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Comparison of Shade Materials for Agricultural Worker Heat Exposure Mitigation

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ABSTRACT

Objectives: Agricultural workers are at high risk of morbidity and mortality from workplace heat stress. Shade contributes to reduced heat exposure by blocking solar radiation. Though several US states have adopted occupational heat rules that require shade, implementation of specific shade approaches is typically not specified in rules. We compared different shade materials for agricultural worker heat exposure mitigation to inform decision-making.

Methods: We conducted a quantitative field comparison study over three summer days in a real-world agricultural setting in Central Washington State. We examined the effect of five different shade materials on solar radiation and heat exposure, measured using Black Globe (BG) and Wet Bulb Globe Temperature (WBGT) sensors, respectively. We used multivariable linear mixed-effects regression to examine the effect of different materials on BG and WBGT while accounting for repeated measures and small cluster sizes. We also performed a qualitative assessment of shade preferences among agricultural partners, including workers and supervisors.

Results: The mean (SD) dry air temperature across all study days was 28.3(1.3)°C [82.9(2.4)]°F. Shade materials reduced BG by 6.1–8.8°C and WBGT by 1.7–2.2°C, on average, depending on the material, compared to no shade. Compared to no shade, the largest reduction in BG (−8.81ºC) was seen for a hay tarp material (HAY: 95% Confidence Interval [CI]: −9.39, −8.23) followed by an 80% monofilament material (M80: −7.68°C; 95%CI −8.27,-7.10). For WBGT, we also found the largest reductions among HAY (−2.22°C; 95%CI −2.44,-2.00) and M80 (−2.07°C; 95%CI −2.29,-1.84). Comparing between shade materials, we did not find substantial differences in BG and WBGT. Ease of use and mobility of shade structures near work locations, in addition to effectiveness in reducing heat exposure, was identified in qualitative analyses as factors that may influence workplace shade implementation decisions.

Conclusions: In this study, we found that all studied shade materials significantly reduced BG and WBGT compared to no shade, but we observed no substantial differences in heat exposure mitigation between the shade materials themselves. For similarly performing shade materials, worker and supervisor preferences and practical considerations should be considered when selecting shade approaches in specific workplaces that are likely to be adopted and sustained.

KEYWORDS
Farmworker; heat exposure; heat stress; shade

Introduction

Agricultural workers are at high risk of morbidity and mortality from workplace heat stress. United States (US) Bureau of Labor Statistics data indicate that the agricultural industry has 35 times the rate of occupational heat-related deaths compared to all industries.[1] Occupational heat stress is associated with heat-related illnesses, which can be fatal,[2] heat-related traumatic injuries,[3] and acute kidney injury[4] among agricultural workers. Workers who are new to the job, returning from a prolonged absence or working at the onset of a heat wave may not be heat acclimatized and may be at increased risk of heat-related illness.[5] Acclimatization is physiological adaptation that occurs during repeated exposure to a hot environment.[6] Extreme heat events, which increase the risk of heat-related illness for workers, are projected to increase in frequency and intensity in the future.[7] During the US Pacific Northwest extreme heat dome event from June 25–30, 2021, there was an increase in

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Washington State Fund workers' compensation claims for occupational heat-related illness, with the top number of claims occurring among farmworkers and laborers.[5]

Occupational heat stress is comprised of ambient heat exposure, internal body (i.e., metabolic) heat from physical work, and clothing that impairs body heat dissipation, such as non-breathable personal protective equipment.[2] Ambient heat exposure can be measured with a Wet Bulb Globe Temperature (WBGT) monitor, which consists of a dry air sensor to measure air temperature, a wet bulb sensor to measure humidity, and a black globe sensor to measure radiant heat (e.g., sun).[2] These parameters are combined to assess WBGT, a gold standard metric of net heat exposure.[2] Controls that reduce metabolic heat, such as administrative rest breaks, and that reduce radiant heat, such as shade, can help to reduce overall heat stress in outdoor environments where engineering controls such as air-conditioning are not practical.[2]

