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Farmworker-Relevant Heat Exposure in Different Crop and Shade Conditions

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Abstract

Objectives.—Agricultural workers are at risk of heat-related illness, which is preventable. Few field studies have compared farmworker-relevant heat exposure in different conditions. We examined heat exposure over time in different potential shade and work locations to inform future occupational heat prevention approaches.

Methods.—We assessed heat exposure in Eastern Washington State (WA) cherry and grape fields in August 2022. QUESTemp° monitors recorded Wet Bulb Globe Temperature (WBGT) and Black Globe Temperature (BGT) every 10 minutes from approximately 07:00–14:00 for 3 days in the center of crop rows (mid-row), under portable shade structures (shade), and in open field (open) locations. Linear mixed effects regression (LMER) models compared WBGT and BGT among field locations. Hourly time-weighted average WBGT and comparisons with occupational exposure limits (OELs) were computed for different hypothetical work-rest cycles, assuming different worker effort levels, rest locations (mid-row versus shade), and acclimatization statuses, during the hottest sampling hours.

Results.—Across all crops and locations during the study period, the mean/SD air temperature was 31°C(88°F)/3.9°C(6.9°F), with a maximum temperature of 39°C(102°F) and a mean/SD relative humidity of 30%/9.6%. LMER models suggested no significant difference in mid-row versus open WBGT but significantly lower WBGT in shade versus open locations for both cherries (main effect −5.14: 95% confidence interval [CI] −6.97,−3.32) and grapes (−6.20: 95%CI −7.73,−4.67), though this difference diminished over the course of the day. BGT was significantly higher in the mid-row than the shade (cherries main effect 14.33: 95%CI 9.52,19.13 and grapes 17.10: 95%CI 13.44,20.75). During the hottest sampling hour, exceedances of OELs were reduced with assumptions of increased shaded break lengths, reduced effort level, and acclimatization.

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Conclusions.—Shade canopies, but not the crops studied, provided significant reductions in heat exposure. We observed increased protection from heat assuming longer shaded breaks and reduced effort levels. Results highlight the need for additional field research on the effectiveness, feasibility, and acceptability of different shade types and work-rest cycles to guide employer optimization of best practices for worker protections, including acclimatization before high heat, sufficient shaded rest time, reduced effort levels as the day warms, and avoiding work in peak heat.

Keywords

heat stress; field study; shade; farmworker

Introduction

Agricultural workers experience a heightened risk of heat-related illness (HRI) mortality [1], and their work in the heat is associated with acute kidney injury (AKI) [2] and traumatic injuries [3]. United States (US) Bureau of Labor Statistics (BLS) Census of Fatal Occupational Injuries (COFI) data from 2011–2021 indicate 436 heat-related deaths [4] and from 2000–2010 indicate a yearly average agricultural worker fatality rate from heat of 3.1/100,000 workers, with a risk of heat-related death that is 35 times the risk for all other industries (rate ratio 35.2, 95% confidence interval 26.3–47.0) [1]. Washington (WA) State Fund workers' compensation data analyses from 2006–2017 indicate a high rate of third quarter (July-September) agriculture, forestry, and fishing accepted HRI claims (102.6/100,000 full-time employees), which is likely an underestimate, as HRIs may be underrecognized and underreported because of worker fear of employer retaliation [5].

Heat stress comprises: 1) environmental heat exposure (air temperature, humidity, air movement, and radiant heat including solar radiation); 2) metabolic heat from physical work effort; and 3) the effect of clothing on dissipation of heat [6]. Heat stress contributes to an increased risk of HRI among workers [6]. Environmental heat exposure (or 'heat exposure') within agricultural fields is known to be variable [7]. Factors that impact variability in heat exposure over space and time likely include: irrigation and other sources of humidity, radiant heat from the sun, wind, and heat mitigation controls, such as shade from canopies [6]. Best practice guidelines indicate that heat stress can be reduced by minimizing heat exposure (e.g., shade) and metabolic heat (e.g., rest breaks and/or reduced effort level), and supporting heat loss (e.g., removal of non-breathable personal protective equipment) [6,8].

Although there is currently no federal occupational heat rule in the United States (US), the US Occupational Safety & Health Administration (OSHA) has published an Advanced Notice of Proposed Rulemaking to address the growing threat of heat on worker health [9]. Several US States have existing, new, or updated outdoor occupational heat rules, including WA [10–13]. In WA State's 2023 Outdoor Heat Exposure rule for agriculture [10], shade is defined as "[a] blockage of direct sunlight….[s]hade may be provided by any natural or artificial means that does not expose employees to unsafe or unhealthy conditions and that does not deter or discourage access or use" [10]. Though some growers use crops as potential shade [14,15], there are few studies evaluating the effect of crops versus other potential sources of shade on worker-relevant heat exposure. This information is needed to inform guidance on how best to implement shade to protect workers from heat in field settings and, specifically, to address the following questions: 1) is potential shade from crops adequate for cool-down rest periods in the field?; and 2) how best could work and breaks be organized during the day in a crop block to minimize heat stress?

We sought to begin to address these questions through farmworker-relevant assessments using scientific-grade reference heat exposure monitors in agricultural field settings. Our objectives were to: 1) estimate the relationship between location (within a crop row versus under a shade structure versus in an open area) and heat exposure; and 2) characterize heat stress and its relationship with occupational exposure limits, assuming rest breaks of different durations, within a crop row versus under a shade structure, and different levels of work effort.

Methods

Study site, location, and timeframe

The study was conducted at the Washington State University (WSU) Irrigated Agriculture Research and Extension Center (IAREC) (46°15’08”N, 119°44’20”W), 5 miles northeast of Prosser, Washington, in Benton County [16], where agriculture is a major component of the economy [17]. Central/Eastern WA is dry (18–23 cm [7–9 in] of rainfall annually), with average summer high temperatures in the upper 80 to mid-90s°F (27–34°C) [18]. Top WA crops include apples, grapes, hops, and cherries [17]. Additional details about IAREC are found in the Supplementary methods.

