat and the associated earnings at risk under different greenhouse gas emissions mitigation scenarios and, for the first time, different adaptation measures. With a trajectory of modest greenhouse gas emissions reductions (RCP4.5), outdoor worker exposure to extreme heat would triple that of the late 20th century baseline by midcentury, and earnings at risk would reach an estimated $39.3 billion annually. By late century with that same trajectory, exposure would increase four-fold compared to the baseline with an estimated $49.2 billion in annual earnings at risk. Losses are considerably higher with a limited-mitigation trajectory (RCP8.5). While universal adoption of two specific adaptation measures in conjunction could reduce future economic risks by roughly 90%, practical limitations to their adoption suggest that emissions mitigation policies will be critical for ensuring the wellbeing and livelihoods of outdoor workers in a warming climate.

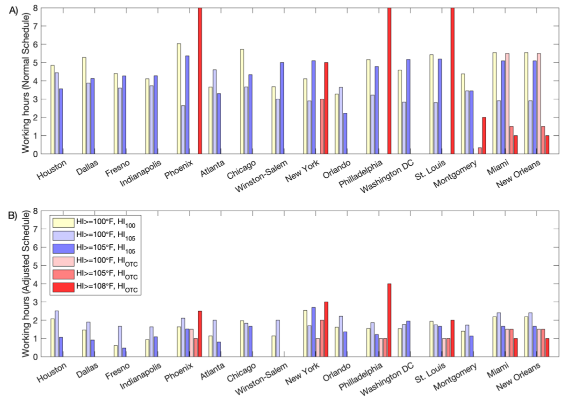

Figure S1. For a normal daytime work schedule (A) and an adjusted daytime work schedule (B), average number of hourly observations of heat indices above 100°F (37.8°C) on days when daily maximum heat indices were between 100 and 104°F (37.8-40.0°C), the number of hourly observations of heat indices above 100°F and 105°F (40.6°C) on days when daily maximum heat indices were greater than 105°F (40.6°C) but not off the chart (OTC), and the number of hourly heat indices above 100°F, 105°F, and 108°F (42.2°C) on days when daily maximum heat indices were OTC for the 16 different ASOS stations. Hourly observations covered the period 2001-2020.

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Abstract

Outdoor workers perform critical societal functions, often despite higher-than-average on-the-job risks and below-average pay. Climate change is expected to increase the frequency of days when it is too hot to safely work outdoors, compounding risks to workers and placing new stressors on the personal, local, state, and federal economies that depend on them. After quantifying the number of outdoor workers in the contiguous United States and their median earnings, we couple heat-based work reduction recommendations from the US Centers for Disease Control and Prevention with an analysis of hourly weather station data to develop novel algorithms for calculating the annual number of unsafe workdays due to extreme heat. We apply these algorithms to projections of the frequency of extreme heat days to quantify the exposure of the outdoor workforce to extreme heat and the associated earnings at risk under different greenhouse gas emissions mitigation scenarios and, for the first time, different adaptation measures. With a trajectory of modest greenhouse gas emissions reductions (RCP4.5), outdoor worker exposure to extreme heat would triple that of the late 20th century baseline by midcentury, and earnings at risk would reach an estimated $39.3 billion annually. By late century with that same trajectory, exposure would increase four-fold compared to the baseline with an estimated $49.2 billion in annual earnings at risk. Losses are considerably

higher with a limited-mitigation trajectory (RCP8.5). While universal adoption of two specific adaptation measures in conjunction could reduce future economic risks by roughly 90%, practical limitations to their adoption suggest that emissions mitigation policies will be critical for ensuring the wellbeing and livelihoods of outdoor workers in a warming climate.

Keywords: Climate change, occupational health, labor economics, outdoor workers

1. Introduction

Outdoor workers are among the most vulnerable people to heat-related illness – a condition in which the body is unable to successfully thermoregulate heat stress and, as a result, the core body temperature increases. Heat-related illness includes a range of conditions, from the relatively mild (e.g., heat cramps) to those more severe, such as heat stroke and can even lead to death (Gauer and Meyers, 2019). For outdoor workers, chronic exposure to extreme heat can also lead to other adverse health outcomes, such as acute kidney injury (Mix et al., 2018; Wesseling et al., 2020). In the United States, outdoor workers face a disproportionate risk of heat-related death (Gubernot et al., 2015) and among outdoor workers, heat-related fatalities occur disproportionately among Black and Hispanic or Latino people (Gubernot et al., 2015).

Currently, there are few mandatory protections in place to prevent heat-related illnesses and deaths in the workplace at either the federal or state level. The National Institute for Occupational Safety and Health (NIOSH) under the Centers for Disease Control and Prevention (CDC) have published a detailed set of recommendations for employers to follow to protect employees from heat-related illness (Jacklitsch et al., 2016). However, only a small number of states – including California (Heat Illness Prevention in Outdoor Places of Employment, 2015) and Washington (Washington Department of Environmental & Occupational Health Sciences, 2021) – have enacted regulations requiring employers to take specific measures to prevent heat-related illness among employees.

Moving forward, the hot and humid conditions that can lead to heat-related illness and death are projected to increase dramatically across the United States as a result of human caused climate change (Vose et al., 2017; Dahl et al., 2019). Dahl et al. (2019) found that the frequency of days with maximum daily heat index values above 100°F (37.8°C) increases four-fold nationally by the end of the 21st century under a high-emissions scenario relative to late 20th-century conditions. Despite the likely increase in risks outdoor workers will face due to continued climate change in the coming decades, their disproportionate exposure to extreme heat, and their importance to US society, few studies have attempted to quantify the impacts of future extreme heat on the wellbeing and livelihoods of outdoor workers. As a result, several critical knowledge gaps remain.

First among these gaps is a lack of knowledge regarding where outdoor jobs are concentrated in the United States and how those patterns intersect with areas where extreme heat conditions are projected to occur more frequently as a result of human-caused climate change. Critically, most studies examining the effect of increasing extreme heat conditions on outdoor workers use industry-level rather than occupation-level data (Neidell et al., 2020; Tigchelaar et al., 2020; Zivin and Neidell, 2015) or only examine one sector of workers (*e.g.*, Tigchelaar et al., 2020).

Second, understanding local, state, and regional variability in outdoor worker exposure and vulnerability is critical for designing effective climate resilience policies, as is understanding the range of potential climate conditions we face. However, many studies examining the effect of increasing extreme heat on outdoor workers to date have used coarse-resolution models, a single greenhouse gas emissions scenario, or constrained estimates of the heat-humidity combination (Dunne et al., 2013; Tigchelaar et al., 2020).

A third knowledge gap for addressing the scope of the problem includes the macro- and micro-economic impacts of climate change on outdoor workers. Previous studies (Dunne et al., 2013; Neidell et al., 2020; Zivin and Neidell, 2015) have given little attention to the consequences of climate change for the earnings of individual workers in a range of outdoor occupations. Finally, while efforts have quantified the economic benefits of greenhouse gas emission reductions on the outdoor work sector (Dunne et al., 2013; Neidell et al., 2020; Zivin and Neidell, 2015), none, to our knowledge, quantify the economic benefits of implementing adaptation measures that could enhance worker safety.

Given the gaps in our understanding of how heat is likely to impact outdoor workers as a result of human-caused climate change, this study focuses on three primary research objectives. First, this study aims to intersect spatial patterns of outdoor work across the contiguous United States with twenty-first century extreme heat projections to identify outdoor worker populations at particular risk of increasing exposure. Within this objective, we couple public health guidelines with an analysis of weather station data to develop novel algorithms for quantifying the number of workdays that could become unsafe under different global warming scenarios. Second, this study aims to quantify the individual and collective earnings at risk due to future extreme heat across a comprehensive suite of outdoor occupations. Third, this research aims to evaluate the macro and micro economic benefits of both emissions reductions and adaptation measures by analyzing multiple greenhouse gas emissions scenarios (RCP4.5 and RCP8.5) as well as two commonsense adaptation policies.