Several states, including California,[8] Washington State (WA),[9] Oregon,[10] Colorado,[11] Nevada,[12] and Maryland,[13] have adopted occupational heat rules or laws that cover outdoor agricultural workers and are intended to reduce adverse health effects of workplace heat stress. Additionally, in 2023, the US Occupational Safety & Health Administration (OSHA) proposed an indoor and outdoor occupational heat rule.[14] These rules include requirements for hydration, shade, and other protections. However, specifics for how shade, and other provisions such as hydration and rest, can be implemented may not be fully specified in rules, and additional research could inform which approaches may be most effective. In the interim, employers must decide how to implement protections.

Few studies have systematically characterized the prevalence of employer-provided shade in agricultural settings. Results from in-person interviews of farmworkers in Georgia, where there is no state heat rule, suggested that about one-third of workers had no access to shade.[15] A survey study of WA crop workers in 2013 reported that the majority (92%) of workers reported access to shade from trees at work.[16] However, our previous study of heat exposure in WA field conditions indicated that pop-up shade canopies but not cherry trees or grape crops, were associated with substantial reductions in heat exposure measured using a WBGT monitor, suggesting that the crops studied were not effective sources of shade.[17] Although a more humid setting, a study in North Carolina similarly found higher WBGT in the center of tall-growing sweet corn and tobacco fields compared to the field perimeter.[18]

Agricultural workers in the US have reported a variety of different types of workplace shade approaches, including trees, vehicles, commercial shade structures, and an absence of shade.[15,17,19] In WA, some growers have used crops and pop-up shade canopies, others are experimenting with mounting shade cloths on posts, and tractor stores are starting to sell mobile shade trailers (2025 personal communication of the Pacific Northwest Agricultural Safety & Health Center with JTS). There are several studies evaluating tent cover materials used by the unhoused in hot climates,[20,21] but research on approaches to shade materials relevant to agricultural workers is limited. Additional information on the effectiveness, feasibility, and acceptability of different shade approaches is needed to guide recommendations for rule implementation.

The overall objectives of this study were to compare different shade materials and approaches for agricultural worker heat exposure mitigation and to determine agriculture partner shade preferences. WA's permanent outdoor heat exposure rule was updated in 2023 to require shade above an ambient temperature of 80°F.[9] The results of the study are intended to assist growers in WA and states with similar climates, populations, and settings with decisions about which shade materials and approaches to implement to protect workers from heat exposure.

Methods

Quantitative study

Study site, location, and timeframe

The quantitative study was conducted by the Washington State Labor and Industries' (L&I) Safety & Health Assessment and Research for Prevention (SHARP) Program in Central/Eastern

WA, a dry (18–23 cm [7–9 in] of rainfall annually) agriculturally intensive area with mean maximum summer temperatures of 27–34°C (high 80 to mid-90s°F).[22] The study was conducted in an open field covered with dirt and patchy ground cover at Washington State University's (WSU) Irrigated Agriculture Research and Extension Center (IAREC), in Benton County, Central/Eastern WA (Figure 1). As previously described,[17] IAREC is comparable to real-world agricultural work settings because of its commercial-grade crop blocks consisting of typical regional crops. Apples, hops, and grapes are among the 10 agricultural commodities with the highest production value in WA, and WA is the number one producer of apples, hops, and cherries in the US.[23] The study took place on August 19–21 (Days 1–3), 2024, a typically hot time of year in Central/Eastern WA.

Figure 1. Study site with different shade materials mounted on canopy frames.