IAREC is comparable to real-world agricultural settings because of its commercial-grade crop blocks. IAREC crops are representative of the type of crops that typically require workers to perform manual work (e.g., harvesting, thinning, pruning, tying). Furthermore, Benton County is one of the warmest counties in the Columbia River agricultural region [19]. In WA, some growers have used crops and pop-up shade canopies, similar to those used in our study, as potential shade or are trying to determine how best to provide shade (2024 communication of the Pacific Northwest Agricultural Safety & Health Center with JTS).

The study was conducted in sub-acre IAREC wine grape and cherry blocks. Cherry and grape crops are planted in rows across the block. Cherry trees are typically pruned below four meters (14 feet), the limit of practical harvest [20]. Most grape trellises provide about 2 meters (6 feet) of support, and row spacing is typically the same or greater than the height of the crop to avoid row-to-row shading [21]. In WA, grapes are typically harvested from August-November and cherries in June-August [22]. Additional details about the grape and cherry blocks are found in the Supplementary Methods.

We collected measurements in crop rows, under standard shade structures (described below), and in open areas (Figure 1). A 30 square meter (10 × 10 foot) store-bought white shade canopy (Ozark Trail, Bentonville, AR) was placed at approximately mid-block at the south end of each block (canopies were too large to fit between rows) (Figure 2). This size shade structure was chosen because the research team could easily set it up in the field,

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it is a common size used in crop operations, and this size is allowable under the WA Outdoor Heat Exposure rule in situations where the number of workers on a meal or rest period can be accommodated [10]. We also collected measurements in an open area on the southeastern end of the grape block and in a southwestern area of the cherry block. There were constraints to sampling open areas in exactly the same place relative to the shade structure and crops because of the different layouts of the crop blocks, yet our shade structure positioning matched typical positions used during normal work operations.

The study was conducted for 3 consecutive days on August 16–18 (Days 1–3), 2022. We sampled in August because August is typically a hot time of year in Central/Eastern WA with peaks in daily temperatures that are generally the highest among all months, representing among the highest levels of potential occupational outdoor ambient heat exposure experienced by WA workers [19]. July and August are also typically months with high numbers of Washington State Fund workers' compensation claims for HRI [5]. Details of the field safety plan are provided in the Supplementary Methods.

Instruments & sampling plan

We sought to assess exposure relevant to farmworkers, defined as individuals who work outdoors on farms, including self-employed individuals, seasonal and migrant workers, and farmers who engage in agricultural activities or tasks outdoors on farms. We placed QUESTemp° monitors (TSI® Inc, Minnesota, USA) in the blocks on tripods at the mid-point of each row (mid-row), under a standard shade structure (shade), and in an open area free of shade and crops (open). This design is detailed in the sampling plan shown in Figure 2, which depicts one of several crop rows within the crop block. QUESTemp° monitors contain sensors that measure parameters (Black Globe, Wet Bulb, Dry Air) needed to calculate Wet Bulb Globe Temperature (WBGT), a measure of heat exposure that accounts for temperature, humidity, wind speed, and visible and infrared radiation (e.g., sunlight) and is associated with human HRI [6]. Devices were placed at a height of about 1.5 meters (five feet) to approximate exposure at the average height of the upper bodies of workers. We aimed to collect data during hours when farmworkers often work. During tree fruit harvest, the mean (standard deviation) length of the work-shift has been reported to be 6.8 (1.5) hours, with workers starting on average around 06:00 [23]. Logistical constraints prevented starting data collection at 06:00. Data collection began and ended between approximately 07:20–09:20 and 13:50–14:20, respectively, depending on the day and location.

Seven QUESTemp° area heat stress monitors (five QUESTemp°34s, one QUESTemp°36, and one QUESTemp°46) were factory calibrated prior to use. Different models of QUESTemp° monitors were used because these were the only monitors available to study researchers. Trial measurements were performed in climate-controlled laboratory and outdoor settings to confirm consistency of measurements between instruments, including the QUESTemp°46. In each block, QUESTemp° monitors were placed 0.9 meters (3 feet) east of the crop row, under the shade from the shade structure, and in the open area. We chose 3 feet to mimic a workers' 'arms-length' distance to the crop. Shade from the shade structure was not necessarily directly under the shade structure, depending on the time of day, and instruments were moved throughout the course of the day to ensure the device remained in the shade. The location of QUESTemp° monitors were randomized each day across blocks, except for the QUESTemp°46 monitor, which was placed in the grape open area each day. The QUESTemp°46 monitor, unlike the other the QUESTemp° monitors, has a waterless wet bulb system that estimates the Wet Bulb Temperature (WBT) from the %Relative Humidity (%RH), Dry Bulb Temperature (DBT), and Black Globe Temperature (BGT), with an airflow adjustment (default 2.0 ms^{-1} for outdoor environment) [24]. We placed the QUESTemp°46 monitor in the grape open area because we anticipated low values and minimal variation in humidity or wind speed in this area. After an operational check using the verification module each day, QUESTemp° monitors were set to log data (DBT, BGT, WBT, outdoor WBGT [$WBGT_{out}$]) every 10 minutes. Wind speed was assessed using data from WSU's AgWeatherNet weather station network [25] and field observations performed as described in the Supplementary Methods.

Data download and processing

At the end of each field day, data from QUESTemp° monitors were downloaded using TSI® Detection Management Software.

Analyses

Descriptive exposure analyses—We first conducted descriptive data analyses and visualizations (scatter and line plots) to characterize variation by crop and location (mid-row, open, and shade) over time in terms of DBT, BGT, WBT, and $WBGT_{out}$. For outdoor environments, WBGT was derived using the equation in the Supplementary Methods.