To achieve these objectives, we couple fine-resolution extreme heat frequency projections for the contiguous United States from Dahl et al. (2019) with county-level data from the US Census's American Community Survey to quantify changes in the frequency of unsafe workdays– defined here as the number of days per year with a heat index above 100°F (37.8°C, D_{100}) – over the 21st century using two different global warming scenarios. We consider two greenhouse gas emissions scenarios (RCP4.5 and 8.5, see Methods for details) utilized by Dahl et al., (2019) and two time periods (midcentury, 2036-2065, and late-century, 2070-2099) compared to late 20th century (1971-2000) conditions. We further examine the economic impacts to the livelihoods of outdoor workers by calculating the earnings at risk of being lost due to unsafe workdays. We then apply our methodology to two potential adaptation options – using an adjusted work schedule that shifts work hours to cooler times of day and lightening workloads – to assess their potential benefits. We use these results to consider the regulatory gaps that should be filled to protect worker health, as well as the livelihoods of workers and their employers in order that no individual is faced with choosing between income and their health.

2. Methods

2.1 Identification of outdoor worker occupations

We used data from the US Bureau of Labor Statistics' (BLS) Outdoor Requirements Survey to identify occupations for which a significant portion (defined here by approximately two-thirds, or, 65.2% or more) of jobs require outdoor work (Bureau of Labor Statistics, no date). Information on occupations was available at different levels of specificity. For example, protective service occupations included police officers and firefighters. We selected the level for which county-level data were consistently available. This method yielded seven outdoor-work occupational categories: Protective service; buildings and grounds cleaning and maintenance; farming, fishing, and forestry; construction and extraction; installation, maintenance, and repair; transportation; and materials moving.

2.2 Outdoor worker data

We determined the number of workers in each occupational category as well as their associated median annual earnings for each county using five-year average data (2013–2017) from the US Census Bureau's American Community Survey (ACS; U.S. Census Bureau QuickFacts: United States, 2017). This was the only data source for which occupation and earnings data were available at the county level for most of the US civilian workforce, including self-employed individuals.

In order to focus solely on the economic consequences of climate change on its own, we assume no change in the size of the US population or the outdoor workforce over time. While various population change scenarios were considered, each involved assumptions with similar repercussions to holding population constant. For instance, applying the contemporary fraction of outdoor workers per county to future time periods assumes no future inflection points in the automation of outdoor jobs or environmentally caused shifts in where and by whom outdoor work takes place.

2.3 Extreme heat data

To quantify the annual frequency of extreme-heat days historically and in the future, we utilized data developed by Dahl et al. (2019; hereafter D19). D19 developed fine-resolution, twenty-first century projections of the heat index – a heat stress index used by the US National Weather Service that combines temperature and relative humidity to produce a "feels like" temperature. In their study, D19 used statistically downscaled data (4-km grid resolution; Abatzoglou and Brown, 2012) covering the contiguous United States from 18 climate models from the 5th Coupled Model Intercomparison Project (CMIP5) to calculate a daily maximum heat index from April through October between 1971 and 2099.

The heat index calculation was performed using the National Weather Service's heat index algorithm (National Oceanic and Atmospheric Administration, 2014) with daily maximum temperature and daily minimum relative humidity as the two input variables. This pairing provides a conservative estimate of the daily maximum heat index as daily maximum temperature does not always coincide with the daily minimum in relative humidity. The authors then tallied the number of days when the daily maximum heat index exceeded a suite of heat index thresholds relevant to both the National Weather Service and human health including 100°F (37.8°C; D_{100}), 105°F (40.6°C; D_{105}), and "off-the-charts" (OTC) conditions (D_{otc}). The latter refers to days where the combination of temperature and relative humidity exceeds the bounds of the National Weather Service heat index algorithm. It should be noted that the heat index calculation is designed to represent apparent temperatures in the shade, with notably higher sensible temperatures in direct sun (US Department of Commerce, no date).

We utilized D19's results from the RCP4.5 and RCP8.5 scenarios to analyze conditions during two time periods, midcentury (2036-2065) and late-century (2070-2099), in addition to the historical period (1971-2000; Meinshausen et al., 2011). These scenarios were constructed in order to examine the changes in climate induced by future changes in global greenhouse gas emissions. Under RCP4.5, emissions peak near 2040 then begin to decline, resulting in a global mean temperature change of roughly 2°C by the end of the century. Under RCP8.5, emissions continue to rise through the end of the century, causing global mean temperature to rise by approximately 4°C (IPCC, 2014). It is important to note that recent studies suggest that the RCP8.5 trajectory is unrealistically dependent on coal as a future energy source (Ritchie and Dowlatabadi, 2017); however, the late-century warming projected by RCP8.5 has not been ruled out, particularly given the increased climate sensitivity of the latest generation (*i.e.*, CMIP6) of climate models (Zelinka et al., 2020).

2.4 Calculating unsafe workdays, earnings at risk, and worker heat exposure

We examined the effect of increasing extreme heat on outdoor work conditions and worker earnings using an array of climate mitigation and adaptation options (Table 1). As described in greater detail below, we quantify unsafe workdays and related risks to outdoor worker earnings in counties across the United States for RCP 4.5 and 8.5 at both mid and late century. We also quantify the benefits of shifting work schedules to cooler parts of the day by examining how this adaptation would affect the number of unsafe workdays and worker earnings under both a *normal* work schedule, in which work is carried out during daytime hours, and under a so-called *adjusted* work schedule, in which work is carried out during the coolest contiguous 8-hour daytime period, typically between 5:00 and 13:00 local standard time in the weather station data described below. Finally, we consider the benefits of reducing workloads from moderate to *light* levels (described below).

Emission Scenario	Work schedule	Workload
RCP 4.5	Normal	Moderate
RCP 4.5	Normal	Light
RCP 4.5	Adjusted	Moderate
RCP 4.5	Adjusted	Light
RCP 8.5	Normal	Moderate
RCP 8.5	Normal	Light
RCP 8.5	Adjusted	Moderate
RCP 8.5	Adjusted	Light

Table 1. Array of climate mitigation and adaptation options for which unsafe workdays and earnings at risk were calculated.

We developed algorithms to calculate the work time at risk of being lost as a result of extreme heat using an analysis of weather station data in concert with heat-based guidance from the CDC’s NIOSH (Table 2; Jacklitsch et al., 2016), and assumed this guidance would be followed. NIOSH recommends reducing work time for moderate levels of work when a heat stress metric equivalent to the heat index rises above 100°F (37.8°C; OSHA, 2021 ref). These recommendations are intended to estimate another commonly used indicator of heat stress conditions – the Wet Bulb Globe Temperature (WBGT, Morris et al., 2019) – using commonly available meteorological data. The recommendations are based on air temperature with suggestions for how to adjust those temperatures for higher or lower relative humidity conditions and sun exposure. However, the guidance provides only a gross estimate of how to adjust the air temperature based on whether conditions are sunny or partly cloudy to account for the WBGT's radiant heat term. Similarly, OSHA guidance on the use of the heat index for heat illness prevention notes that the heat index could be up to 15°F (8.3°C) higher in direct sunlight (OSHA, no date).