Shade materials

Five shade materials plus one control (no shade material) condition were evaluated. The shade materials were selected because they were of interest to agricultural partners, as determined through conversations with WA L&I's Division of Occupational Safety & Health Outreach staff and the Pacific Northwest Agricultural Safety and Health Center, who directly interact with employers and workers. All shade conditions consisted of shade material mounted on one of the six gazebo-style 3.05 m ×3.05 m (10 ft × 10 ft) steel straight leg simple push canopy frames with a center height of 2.82 m (9.25 ft, Ozark Trail® Outdoor Equipment, Bentonville AR). The materials were placed on the tops of the frames with all sides open to the ambient air. The control condition of No Shade (NOS) was a canopy frame with no mounted material. Details of the materials are provided in the Supplementary Methods. In brief, Material one (CAN) was a heavy-duty light grey material with a reflective undercoating. Material two was a thick hay tarp (HAY) with a white outer color and a black underside that was mold, mildew and acid resistant. Material three was highly reflective aluminized shade fabric (A70) with a shade percentage rating of 70–75%. Material four was SilviShade (S80), a highly reflective aluminized shade fabric with a shade percentage rating of 80%. Material five was a black monofilament shade cloth (M80) with a shade percentage rating of 80%. Through visual inspection, the authors subjectively determined that HAY had the least porosity to permit wind passage, while A70 was determined to be the most porous allowing wind to pass.

Instruments, sampling plan, data download & processing

Figure 2 shows the locations of the shade materials, which were randomized on the first day and systematically rotated on each subsequent day to ensure materials did not end up in the same position on consecutive days by chance. Shade canopies were spaced 3.05 m (10 ft) apart along a north–south transect to avoid shading of one canopy by another.

Six portable heat exposure monitors were mounted on six 1.14 m (3.75 ft) high tripods

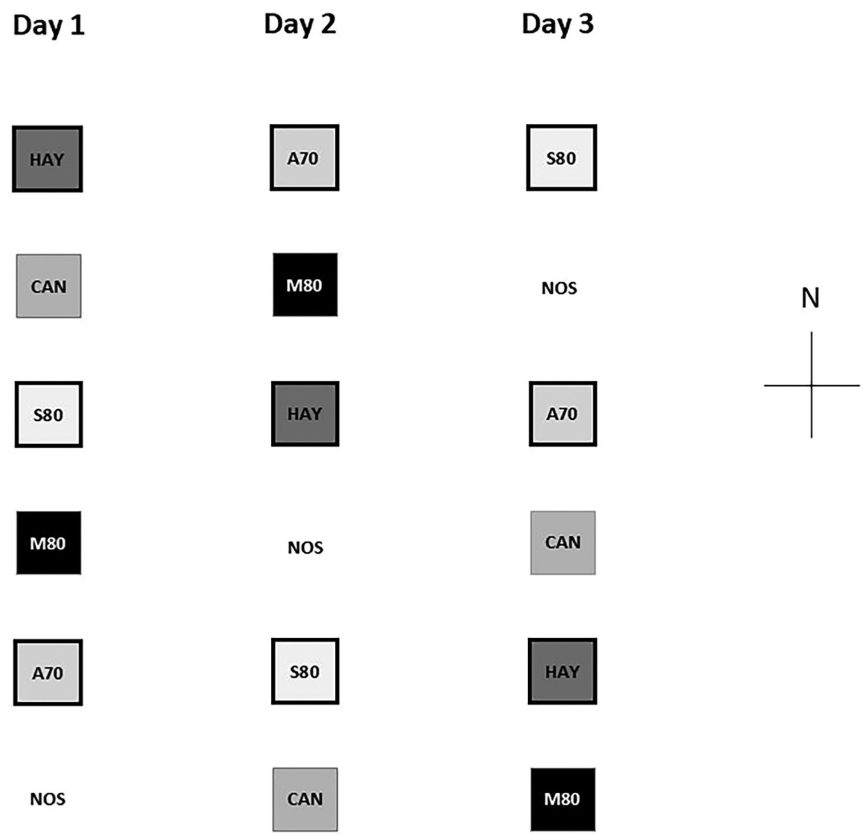

Figure 2. Placement of shade materials relative to each other on each study day.