Inferential exposure analyses—Multivariable linear mixed effects regression (LMER) models were used to examine temperature exposure (BGT and $WBGT_{out}$) in locations (mid-row, open, and shade) among cherry and grape crops over time. LMER model structures were identical for $WBGT_{out}$ and BGT but with differing references for each outcome, namely open for $WBGT_{out}$ and shade for BGT. Reference location categories per model were chosen to represent the location with the greatest hypothesized difference from the two alternative locations, promoting ease of model results interpretation as reductions in $WBGT_{out}$ in potential shade conditions (compared to open areas) and increases in BGT without shade (compared to under shade canopies). Fixed factors included sampling location, hour, and a location by hour interaction. Random factors included the clustering of hours (six to eight hours per day, with six samples recorded per hour) within days (3 sample days). We did not directly examine differences in exposure between cherries and grapes due to differences in crop architecture (e.g., trees versus lower lying vines) and different harvesting practices. Presented model results, such as confidence intervals and p-values, utilized the Kenward and Rogers degrees of freedom correction for small cluster sizes [26]. Analyses were conducted with R, version 4.2.0 (Vienna, Austria) [27]. The lme4 package and LMER modeling function were utilized to derive model estimates [28].

Comparison with occupational exposure limits—We conducted an analysis of measured exposures, compared to occupational exposure limits (OELs), during the final 3 full hours of each day during which data were collected (11:00, 12:00, 13:00), which corresponds to study hours when the hourly mean DBTs in the mid-row were approximately at or above 32°C (90°F) but less than 38°C (100°F). National Institute for Occupational Safety and Health (NIOSH) heat stress Recommended Exposure Limits (RELs) and Recommended Alert Limits (RALs), which align with American Conference of Governmental Industrial Hygienists (ACGIH) heat stress Threshold Limit Values (TLVs)® and Action Limits, were calculated for each hour using time-weighted average metabolic rates (TWA-Ms) by applying the equations outlined in the Supplementary Methods [6,8]. The REL represents the exposure level at which most healthy hydrated acclimatized workers can sustain thermal equilibrium, and the RAL represents the exposure level for most healthy hydrated unacclimatized workers [6].

Each 10-minute $WBGT_{out}$ measurement was assigned a category within the hour (0–9 min, 10–19 min, 20–29 min, 30–39 min, 40–49 min, 50–59 min) based on the timestamp of the measurement. Hourly break lengths of 0, 10, and 20 minutes were evaluated, with break times assumed to be at the end of each hour, since heat exposure generally increased during the course of each hour. Ten and 20 min break lengths per hour were selected based on what has been reported in WA agricultural field work [23], review of the WA Outdoor Heat Exposure rule rest break requirements [10] and WA agriculture required meal and rest periods [29], as indicated in the Supplementary Methods, and science-based guidelines [6,8]. Hourly TWA-$WBGT_{out}$ was calculated as recommended by NIOSH and ACGIH [6,8] and as described in the Supplementary Methods. Hourly TWA-$WBGT_{out}$ and differences from RALs or RELs (TWA-$WBGT_{out}$ – RAL or TWA-$WBGT_{out}$ – REL) were computed, assuming hypothetical work in the mid-row at either light (180W) or moderate (300W) metabolic rate work, for two break locations: mid-row and shade. Positive differences indicate an increased risk of elevated core body temperature and risk of HRI. Negative differences represent exposures below the OEL. Difference values close to zero indicate exposures close to the OEL. Differences were averaged across the 3 study days.

Results

Descriptive exposure analyses

Data were collected in the cherry block from 08:25 −14:18 on Day 1, 07:44–14:14 on Day 2, and 07:21–13:51 on Day 3 and in the grape block from 09:21–14:11 on Day 1, 08:15–13:57 on Day 2, and 07:49–13:55 on Day 3. Across all sampling days, locations, and both crop blocks, QUESTemp° monitors recorded a mean/SD DBT of 31°C (88°F)/3.9°C (6.9°F), with a minimum DBT of 22°C (72°F), a maximum DBT of 39°C (102°F), and a mean/SD RH of 30%/9.6% (range 14–65%). Maximum values of DBT, BGT, WBT, and $WBGT_{out}$ by crop and day are shown in Supplementary Table 1. The mean/SD wind speed across the 3 days was 1.5/0.5 ms^{-1}.

Figures 3 & 4 show DBT, BGT, WBT, and $WBGT_{out}$ over time by crop and location in the cherry and grape blocks. In general, DBT increased over the course of the sampling period each day. BGT tended to be generally lowest in the shade when compared to the open area and mid-row. The difference in $WBGT_{out}$ between the shade and open area appeared to decrease over the course of the day. Time series plots by day are shown in Supplementary Figures 1 & 2 and observations of cloud cover and device sun/shade in the Supplementary Results.

Inferential exposure analyses: $WBGT_{out}$ and BGT

Cherry LMER models—Results from our linear mixed effects model of $WBGT_{out}$ in cherries suggest that no significant differences exist in $WBGT_{out}$ when comparing mid-row to open areas (Table 1). Specifically, $WBGT_{out}$ did not differ when comparing the mid-row to open, both in terms of location (0.83: 95% Confidence Interval [CI]: −0.99,2.66; P=0.37) or the slope for hour (0.09: 95% CI −0.09,0.26; P=0.33). However, the model demonstrated a significant difference in $WBGT_{out}$ between shade and open areas for the main effect and over time, such that $WBGT_{out}$ was 5.14ºC lower in the shade than open (−5.14: 95% CI −6.97,−3.32; P<0.001), with an average 0.34 degree higher rate of $WBGT_{out}$ per hour (slope) for shade relative to open (0.34: 95% CI 0.17,0.51; P<0.001).