Recent research found that both the adjusted temperature variable featured in the NIOSH guidance and the heat index are suitable surrogates for WBGT (Bernard and Iheanacho, 2015). For example, Bernard and Ihanacho (2015) suggest that heat index values are within 1.4°F (0.8°C) of the adjusted temperatures for heat index values exceeding 100°F (37.8°C). For adjusted temperatures between 105°F (40.6°C) and 108°F (42.4°C), when NIOSH recommends the cessation of work, heat index values are, on average, 2.5°F (1.4°C) higher than adjusted temperatures. Given uncertainties around applying adjustments to either adjusted temperatures or the heat index based on sun exposure and given the fact that physiological responses to heat exposure vary greatly from person to person, for the purposes of this study we consider heat index an adequate stand-in for adjusted temperature.

Adjusted Temperature or Heat Index (°F)*	Work/rest minutes per hour; moderate workloads (% hourly reduction)	Work/rest minutes per hour; light workloads (% hourly reduction)
90	Normal (0%)	Normal (0%)
100	45/15 (25%)	Normal (0%)
104	30/30 (50%)	Normal (0%)
105	25/35 (58.3%)	Normal (0%)
106	20/40 (66.6%)	45/15 (25%)
108+	0/60 (100%)	35/25 (41.6%)
111+	0/60 (100%)	0/60 (100%)

*Table 2. Work schedule reduction recommendations from the Center for Disease Control and Prevention's National Institutes for Occupational Health and Safety based on moderate and light levels of work (Jacklitsch et al. 2016). These recommendations assume workers are "physically fit, well-rested, fully hydrated, under age 40, and have adequate water intake," as well as assuming there is "natural ventilation with perceptible air movement" (Jacklitsch et al. 2016). *For the purposes of this study and given the strong correlation between the two, we use heat index as a stand-in for adjusted temperature in this study.*

To translate the NIOSH guidance into algorithms that can use climate data to estimate the portion of a workday that is unsafe as a result of extreme heat, we first analyzed hourly temperature and humidity observations from 16 Automated Surface Observing Systems (ASOS) from airports across the US during 2001-2020 (NOAA NCEI, 2021; Supplementary Information). For days in the ASOS dataset with a maximum heat index above 100°F, 105°F, and OTC conditions, following the approach from D19, we tabulate the average number of hours spent above these three thresholds across the full set of weather stations (Table 2). We then used the work/rest guidance from NIOSH (Table 3) to calculate the number of hours that would be unsafe to work during a typical day in which the maximum heat index exceeds 100°F, 105°F, and OTC conditions under the different work scenarios described below. Finally, we coupled these findings with the annual average number of days projected to exceed these three thresholds at mid- and late century under RCP 4.5 and 8.5 from the D19 datasets to estimate the number of unsafe workdays in an average year under these different timeframes and global warming scenarios in counties across the contiguous United States.

To calculate worker heat exposure, we calculated the total D_{100} for each of the seven occupational categories included in this study and for each model and scenario from D19. We then multiplied D_{100} by the number of people in each occupational category (e.g., protective service), and refer to this exposure metric as "person-days" per year.

	Daily Max HI>100°F	Daily Max HI>105°F			Daily Max HI Off the charts				
	Hours > 100°F[1]	Hours > 100°F	Hours > 105°F	Hours > 106°F[2]	Hours > 100°F	Hours > 105°F	Hours > 106°F[2]	Hours > 108°F	Hours > 111°F[2]
Normal Schedule; Moderate Workload	4.7 (0.588)	3.6 (0.525)	4.4 (0.550)	N/A	0.4 (0.05)	2.2 (0.275)	N/A	5.4 (0.675)	N/A
Adjusted Schedule; Moderate Workload	1.6 (0.200)	2 (0.250)	1.3 (0.163)	N/A	1.1 (0.138)	1.1 (0.138)	N/A	1.9 (0.238)	N/A
Normal Schedule; Light Workload	N/A	N/A	0 (0)	3.1 (0.388)	N/A	NA	4.1 (0.513)	N/A	3.9 (0.488)
Adjusted Schedule; Light Workload	N/A	N/A	0 (0)	0.9 (0.113)	N/A	NA	2.9 (0.363)	N/A	1.4 (0.175)

Table 3. Hours (and fraction of an 8-hour daytime shift) above heat index thresholds necessitating work reductions as per NIOSH guidance (Jacklitsch et al., 2016). Values in parentheses are fractions of 8-hr workdays that are used as inputs to the equations above. [1]The 100°F and 108°F thresholds only apply to work reductions under moderate workloads. [2]The 106 and 111°F thresholds only apply to work reductions under light workloads.

2.4.1 Unsafe workdays with no adaptation measures implemented

While there is anecdotal evidence that employers in some occupations and in some places will shift workers' hours to cooler times of the day (Holloway and Etheredge, 2019), one recent survey of outdoor workers' indicated that workers are typically outdoors for most or all of the entire 10 am – 4 pm window that was evaluated in their study (Peters et al., 2016), which according to our analysis of weather station data, overlaps with the majority of the work hours included in the normal work schedule scenario of our study. Put another way, it is therefore reasonable to assume a no-adaptation baseline in which workers are outdoors exposed to heat during the hottest hours of the day.

For moderate levels of exertion, following the NIOSH guidance for the discrete temperature thresholds from the D19 dataset, we calculate the average number of hourly observations of heat indices above 100°F (37.8°C) on days when daily maximum heat indices were between 100 and 104°F (37.8-40.0°C), the number of hourly observations of heat indices above 100°F and 105°F (40.6°C) on days when daily maximum heat indices were greater than 105°F (40.6°C) but not off the chart (OTC), and the number of hourly heat indices above 100°F, 105°F, and 108°F (42.2°C) on days when daily maximum heat indices were OTC for the 16 ASOS stations (Figure S1). Hourly observations covered the period 2001-2020. As our study assumes an eight-hour workday, we capped the number of hours above the extreme heat thresholds used to estimate work schedule reductions at eight. We did so by subtracting time from the number of hours spent above the lowest temperature threshold in a calculation, as we assumed that the normal work schedule will occur during the daytime when peak heat conditions occur (this measure was not necessary for the adjusted work schedule scenarios described below). Table 3 shows the average number of hours across the ASOS stations corresponding to thresholds from Table 2. These data are used to calculate the annual number of unsafe workdays (U) assuming a normal work schedule and moderate workload following the NIOSH recommendations. The calculation was therefore:

$$U = \frac{5}{7}[(D_{100} - D_{105}) * 0.25 * (\frac{4.7}{8}) + (D_{105} - D_{otc}) * 0.583 * (\frac{4.4}{8})$$
$$+ (D_{105} - D_{otc}) * 0.25 * \left(\frac{3.6}{8}\right) + D_{otc} * 1 * (\frac{5.4}{8}) + Dotc * 0.583 * \left(\frac{2.2}{8}\right)$$
$$+ Dotc * 0.25 * (\frac{0.4}{8})]$$

Estimates are scaled by 5/7 to account for the typical 5-day work week; that is, we assume that outdoor workers are exposed to on-the-job heat 5 days per week rather than 7. Instead of reporting our findings in terms of the number of unsafe work hours, we calculate the number of workday equivalents that could become unsafe due to extreme heat exposure (that is, 8 hours of unsafe work). For instance, if work needs to be reduced by 50% during two separate days, we tally this as one full unsafe workday.

2.4.2 Unsafe workdays with adaptation options implemented

We modified the algorithms described above to calculate how effectively two different adaptation options — shifting work hours to cooler times of day and reducing physical workloads from moderate to light — would reduce the number of unsafe workdays and, in turn, earnings at risk due to extreme heat.