placed under each canopy frame to measure the dry bulb (DB) temperature, wet bulb (WB) temperature, black globe (BG) temperature, and relative humidity (QUESTemp° Model 34, TSI®/Quest, Shoreview MN). Outdoor and indoor WBGT, or $WBGT_{out}$ and $WBGT_{in}$, respectively, were calculated and reported by the QUESTemp° using the equations in the Supplementary Methods. The position of each monitor under its canopy was adjusted approximately every 30 min to ensure it was always under cover of shade and never in direct sunlight.

Data were logged at 10-min intervals and downloaded daily to Microsoft Excel on a laptop computer using an RS-232 communication cable and TSI Quest™ Detection Management Software (Version 3.2.3.14, TSI Incorporated, Shoreview, MN). The first 20 min of each day's measurements were removed from the dataset after sensors were placed under canopies or NOS to account for the time it took the monitors to equilibrate. We restricted our analysis to data points where the NOS DB was at or above 26.7°C (80°F), since WA's current permanent outdoor heat exposure requires shade above 80°F.[9] Data from 15:10 to 16:18 on Day 1, 12:35 to 16:26 on Day 2, and 13:25 to 16:29 on Day 3 were analyzed. Wind speed was assessed using data from WSU's AgWeatherNet weather station network.[24]

Quantitative analyses

The primary objective of our quantitative analysis was to assess the effectiveness of commonly used shade materials (CAN, HAY, M80, S80, A70) on reducing heat exposure, when compared to the absence of shade (i.e., NOS). We selected BG temperature as an outcome of interest because we aimed to evaluate the effectiveness of different materials on blocking the sun, specifically. As an additional outcome of interest, we examined how shade materials may impact $WBGT_{out}$. We focused on $WBGT_{out}$ rather than $WBGT_{in}$ because shade materials do not fully block solar radiation, but we also examined $WBGT_{in}$ in sensitivity analyses. Our study conditions were relatively dry (mean relative humidity across all sampling days 20.6–24.6%, depending on the shade condition), and therefore humidity was not expected to play as prominent a role in "real feel" temperature as in hot humid climates.

We conducted several secondary analyses to address the following questions that we anticipated might arise when agricultural supervisors make decisions about shade: 1) Is there a difference in sun blockage between aluminized (reflective) versus black monofilament (absorbent) materials?; 2) Is there a difference in sun blockage between materials with different shade percentage ratings?; and 3) Is there a difference in net heat exposure between non-porous and porous materials? To address these questions, we examined: 1) the difference between the aluminized materials A70 and S80 versus the monofilament M80 (reference) on BG; 2) the difference between the different percentage rating materials S80 and M80 versus A70 (reference) on BG; and 3) the difference between the potentially least porous material (HAY) and the potentially most porous material (A70, reference) on $WBGT_{out}$, as WBGT is affected not only by solar radiation but also by humidity and wind speed.

Data analyses

We conducted descriptive data analyses to characterize variation by different materials and NOS over time and on different days in terms of BG and $WBGT_{out}$. Multivariable linear mixed-effects regression (LMER) models were used to examine potential variation in heat exposure mitigation (BG and $WBGT_{out}$) among different shade materials and NOS over time. LMER model structures were identical for BG and $WBGT_{out}$. Shade materials were included as a fixed factor, while hours nested within days (hours per day among three sample days) were included as a random factor. Presented model results, such as confidence intervals and *p*-values, utilized the Kenward and Roger degrees of freedom correction for small cluster sizes.[25] Analyses were conducted using R, version 4.2.0 (Vienna, Austria).[26] The lme4 package and LMER modeling function were utilized to derive model estimates.[27]

Qualitative assessment

To provide additional contextual information about worker and supervisor shade preferences, the research team collaborated with the Pacific Northwest Agricultural Safety & Health (PNASH) Center to collect information from attendees, including workers and supervisors, at local WA agricultural safety and health conferences in 2025. Research team members displayed examples of shade materials used in the quantitative study at the PNASH Center booth and asked respondents multiple choice and open-ended questions focused on shade decision-making factors, preferences (e.g., for shade materials and design), and which of the studied shade materials are preferred and why. The research team recorded responses, job title/role, and crop worked in Spanish or English on a paper form from individual respondents or groups of respondents who visited the booth. The research team did not offer incentives for participation.