Results from our linear mixed effects model of BGT suggest that significant differences exist in BGT when comparing open versus shade and mid-row versus shade. Specifically, BGT was 10.49°C higher in the open versus shade (10.49: 95% CI 5.56,15.41; P<0.001) and 14.33°C higher in the mid-row versus shade (14.33: 95% CI 9.52,19.13; P<0.001). The rate of BGT change per hour (slope) did not differ significantly between open and shade (−0.27: 95% CI −0.73,0.19; P=0.25) and was marginally lower for mid-row than shade (−0.43: 95% CI −0.88,0.02; P=0.06).

Grape LMER models—Our linear mixed effects model of $WBGT_{out}$ in grapes demonstrates no significant difference in $WBGT_{out}$ when comparing mid-row to open areas, while $WBGT_{out}$ was significantly lower in the shade than the open area (Table 2). Specifically, $WBGT_{out}$ did not differ among location (0.39: 95% CI −1.13,1.91; P=0.61) or for the rate of $WBGT_{out}$ change per hour (slope) (0.06: 95% CI −0.08,0.20; P=0.42) when comparing measurements taken in the mid-row versus those in the open. However, the $WBGT_{out}$ was, on average, 6.20°C (−6.20: 95% CI −7.73,−4.67; P<0.001) lower in the shade than in the open area, with an average 0.38 degree higher rate of increase in $WBGT_{out}$ per hour (slope) in the shade relative to open (0.38: 95% CI 0.24,0.52; P<0.001).

Results from our linear mixed effects model of BGT suggest that significant differences exist in BGT when comparing open versus shade and mid-row versus shade. Specifically, BGT was, on average, 14.54°C higher in the open (14.54: 95% CI 10.89,18.20; P<0.001) and 17.10°C higher in the mid-row (17.10: 95% CI 13.44,20.75; P<0.001) versus shade. In addition, on average, there was −0.70 (−0.70: 95% CI −1.03,−0.36; P<0.001) and −0.73 (−0.73: 95% CI −1.06,−0.39; P<0.001) degree reduction in the rate of BGT change per hour (slope) for open and mid-row, respectively, relative to shade.

Sensitivity analyses are presented in the Supplementary Results.

Comparison with occupational exposure limits

Figure 5 shows results of mean differences in hourly TWA-$WBGT_{out}$ exposures compared to NIOSH heat stress RAL and REL OELs for different break locations, workloads, and break times during the 11:00, 12:00, and 13:00 hours in cherry and grape fields. In general, light versus moderate metabolic rate work effort was characterized by reduced exposures and lower average difference (TWA-$WBGT_{out}$ minus OEL) values. Breaks in the shade versus breaks in the mid-row were also associated with smaller average difference values for longer break times, but this effect was not as marked as for reduced work effort.

At the 11:00 and 12:00 hours, the average differences transitioned from around zero or negative (exposures below the REL) to positive (exposures above the REL) when breaks were decreased from 20 to 10 minutes at the end of at the hour (e.g., last 20 and 10 minutes of the hour, respectively) for moderate metabolic rate work effort in the shade. For moderate metabolic rate work effort in the mid-row during the 11:00 and 12:00 hours, differences were above zero (exposures above the REL). At the 11:00 and 12:00 hours, the average difference was around zero or negative (indicating exposures at or below recommended levels) for light work for all non-zero break times. At the 13:00 hour, the average difference was above zero (the measured exposure was above the REL) for moderate metabolic rate work effort when 20-minute breaks were assumed at the end of the hour. At the 13:00 hour, the average difference was close to zero or negative (indicating exposures at or below recommended levels) when performing light work. For RALs, average differences were greater than zero (indicating exceedances of RALs).

Discussion

We examined farmworker-relevant heat exposure among cherry and grape crops during peak temperatures of the WA summer heat season, representing conditions encountered by farmworkers during crop work activities, such as harvesting, and during rest breaks. We found little heat exposure reduction offered by the studied crops in the middle of the rows as compared to open areas, suggesting that shade from crop architecture in our study was not effective in reducing heat exposure. In contrast, store-bought portable shade structures were more effective in minimizing heat exposure than open areas and within crop rows. However, at later times of day with higher heat exposure, differences in overall heat exposure among open, shade, and mid-row locations were reduced. We also found larger reductions in heat stress, and corresponding lower values of differences between exposure and OELs, with assumed reductions in work effort levels compared to breaks in the shade versus the mid-row.

While natural shade may be economical and may also mitigate other exposures such as ultraviolet radiation, crops may not always provide effective or safe shade. For example, the effectiveness of natural shade depends on the density of the foliage and the size of the tree canopy [30]. In an agricultural setting, these factors depend on crop maturity and the type of planting system (e.g., fruiting walls may not provide as much shade as tree canopies). WA’s Outdoor Heat Exposure Rule defines shade as ‘[a] blockage of direct sunlight….’ with the intent of reducing heat stress [10], yet we found no significant difference in $WBGT_{out}$ in cherries or grapes, comparing mid-row to open areas, indicating that some crops do not provide adequate shade. Further, certain crops may harbor pests (e.g., insects), contain skin irritants or sensitizers, be coated with pesticides or herbicides, or have thorns or produce dust, thus exposing workers to competing hazards. Although not evaluated in this study, these characteristics may render certain types of natural shade inadequate, per the definition in the WA Outdoor Heat Exposure rule (….”[s]hade may be provided by any….means that does not expose employees to unsafe or unhealthy conditions and that does not deter or discourage access or use" [10]).