To simulate an adjusted schedule in which work is shifted to cooler times of day, we again utilized the ASOS data described above (Figure S1). After identifying the coolest contiguous 8-hour period during daylight hours for each station (5:00-13:00 LST), we determined the number of hours within that period at or above the NIOSH thresholds and modified Equation 1 appropriately using the number of above-threshold hours for each heat index category (Table 3). Thus, the calculation for annual unsafe workdays with a schedule adjusted to the coolest 8-hour daytime shift (A) became:

$$A = \frac{5}{7}\Big[(D_{100} - D_{105}) * 0.25 * \left(\frac{1.6}{8}\right) + (D_{105} - D_{otc}) * 0.583 * \left(\frac{1.3}{8}\right)$$

$$+ (D_{105} - D_{otc}) * 0.25 * \left(\frac{2}{8}\right) + D_{otc} * 1 * \left(\frac{1.9}{8}\right) + Dotc * 0.583 * \left(\frac{1.1}{8}\right)$$

$$+ Dotc * 0.25 * \left(\frac{1.1}{8}\right)\Big]$$

We also simulated the potential benefits of reducing physical workloads from moderate levels to light levels. Because light work can be done in hotter conditions than moderate work, NIOSH guidance for reducing work time based on light levels of work relies on different heat thresholds than those described above for moderate levels of work (Table 2). Applying these thresholds to the ASOS data and using the number of hours above each of the thresholds (Table 3), the calculation for annual unsafe workdays with light levels of work and a normal schedule (L) became:

$$L = \frac{5}{7}[(D_{105} - D_{otc}) * 0.25 * (\frac{3.1}{8}) + D_{otc} * 1 * (\frac{3.9}{8}) + Dotc * 0.25 * (\frac{4.1}{8})]$$

Finally, in addition to simulating shifted work schedules and reduced workloads individually, we simulated the benefit of implementing these two adaptation options in conjunction, again using the ASOS data and the values in Tables 2 and 3. The equation for the annual number of unsafe workdays with both light levels of work and an adjusted schedule (LA) then became:

$$LA = \frac{5}{7}[(D_{105} - D_{otc}) * 0.25 * (\frac{0.9}{8}) + \ D_{otc} * 1 * (\frac{1.4}{8}) + Dotc * 0.25 * (\frac{2.9}{8})]$$

2.4.3 Earnings at risk

To calculate earnings at risk of being lost due to extreme heat exposure for all combinations of time period, emissions scenario, and adaptation option, we assumed annual wages reported by the US Census Bureau are based on a 40-hour work week spread over five workdays, and 50 work weeks per year (250 days per year). We calculated earnings at risk for productivity loss estimates (E) as described above:

$$E=W*(M/T)$$

Where E is earnings at risk; W is unsafe workdays; M is annual median earnings; and T is total workdays per year.

3. Results

3.1 Characterizing outdoor workers

Using data from the ACS, we identified 31.7 million workers across the contiguous United States in the seven occupational categories the BLS identified as requiring outdoor work

(Table 4; Bureau of Labor Statistics, no date). Males made up 83% of the workers included in this analysis. BLS statistics at the national level indicate that 29% of outdoor workforce identified as Hispanic or Latino, disproportionately higher than that of the 19% of the general population (U.S. Census Bureau, 2017; Bureau of Labor Statistics, 2019). People identifying as Hispanic or Latino are disproportionately represented within all outdoor occupation categories with the exception of protective service relative to their representation in the US population as a whole. Similarly, African Americans comprise 13% of the general population but represent roughly 20% of workers in specific outdoor occupations such as protective service and transportation (U.S. Census Bureau, 2017; Bureau of Labor Statistics, 2019).

Occupational category	**Percent of jobs requiring outdoor work**	**Wages (as percent of median)**	**Percent male**	**Percent Black or African American**	**Percent Hispanic or Latino**	**Percent White**
Protective service	89.6	128.0	87.9	20.3	15.3	73.9
Buildings and grounds cleaning and maintenance	65.2	57.1	58.0	14.9	38.2	77.3
Farming, fishing, and forestry	71.1	77.3	74.8	4.4	47.6	89.3
Construction and extraction	92.3	116.1	96.5	7.3	36.4	87.1
Installation, maintenance, and repair	74.9	132.6	96.1	9.1	20.3	84.0
Transportation*	70.6	115.4	81.8	22.0	22.9	72.2
Materials moving*	70.6	81.9	81.8	22.0	22.9	72.2

*Table 4. Summary wage and demographic statistics for the occupational categories included in this study (US Census Bureau 2018; Bureau of Labor Statistics n.d.). *While the American Community Survey breaks Transportation and materials moving into two separate categories, the Bureau of Labor Statistics reports data for the two categories combined, thus all values except those for wages are identical for these two categories.*

Overall, median earnings for some outdoor occupational categories (e.g., protective service) were above the median income for all occupations nationally, but workers in several outdoor occupational categories earned notably less. For example, building and grounds cleaning and maintenance workers earned, on average, 43% less than the US workforce as a whole. Median earnings within each occupational category level reflect the range of earnings associated with each specific occupation within that category.

3.2 Heat exposure

Using the metric of person-days per year and assuming no growth or change in population, the nationwide exposure of the United States' outdoor workers to days with a heat index above 100°F (37.8°C) would increase three- or four-fold by midcentury and four- to seven-fold by late century depending on the warming scenario (Table 5). Historically, 442 counties have had 100,000 or more person-days of heat exposure per year (Figure 1). By midcentury, expansions in the frequency and intensity of days with a heat index above 100°F (37.8°C) increase the number of counties in that category to 1,264 under the RCP4.5 scenario and 1,557 – more than half of all counties – under the RCP8.5 scenario. These shifts grow substantially between midcentury and late century; however, as would be expected by the trajectory of emissions modeled by RCP8.5, exposure ramps up more steeply during the second half of the century under RCP8.5 than under RCP4.5.

		Annual earnings (billions USD) at risk (percent)			
		Normal schedule		Adjusted schedule	
Time Period (scenario)	**Exposure (pdpy)**	**Moderate workload**	**Light workload**	**Moderate workload**	**Light workload**
Historical	315 million	$8.6 (0.8%)	$1.0 (0.1%)	$3.0 (0.3%)	$0.3 (0%)
Midcentury (RCP4.5)	1.1 billion	$39.3 (3.7%)	$7.7 (0.7%)	$14.2 ($1.3%)	$2.4 (0.2%)
Midcentury (RCP8.5)	1.4 billion	$55.4 (5.2%)	$12.3 (1.2%)	$20.1 (1.9%)	$4.0 (0.4%)
Late century (RCP4.5)	1.2 billion	$49.2 (4.7%)	$10.4 (1.0%)	$17.8 (1.7%)	$3.3 (0.3%)
Late century (RCP8.5)	2.1 billion	$107.5 (10.2%)	$33.1 (3.1%)	$39.8 (3.8%)	$11.7 (1.1%)

Table 5. Summary of results for each time period and scenario evaluated in this study. Historical, midcentury, and late century results reflect average conditions from 1971-2000, 2036-2065, and 2070-2099, respectively, and represent the multi-model mean as described by Dahl et al. 2019. Values for earnings at risk and percent of earnings at risk reflect results from the normal and adjusted work schedule scenarios described in the Methods section as well as the moderate and light workload scenarios. All values are in current USD ($).