We found that shade from store-bought canopies used in this study was associated with significant (approximately 5–6°C [9–10°F]) reductions in $WBGT_{out}$ compared to open areas. Although US agricultural workers have reported a variety of different types of workplace shade, from trees to work trailers to vehicles to commercial and novel shade structures, to an absence of shade, there are gaps in the systematic evaluation of different types of shade [31–33]. Shade canopies such as the one used in this study are available in local stores, are easy to set up and take down, and are designed to be safe for use. It is possible that a further reduction in $WBGT_{out}$ could be attained with a shade structure or materials more sophisticated than the simple canopy used in this study; however, practicality and acceptability of other options would need to be considered. Future research should build upon this study's comparison of shade from crops and portable canopies to include an evaluation of different types of shade structures' effectiveness towards mitigating BGT and $WBGT_{out}$. Canopy design choices such as cover material, dimensions, awning, usability, and sustainability should be optimized for mitigating heat stress. Structure siting concerns such as the proximity of shade to work, field landscape, and compliance with food safety rules and audits that discourage meal breaks from being taken in close proximity to certain crops require consideration [34,35]. Future research should also assess: the feasibility, safety, barriers, and ease to using different shade approaches, including structures comprised of novel materials and of those that are readily available on farms; employer acceptability and worker use patterns of different shade approaches; and approaches to educate employers and workers about shade best practices.

Despite the 5° to 6°C reduction in $WBGT_{out}$ that our test canopies provided compared to open areas, we found that when breaks are short and infrequent, the influence of shaded breaks on hourly TWA heat exposures is relatively small. Though ideally shade is available during worktime, we assumed that shade was only present during breaks, as required by WA's Outdoor Heat Exposure rule [10]. Factors that dis-incentivize breaks, such as unpaid breaks and piece-rate payment schemes, may further reduce break durations and frequency. Piece-rate payment has been reported to be associated with HRI symptoms and AKI among agricultural workers [36,37]. In WA State's Outdoor Heat Exposure rule, cool-down rest breaks are paid [10].

Reductions in work effort level from moderate to light or 20-minute hourly breaks in the shade during moderate work were characterized by exposures below or near OELs for acclimatized workers (i.e., REL) during the 11:00 and 12:00 hours. During the hotter 13:00 hour, 20-minute hourly breaks in the shade reduced exposures closer to OELs, assuming acclimatized workers, but reductions in effort level from moderate to light with 10-minute hourly breaks reduced exposures below the REL. The WA Outdoor Heat Exposure rule requires mandatory paid rest breaks of 10 minutes every 2 hours at or above 90°F (32°C) and 15 minutes every hour above 100°F (38°C) [10]. These findings highlight that while portable shade structures reduced heat exposure, factors that influenced internal heat generation, particularly effort level but also break frequency and duration, were important for heat stress reduction in our study.

Our research provides only limited information in one field location and two crops over 3 days, utilizing assumptions about effort level, acclimatization, and rest patterns, and comparing measurements to OELs that represent exposure levels at which most healthy hydrated workers can sustain thermal equilibrium. A recent systematic review by Deshayes et al of work–rest regimens under hot conditions reported that most studies to date have investigated work-rest regimens in laboratory settings for short durations among healthy young males [38]. Deshayes et al identified areas for future work-rest research that could inform policies, including studying: 1) workers in real-world field settings to capture actual worker break and pacing behaviors; 2) effects of work-rest regimens on outcomes beyond estimated core body temperature, including fatigue and cognitive performance, which may affect traumatic injury risk; and 3) different work–rest regimens under the same hot conditions among acclimatized and unacclimatized workers. The WA Outdoor Heat Exposure rule indicates that work-rest period requirements will be re-reviewed by the WA Department of Labor and Industries by July 2026 [10]. Further work-rest research could inform this review, and when combined with findings from future research about the most practical, feasible, and effective types of shade, could inform detailed best practice recommendations.

Heat exposure was not below OELs, assuming unacclimatized workers (i.e., RAL), during the 11:00, 12:00, or 13:00 hour, given our study assumptions. This finding underlines the importance of acclimatization, which involves gradual increases in work in the heat to induce protective physiological adaptations [39]. These adaptations include a greater maximum sweat rate, lower body temperature, and reduced cardiovascular strain and can protect against an additional 2–3°C WBGT of heat exposure [40]. Of United States outdoor worker heat deaths, 79% occurred among unacclimatized workers, defined as beginning a new job within the past 2 weeks or returning to work from an absence of more than a week, according to 2011–2016 data [41]. Further research is needed to develop a practical method to determine the level of acclimatization of workers in the field. However, workers who may not be acclimatized and thus may need additional protections can be identified as those who are new to working in the heat, returning from a prolonged absence, or working during sudden increases in heat stress. Shifting work to cooler parts of the day should also be considered, taking care not to introduce other hazards related to poor lighting, insufficient sleep, or unnecessary reduction in work hours resulting in a reduction of eligibility for overtime pay to which farmworkers in WA are entitled [42].

Strengths and Limitations

Our study is the first to examine variation in farmworker-relevant heat exposure in open sun, within crop rows, and under store-bought portable shade structures. Our study has notable limitations. We conducted observations over only 3 days (max mid-row dry air temperature for each sampling day, averaged across crops, ranging from 98.2–99.5°F) within two crops in Central WA, so our results may not be generalizable to other crops, shift periods, locations, or environmental conditions with more heat or humidity. Our study did not examine how the siting of portable shade structures (e.g., elevation, geospatial coordinates) impacts exposure. Finally, our exposure measurements were taken at fixed points rather than personal monitors on actual workers, so our measurements may not fully represent actual worker heat stress, which may vary at an individual level.