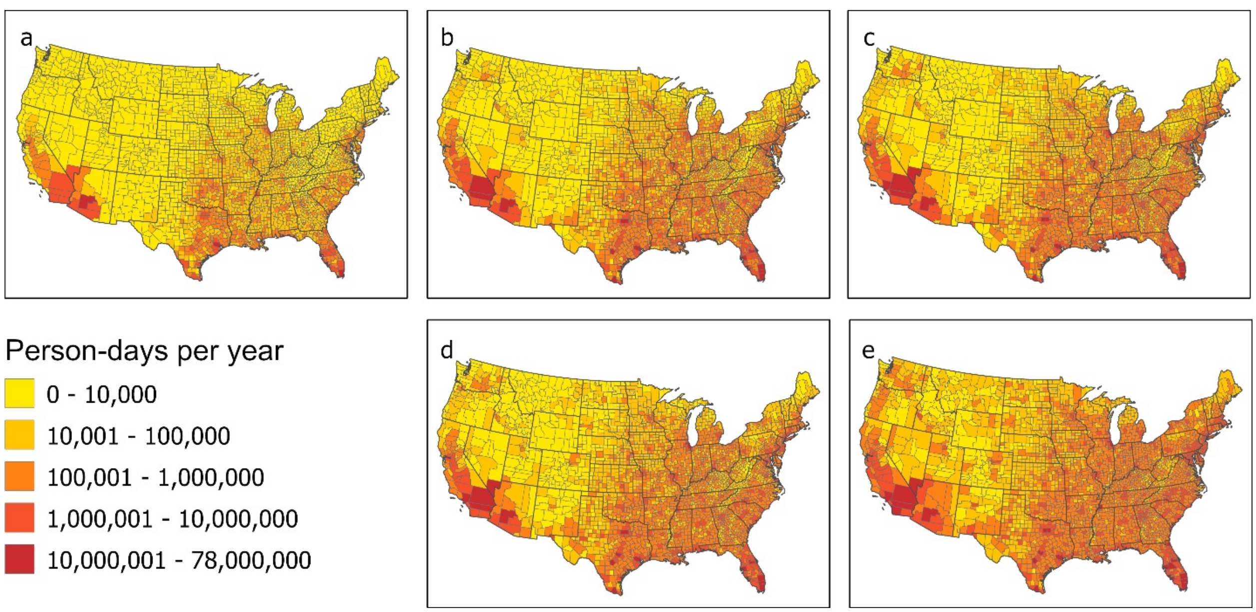

Figure 1. Person-days per year with a heat index above 100°F (37.8°C) for outdoor workers. a) Historical period (1971-2000); b) Midcentury (2036-2065) for RCP4.5; c) Late century (2070-2099) for RCP4.5; d) Midcentury for RCP8.5; and e) Late century for RCP8.5.

Urban counties have historically had the highest number of person-days per year of extreme heat exposure owing to the fact that, on a county-by-county basis, they have the largest populations (Figure 1). As home to the cities of Miami, Phoenix, and Houston, Miami-Dade County, Florida; Maricopa County, Arizona; and Harris County, Texas, have historically been the only three counties in the United States to experience, on average, 10 million or more person-days per year with a heat index above 100°F (37.8°C). By midcentury, driven by the increased frequency and intensity of extreme heat, the list of counties experiencing such heat grows to encompass an additional 10 (RCP4.5) to 14 (RCP8.5) counties, including Los Angeles, California; Las Vegas, Nevada; and Chicago, Illinois. By late century, under RCP8.5, 24 counties are projected to experience 10 million or more person-days per year with a heat index above 100°F (37.8°C). These counties still all represent urban centers and include Queens, New York, one of the five boroughs of New York City. When considering our results for urban areas, it is important to note that statistically downscaled climate projections used to generate these results do not capture changes in urban heat island dynamics or other land cover changes that can affect the intensity of heat at the local level.

Heavily agricultural areas across the Southwest and Southeast regions, such as the Central Valley in California and inland counties in Central Florida, also stand out in the historical time periods as having high exposure (in person-days per year) due to a combination of relatively frequent days with a high heat index and relatively large numbers of people engaged in outdoor work. However, in many other rural or suburban areas, while the absolute number of outdoor workers is relatively low compared with urban areas, outdoor workers comprise a larger share of the working population (i.e., the total civilian employed population ages 16 years and over). In 63% of US counties—or 1,972 out of a total of 3,108--outdoor workers comprise 25% or more of the total working population. Historically, only 132 of these counties experienced 30 or more days per year with a heat index above 100°F (37.8°C), when work reductions would have been recommended. This number increases by mid-century to 982 and

1,173 counties under RCP4.5 and RCP8.5, respectively. By late century, such conditions would impact 1,086 counties under RCP4.5 and 1,561 counties under RCP8.5.

3.3 Unsafe workdays and earnings at risk

Assuming normal work schedules and moderate workloads, we find that nationwide, nearly 3 million outdoor workers already experience 7 or more unsafe workdays per year – primarily across portions of the Southwest, Southern Great Plains, Midwest, and Southeast (Figure 2). By midcentury, however, the number of workers experiencing 7 or more unsafe workdays per year would rise to nearly 14 million under RCP4.5 or 18.4 million under RCP8.5. By late century, 17.1 million workers nationwide would experience 7 or more unsafe workdays per year (RCP4.5). This number would grow to 27.7 million under RCP8.5.

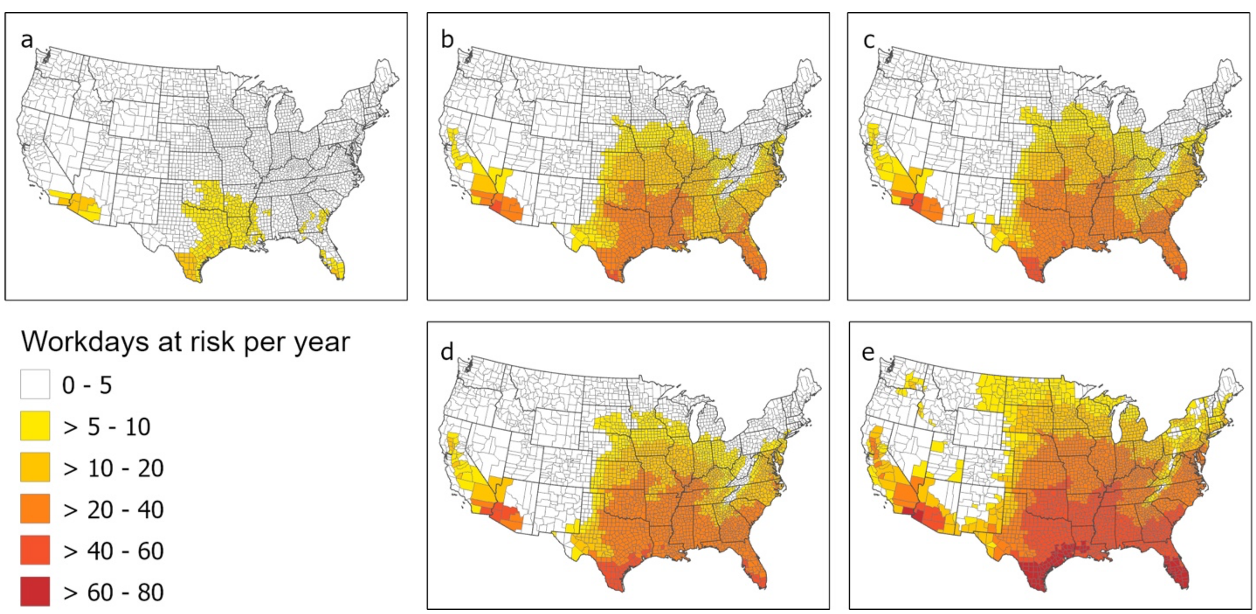

Figure 2. Workdays at risk per year due to extreme heat given normal work schedules and moderate workloads. a) Historical period (1971-2000); b) Midcentury (2036-2065) for RCP4.5; c) Late century (2070-2099) for RCP4.5; d) Midcentury for RCP8.5; and e) Late century for RCP8.5.

Assuming that workers are not paid for the hours during which it is too hot to work or offered a change in the times of day during which they work, the rise in unsafe working conditions would translate to substantial financial losses for outdoor workers and, by extension, the nation as a whole. Under RCP4.5, 3.7% (or a total of $39.3 billion) of outdoor workers' earnings nationwide would be at risk by midcentury and 4.7% (or a total of $49.2 billion) would be at risk by late century (Figure 3). Earnings losses would be higher under RCP8.5, with 5.2% (or a total of $55.4 billion) of outdoor workers earnings at risk by midcentury and 10.2% (or a total of $107.5 billion) at risk by late century. However, these national averages and totals obscure a growing number of counties where much higher percentages of wages are at risk as extreme heat becomes more frequent and more severe. By midcentury, 10% or more of annual earnings would be at risk from extreme heat for 4.1 million workers across the country under RCP4.5, or 7.1 million workers under RCP8.5. By late century, under RCP4.5, 6.0 million workers would experience that level of earnings reductions, or 13.4 million workers under RCP8.5.

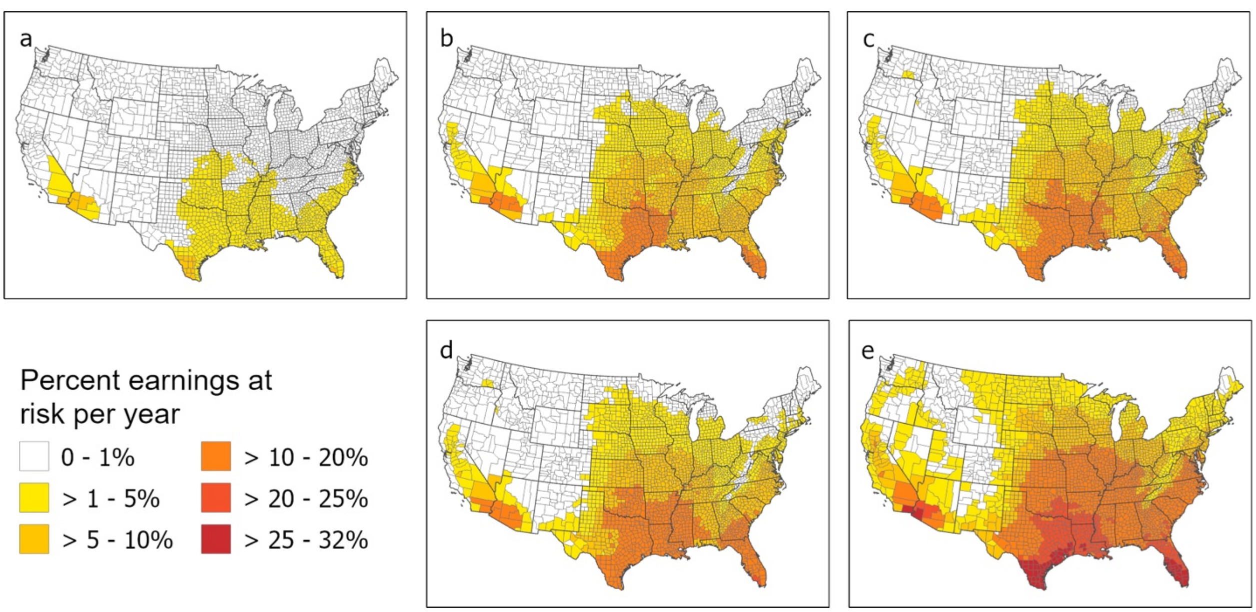

Figure 3. Percent of outdoor workers' earnings at risk annually due to extreme heat. a) Historical period (1971-2000); b) Midcentury (2036-2065) for RCP4.5; c) Late century (2070-2099) for RCP4.5; d) Midcentury for RCP8.5; and e) Late century for RCP8.5.

By midcentury, at the individual level, the average outdoor worker in the United States risks losing approximately $1,200 in earnings per year under RCP4.5 and approximately $1,700 per year under RCP8.5. In the 10 counties with the highest losses, however, average losses are substantially higher: approximately $5,600 per year under RCP4.5 and nearly $7,000 per year under RCP8.5. In terms of absolute dollar values, at midcentury under RCP8.5, total potential losses are highest for construction and extraction occupations, owing to the fact that a high percentage of outdoor workers are employed in that category.

3.4 Benefits of implementing adaptation measures

Results presented thus far indicate that protecting worker health by implementing temperature-appropriate work/rest schedules could come at a significant cost both to individual workers and to the broader economy. While maintaining work/rest schedules aimed at protecting worker health, the two adaptation measures simulated in this analysis — adjusting work schedules to cooler hours of the day and reducing workloads from moderate to light levels — were both found to reduce the number of unsafe workdays and earnings at risk due to extreme heat (Table 5). Most effective, however, was the combination of the two measures when implemented in conjunction.

Compared to a baseline of maintaining a normal work schedule, adjusting work hours to cooler times of day while maintaining moderate workloads would reduce the number of workers with 7 or more workdays at risk annually due to extreme heat from 14.0 million to 6.5 million under RCP4.5 and from 18.4 million to 9.2 million under RCP8.5 in the midcentury time period (Figure 4). Compared to a baseline of maintaining a normal work schedule and moderate workloads, reducing workloads to light levels again would reduce the number of workers with 7 or more workdays at risk annually. In this case, the number of workers carrying this level of risk would decline from 14.0 million to 0.7 million under RCP4.5 and from 18.4 million to 4.9 million under RCP8.5 in the midcentury time period. If work schedule adjustments and work level reductions were implemented together, virtually no workers would risk losing 7 or more workdays per year by midcentury with either emissions scenario. By late century, universal implementation of both adaptation measures combined with emissions reductions consistent with the RCP4.5 pathway would reduce the number of workers experiencing 7 or more unsafe workdays per year to virtually none compared with 27.7 million workers who would experience such losses with the higher emissions RCP8.5 scenario and no adaptation measures implemented. These adaptation measures have significant benefits for preserving workers' earnings as well: If both measures were implemented in conjunction, virtually no outdoor workers in the United States would be at risk of losing 5% or more of their earnings annually even by late century and with the high-emissions RCP8.5 scenario.