Conclusions

Our results address an important gap in the literature, suggesting that common practices to reduce heat stress, including worker breaks under natural or artificial shade sources, may vary in effectiveness depending upon shade type, time of day, and duration of breaks in the shade. We also confirm that addressing effort level is an important consideration in heat stress mitigation strategies. Our findings inform future research to better understand the effectiveness, feasibility, and acceptability of different shade sources and work-rest strategies. Results of future work can inform specific workplace best practice strategies and policies to reduce heat stress among agricultural workers by optimizing work-rest cycles, shade strategies, and shift times during periods of high heat.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability statement:

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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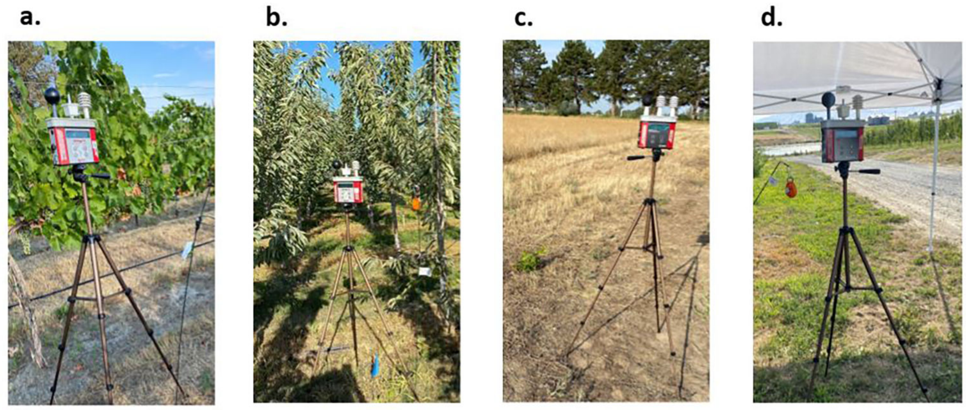

Figure 1.
Examples of sampling in grape and cherry blocks. **a)** Mid-row grapes, **b)** Mid-row cherries, **c)** Open area grapes, **d)** Shaded area cherries. Orange devices are D2 DROP wireless temperature and humidity data loggers (Kestrel ®, Pennsylvania, USA), which were deployed, but data from these instruments were not analyzed for this study.

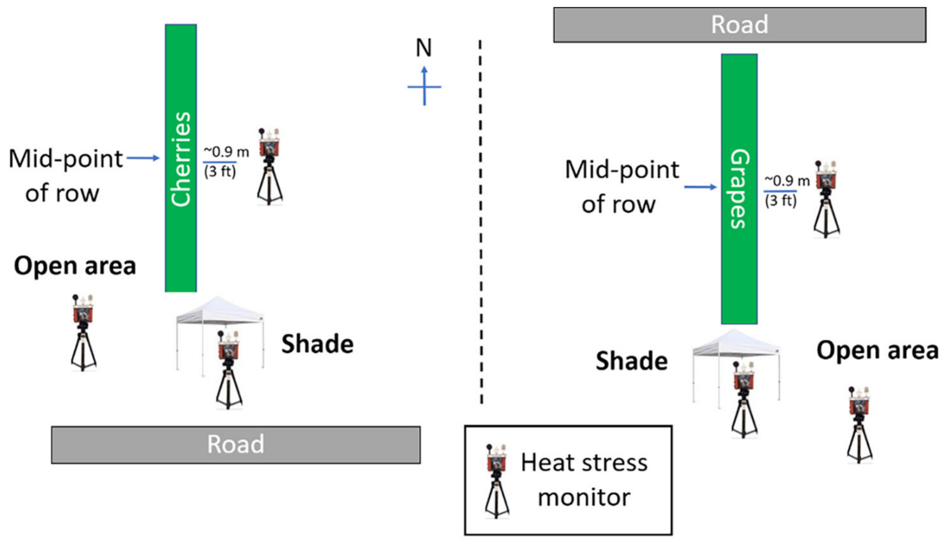

Figure 2.
Sampling plan

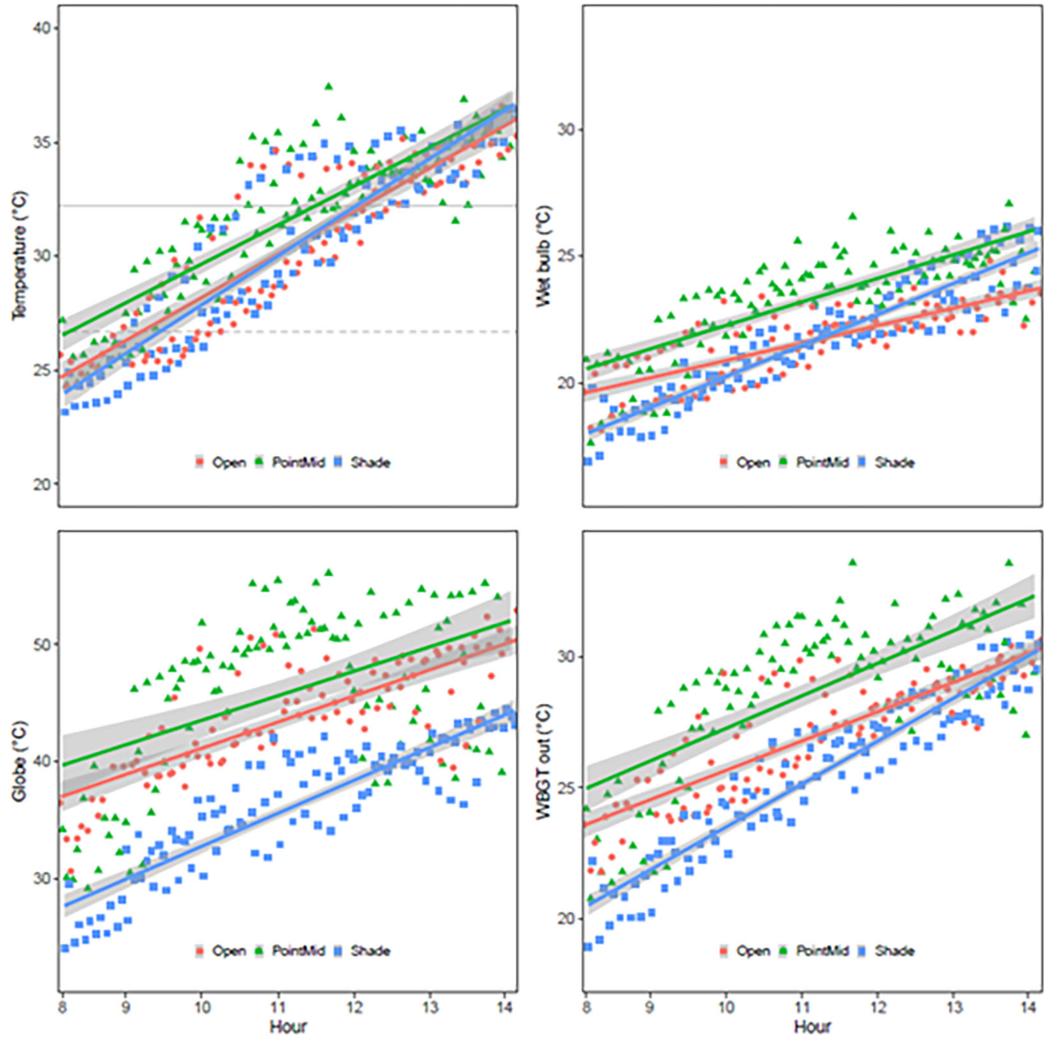

Figure 3.
Dry Bulb Temperature, Black Globe Temperature, Wet Bulb Temperature, and $WBGT_{out}$ over time by location in the cherry block
Best fit lines (temperature on hour) and 95% confidence intervals are for Days 1–3
Note: Dashed gray line = 27°C (80°F), solid gray line = 32°C (90°F)

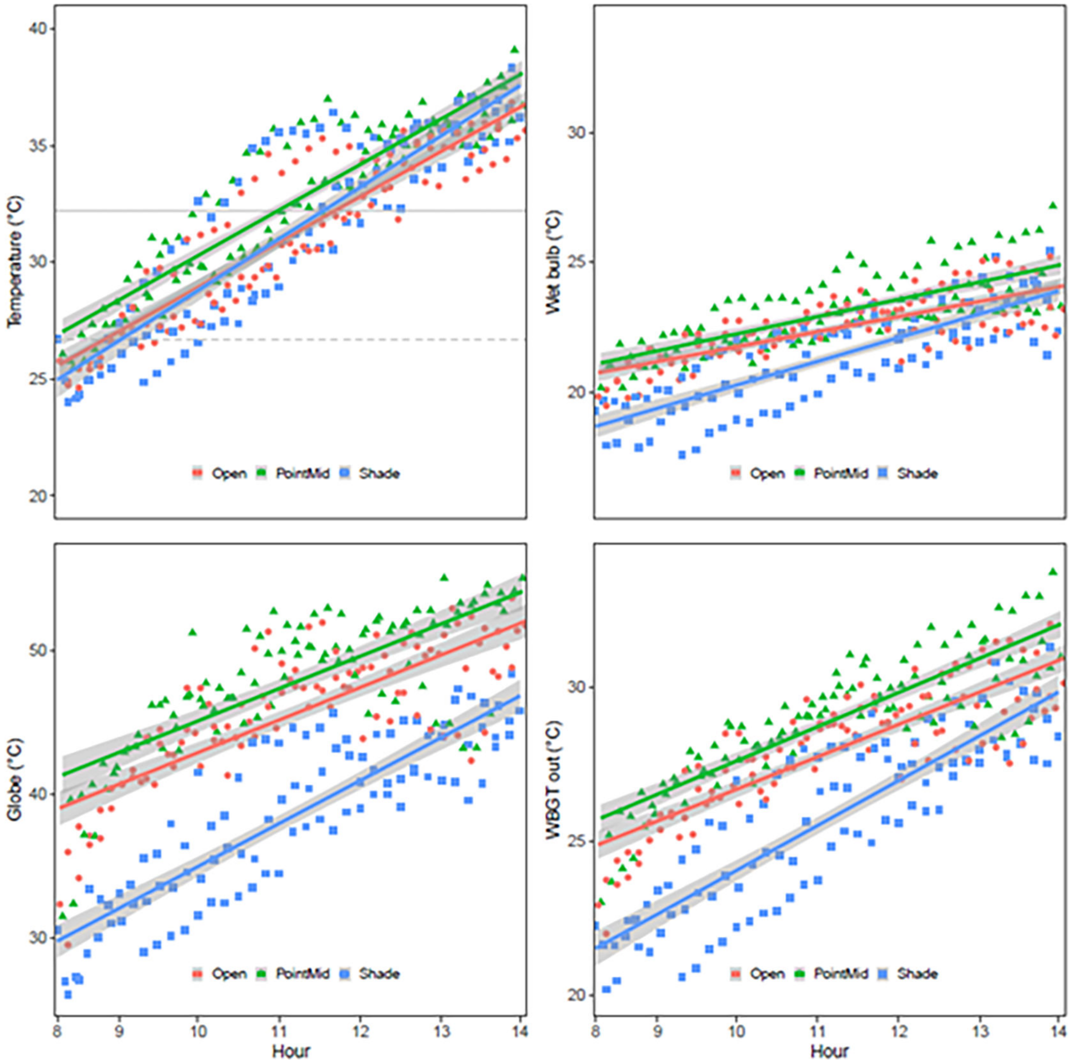

Figure 4.