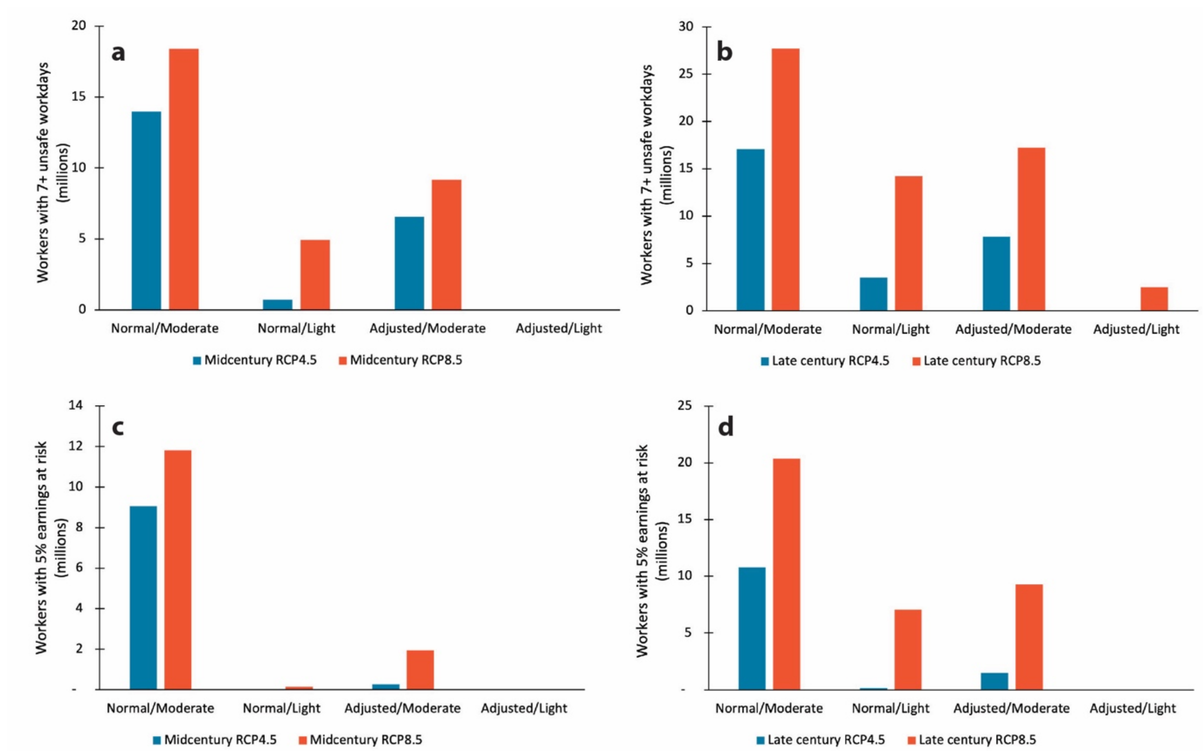

FIGURE 4: Workers at risk of significant losses in workdays or earnings as a result of extreme heat with the implementation of different adaptation measures: a "normal" work schedule with moderate workloads (Normal/Moderate); a "normal" work schedule with light workload (Normal/Light); an adjusted work schedule with moderate workloads (Adjusted/Moderate); and an adjusted schedule with light workloads (Adjusted/Light). Graphs show the number of workers nationwide experiencing 7 or more unsafe workdays per year by midcentury (a) and late century (b) as well as the number of workers for whom 5% or more of annual earnings are at risk by midcentury (c) and late century (d).

4. Discussion

4.1 Comparisons to previously published studies

These results show that increasingly frequent extreme heat could heavily burden the health and livelihoods of outdoor workers as well as the livelihoods of their employers vis-à-vis a decline in the number of safe working hours or days. As there are no mandatory heat protection standards for workers across much of the US, the implementation of heat-related work time or workload reductions or shifts in work schedules such as those quantified here is predicated on the notions that a) worker health will be the top priority in deciding whether or not work will be carried out; and b) employers will follow NIOSH's health-based recommendations. If not coupled to income guarantees, health-focused reductions in the amount of time outdoor workers spend working would put workers' earnings in jeopardy. This analysis also shows, however, that both emissions reductions and, in particular, adaptation measures have the potential to mitigate the number of unsafe workdays as well as the potential losses to workers' earnings over this century.

Our findings are directionally consistent with a growing body of literature indicating that extreme heat is already impacting worker health, capacity, and productivity around the world and will increasingly do so as our climate continues to warm (Dunne et al., 2013; Zander et al., 2015; Kjellstrom et al., 2016; Takakura et al., 2017). For US agricultural workers specifically, work by Tigchelaar et al. (2020) has shown that the frequency of unsafe working conditions would double given a global mean warming of 2°C above pre-industrial temperatures and would triple with a global mean warming of 4°C (Tigchelaar et al., 2020). Such warming levels are roughly consistent with midcentury and late century warming projections under RCP8.5. Given differences in the Tigchelaar et al.'s methodology — including their use of lower-resolution climate models, a simplified methodology for heat index projections, and industry-based classifications as opposed to the occupation-based classifications used here — the broad consistency between our results and theirs is notable.

Coupling American Time of Use Survey (ATUS) data by industry to observations and projections of temperature, Neidell et al. find that, during periods of economic growth in the United States, outdoor workers measurably reduce their work time when temperatures rise (Neidell et al., 2020). Similarly, Hsiang et al. 2017 used data based on the ATUS (Zivin and Neidell, 2015) to project the change in labor supply due to climate change over the course of this century and found a roughly 0.5% °C^{-1} decline in labor supply for high-heat-exposure jobs, which implies a smaller change by late century than our findings suggest absent the implementation of adaptation measures (Hsiang et al., 2017). The differences in our results may be due to Neidell et al.'s inclusion of periods of economic contraction, the heat stress metrics used, or functional differences between what workers and their employers do in reality in response to heat versus the breaks in work that employees *should* be afforded. It is also possible that workers and their employers are already shifting work schedules and workloads somewhat such that Neidell et al.'s results would reflect a reality that is closer to one of the adaptation scenarios we analyzed.

In terms of the efficacy of potential adaptation measures, Tigchelaar et al. 2020 conclude that while increasing workers' rest time and decreasing the level of effort associated with their work would reduce workers' heat exposure, such measures would come with costs to productivity, earnings, and labor costs for employers. Our results suggest that, without guarantees of payment for rest periods, simply adding additional rest periods to workers' schedules without shifting work hours to cooler times of day or reducing workloads could provide health benefits but would also come at a significant cost to workers and the national economy. In contrast, shifting work to cooler times of day and reducing workloads while continuing to provide the necessary rest breaks would likely reduce heat stress and minimize financial repercussions.

4.2 Broader implications

Given that Black and Hispanic or Latino workers are disproportionately represented in many outdoor occupations, losses in outdoor workers' earnings could exacerbate existing inequities in health outcomes, poverty rates, and economic mobility, all of which have accumulated from centuries of systemic racism. The health and lives of undocumented and migrant workers, who are likely underrepresented in the data underlying this study, could also be disproportionately affected by increases in extreme heat owing to the fact that fear of deportation and payment practices for these workers often discourage them from taking breaks, reporting symptoms of heat illness, or reporting employers' negligence to provide a safe working environment (Gubernot et al., 2014; Moyce and Schenker, 2017). A climate-altered future could also necessitate radical shifts in outdoor work, such as increased replacement of outdoor workers by technology, as well as shifts in where and when certain occupations are performed. Without attention to justice and equity, such changes could fall especially hard on the working class.

Communities — particularly those where outdoor workers make up a large proportion of the workforce — would likely experience adverse outcomes as a result of reduced outdoor worker labor and earnings. A loss in the amount of time outdoor workers can safely perform their jobs could disrupt the essential services they provide, from building maintenance and construction to law enforcement and the harvesting of food crops. Further, if employer costs rise due to changes needed to cope with extreme heat, costs could ultimately be borne on the shoulders of consumers. Reduced earnings for outdoor workers could also reduce local revenue from income taxes in some communities, affecting the public services dependent on that revenue.

While beyond the scope of the present study, if emissions continue to rise and/or if employers fail to implement worker protection measures, the impacts to the health of outdoor workers and to the US healthcare system could be significant. For example, the 2018 US National Climate Assessment found that under RCP8.5, annual heat- and cold-related mortalities across large cities in the United States would reach 9,000 by late century (Ebi et al., 2018). Considering their higher risk of heat-related fatalities among outdoor workers, outdoor workers could disproportionately bear that burden.

In addition to those studied here, many additional factors could influence outdoor workers' schedules or the nature of their work as the climate warms. For example, one could imagine certain types of outdoor work, such as planting crops, being shifted largely to pre-dawn hours. Other types of outdoor work, such as roofing, cannot be done at such times because of the disruption it would cause to homeowners and communities during sleeping hours. For the workers themselves, previous studies suggest that performing "shift work," or work that is done outside standard daytime working hours, can be associated with poorer diet (Souza et al., 2019) as well other negative health outcomes (Shan et al., 2018) (Hansen, 2017). Thus, while our results simulate the benefit of shifting work to cooler hours of the day, in practical terms, the extent to which work hours for certain types of work can be shifted may be limited and shifting work hours could have drawbacks for worker health.

Similarly, there may be limits to how much physical workloads can be reduced. While we have simulated a shift from moderate to light workloads in the present analysis, barring advances in the automation of the tasks typically associated with moderate workloads, the fact remains that there are work-related functions that will continue to necessitate at least moderate levels of physical exertion. As a result, the potential benefits of workload adjustments and/or work schedule shifts quantified here are likely overestimates in some instances but provide useful comparisons with typical work conditions.

4.3 Limitations and areas for future research

This study has several limitations that should be noted. The ACS dataset used here do not fully capture all outdoor workers because it focuses only on occupations for which outdoor work is essential. Each occupational category in the analysis contains a number of sub-categories. For example, protective service includes firefighters and police officers. Some sub-categories are not clearly outdoor occupations; in other instances, sub-categories could be listed under other occupational categories that largely do not conduct work outdoors and would thus be excluded from our analysis. Furthermore, workers in some occupations (e.g., preschool and elementary school teachers) typically conduct work outdoors but outdoor work is not necessarily essential for conducting those jobs. This analysis does not include those occupations. Similarly, the COVID-19 pandemic necessitated people in a broad variety of occupations to shift their work at least partially outdoors; those occupations are not included here. The analysis also does not include agricultural and construction managers, as ACS includes these workers into a broader category of managers. Finally, ACS data lack precision at smaller geographic areas. Total outdoor worker counts should therefore be taken with caution at small geographic areas (e.g., counties) as well as for the reasons listed above.

This study assumes that outdoor workers are evenly distributed over the area of each county and that there is no change, redistribution, or growth in population of outdoor workers over time. Nor does it include many additional adaptation measures that could lessen future heat exposure, such as the greater use of protective clothing or the potential for human acclimatization to hotter conditions. In this sense, the study is focused on changes in exposure and risk resulting exclusively from climate change.

The extreme heat data underlying this study have some limitations as well. For example, daily minimum heat index values and multi-day heat waves are known to affect heat-health outcomes but are not considered. In addition, we utilize county average heat statistics, and do not consider their spatial variability within a county. For much of the United States counties are small enough that this spatial variability is likely to not be important. However, in counties with a larger area, such as in parts of the Western United States, such variability could be important and is not considered. The data also do not capture current or future urban heat island dynamics or other land cover changes that can affect the intensity of heat at the local level. Following our analysis of weather station data, we applied our assumptions about the persistence of extreme heat uniformly across the country, though conditions do vary from region to region.

Recent research has shown that cases of heat-related illness in the United States begin to rise when the heat index reaches 80°F, which is well below the 100°F (37.8°C) threshold identified by the CDC and used in this study (Morris et al., 2019; Vaidyanathan et al., 2019). A lower heat index threshold (e.g., 80°F (26.7°C)) is particularly justified when outdoor workers must wear protective clothing, such as when applying pesticides to crops (Ferguson et al., 2019). Given that our study only considers work reductions on days when the heat index is above 100°F (37.8°C) as well as light and moderate (but never heavy exertion), our estimates of unsafe workdays and earnings at risk may be conservative. On the other hand, because the heat index tends to be higher than the adjusted temperature, particularly for adjusted temperatures above 105°F (40.6°C), our application of the heat index to the NIOSH work reduction guidance could lead to a slight overestimation of the number of hours necessitating work reductions on days with a heat index above 105°F (40.6°C).

4.4 Policy Implications

In all but two US states — California and Washington — there are no enforceable heat protection standards for outdoor workers. While the OSH Act requires that employers provide employees with a workplace that is free of hazards that could cause serious physical harm or death, there are no federal measures that employers are mandated to follow to ensure that preventable heat-related illnesses and deaths are in fact prevented. Rather, employers are provided with recommendations from OSHA and NIOSH. The lack of standards enforceable under state or federal law is a clear gap in heat-health policies in the United States.

This research may provide data useful for workers and advocates for workers' rights, as well as for policymakers seeking to understand how climate mitigation and adaptation measures could affect their jurisdictions and constituents. The results of our research show that under ideal circumstances, adaptation measures can prevent the majority of outdoor worker exposure to unsafe work time, as well as the majority of earnings losses. However, as discussed above, reducing work schedules and lightening workloads will not be possible in many instances, and in some instances, such adaptation measures can have their own adverse consequences for outdoor worker wellbeing. As a result, it is critical that mitigation measures also be taken to limit the increase in extreme heat conditions.

Any new heat-safety policies must prioritize the health, well-being, and safety of workers who have faced longstanding inequities, with guarantees of fair wages and benefits, safe working conditions, legal safeguards to protect worker rights, access to medical care, and access to safe, affordable, cool housing. For many outdoor workers, particularly in agricultural occupations, housing is provided by employers as part of their compensation (Coronese et al., 2019). While OSHA requires that such housing meet a basic set of criteria, revision of those criteria to ensure adequate cooling could be merited (Occupational Safety and Health Administration (OSHA), 2005). Agricultural and construction work are among the occupations that most expose workers to heat stress (Gubernot et al., 2015); these occupations include high proportions of low-wage, migrant, and undocumented workers and people of color (Passel and Cohn, 2015; U.S. Census Bureau, 2017; Bureau of Labor Statistics, 2019; USDA Economic Research Service, 2020). Language barriers, gaps in health insurance, and concerns about immigration status compound the consequences of a lack of protective standards and leave workers who experience heat-related injuries or on-the-job illnesses with little to no legal recourse (Guild and Figueroa, 2018).

5. Conclusions

This research shows that outdoor workers in the United States would experience marked increases in heat exposure in the coming decades as a result of human-caused climate change. We show that this increased exposure would lead to significant adverse impacts to outdoor worker health, work schedules, and earnings. At the same time, we show that adaptation measures such as shifting work schedules and lightening workloads could prevent the majority of outdoor worker exposure to unsafe work time as well as the majority of outdoor worker earnings losses. As these adaptation measures will not always be possible, and may create their own risks to outdoor workers, it is critical that ambitious mitigation measures also be taken to limit the rise of extreme heat conditions across the United States. We show that such mitigation measures would also be effective in reducing outdoor worker heat exposure and earnings losses. Given the risks facing outdoor workers, mandatory heat protection measures that follow NIOSH's recommended standards must be put in place, with particular attention to aspects of outdoor work such as work schedules, workloads, access to sufficient shade, and hydration. Protective measures should also be put in place that protect the livelihoods of both workers and employers in the face of extreme heat, such that neither party is faced with deciding between the health and wellbeing of workers, and their earnings.

Contributions

Contributed to conception and design: RL, KD

Contributed to acquisition of data: RL, KD, JTA

Contributed to analysis and interpretation of data: RL, KD, JTA

Drafted and/or revised the article: RL, KD, JTA

Approved the submitted version for publication: RL, KD, JTA

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Competing Interests

The authors declare no competing interests.

Data Accessibility Statement

All novel data including unsafe workday, earnings at risk, and worker exposure data will be made publicly available through the Union of Concerned Scientists website.

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