Dry Bulb Temperature, Black Globe Temperature, Wet Bulb Temperature, and $WBGT_{out}$ over time by location in the grape block

Best fit lines (temperature on hour) and 95% confidence intervals are for Days 1–3

Note: Dashed gray line = 27°C (80°F), solid gray line = 32°C (90°F)

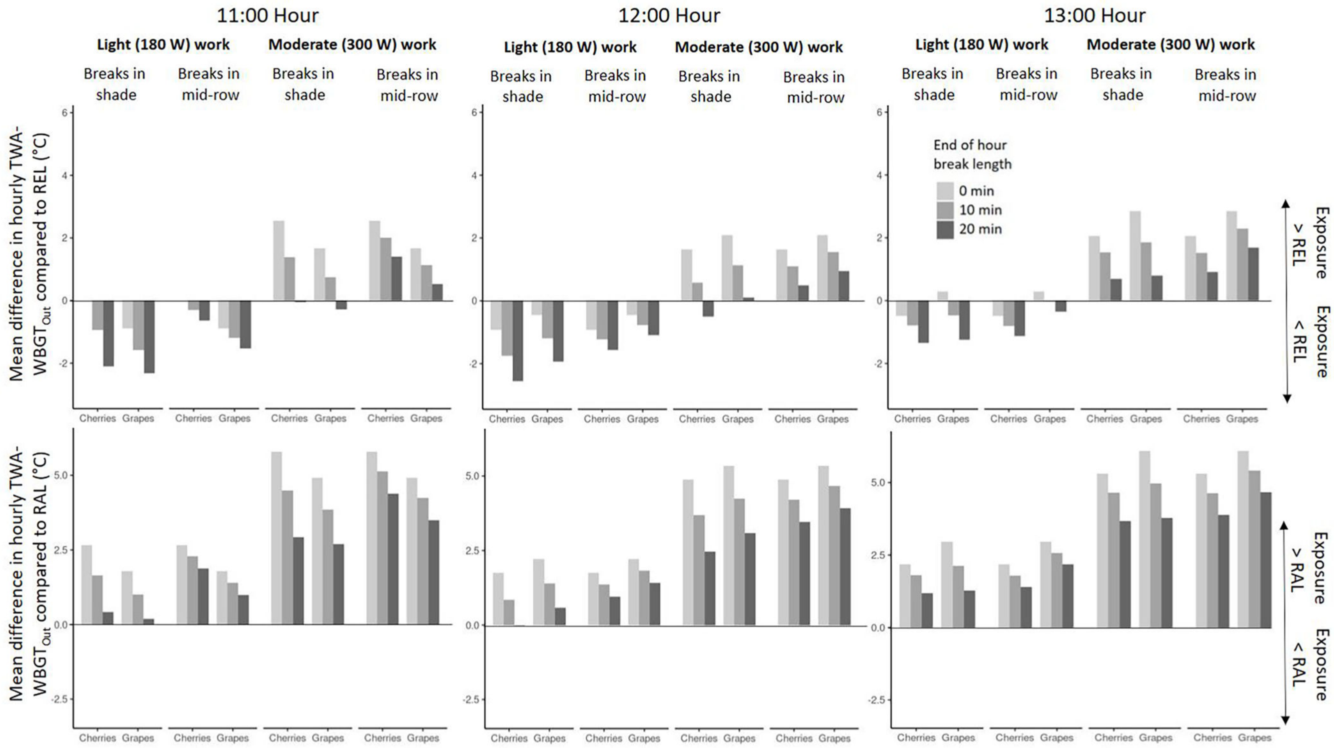

Figure 5.

Differences** in hourly $WBGT_{out}$ exposures from NIOSH heat stress RALs and RELs for different break locations, workloads, and break times in cherry and grape fields

**Differences were computed as hourly TWA-$WBGT_{out}$ – RAL or hourly TWA-$WBGT_{out}$ – REL. The Recommended Exposure Limit (REL) represents the exposure level at which most healthy hydrated acclimatized workers can sustain thermal equilibrium, and the Recommended Alert Limit (RAL) represents the exposure level for most healthy hydrated unacclimatized workers [6].

Mean differences across the 3 study days are plotted.

Positive differences indicate an increased risk of elevated core body temperature and risk of heat-related illness. Values close to zero indicate exposures close to the recommended limits. All scenarios assumed regular work clothes.

Table 1.

Multivariable linear mixed effects models for cherries

Effect		$WBGT_{out}$ Estimate (Standard Error; 95% Confidence Interval)	Black Globe Temperature Estimate (Standard Error; 95% Confidence Interval)
Location	**Open**	Ref	10.49 (2.50; 5.56, 15.41) *
	Mid-row	0.83 (0.93; −0.99, 2.66)	14.33 (2.44; 9.52, 19.13) *
	Shade	−5.14 (0.93; −6.97, −3.32) *	Ref
Hour		1.16 (0.13; 0.91, 1.40) *	2.59 (0.35; 1.90, 3.29) *
Location*Hour	**Open**	Ref	−0.27 (0.23; −0.73, 0.19)
	Mid-row	0.09 (0.09; −0.09, 0.26)	−0.43 (0.23; −0.88, 0.02) ^
	Shade	0.34 (0.09; 0.17, 0.51) *	Ref

* $p \leq 0.001$;

^ $p = 0.06$

Reference (ref) categories: Open for $WBGT_{out}$ and shade for BGT

Table 2.

Multivariable linear mixed effects models for grapes

Effect		$WBGT_{out}$ Estimate (standard error; 95% confidence interval)	Black Globe Temperature Estimate (standard error; 95% confidence interval)
Location	**Open**	Ref	14.54 (1.86; 10.89, 18.20)*
	Mid-row	0.39 (0.77; −1.13, 1.91)	17.10 (1.86; 13.44, 20.75)*
	Shade	−6.20 (0.78; −7.73, −4.67)*	Ref
Hour		0.99 (0.12; 0.75, 1.22)*	2.77 (0.30; 2.18, 3.36)*
Location*Hour	**Open**	Ref	−0.70 (0.17; −1.03, −0.36)*
	Mid-row	0.06 (0.07; −0.08, 0.20)	−0.73 (0.17; −1.06, −0.39)*
	Shade	0.38 (0.07; 0.24, 0.52)*	Ref

*p≤0.001

Reference (ref) categories: Open for $WBGT_{out}$ and shade for BGT