Information from the paper forms was entered in Spanish or English into an electronic database. Responses from participants working in Washington State were included in the analysis. Demographic information was described and tabulated. Each member of the Spanish/English bilingual/bicultural research team (ECS, SFA, MB) independently developed themes and codes, which through consensus were then consolidated into a single codebook of categories and definitions. To ensure inter-analyst agreement, two research team members independently coded each question. The research team discussed and resolved incongruities between coders. The qualitative study was reviewed and determined to be exempt by the Washington State Institutional Review Board.

Results

Quantitative study

Descriptive results

The study sample, which was restricted to measurements at times when the NOS DB was at or above 26.7°C (80°F), consisted of 284 observations. Table 1 shows heat exposure metrics summarized by material. Figures 3 and 4 show BG and

Table 1. Heat exposure metrics by shade material across all three sampling days in the study sample ($N = 284$)*.

	$WBGT_{out}$ (°C)		BG (°C)		WB (°C)		DB (°C)		RH (%)	
Shade material	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)
NOS	24.1 (1.1)	24.1 (22.0, 27.0)	41.4 (3.3)	42.3 (35.0, 47.5)	18.6 (0.6)	18.5 (17.5, 20.6)	28.3 (1.3)	27.8 (26.9, 31.7)	20.6 (2.1)	20.5 (17.0, 24.0)
A70	22.5 (0.9)	22.4 (20.9, 24.3)	35.3 (2.1)	35.4 (31.6,40.2)	18.0 (0.6)	17.9 (16.9, 19.4)	28.0 (1.4)	27.7 (26.1, 31.9)	22.3 (3.0)	22.0 (16.0, 28.0)
CAN	22.3 (0.9)	22.3 (20.5, 24.2)	34.4 (2.1)	34.2 (30.5, 38.5)	18.1 (0.6)	18.0 (16.8, 19.4)	28.1 (1.5)	27.7 (26.2, 31.7)	24.1 (2.8)	24.5 (18.0, 29.0)
S80	22.2 (1.0)	22.0 (20.6, 24.6)	34.7 (2.1)	34.6 (31.0, 38.6)	17.8 (0.7)	17.6 (16.9, 19.9)	27.9 (1.6)	27.4 (25.9, 31.7)	24.2 (2.5)	25.0 (18.0, 28.0)
M80	22.1 (0.8)	22.0 (20.7, 23.9)	33.7 (1.9)	34.0 (30.4, 37.5)	17.9 (0.6)	17.7 (16.9, 19.3)	28.1 (1.3)	27.7 (26.5, 31.3)	24.1 (3.4)	24.0 (17.0, 30.0)
HAY	21.9 (0.7)	21.8 (20.4, 23.6)	32.6 (1.7)	32.6 (28.9, 35.7)	18.0 (0.4)	17.9 (17.1, 19.2)	28.1 (1.4)	27.8 (26.2, 31.2)	24.6 (3.9)	24.0 (17.0, 30.0)

A70 = Aluminet®; BG = black globe temperature; CAN = canopy cover; DB = dry air temperature; HAY = hay tarp; M80 = monofilament shade cloth; NOS = no shade; RH = relative humidity; S80 = SilviShade; SD = standard deviation; WB = wet bulb temperature; $WBGT_{out}$ = wet bulb globe temperature (outdoor) calculated as $WBGT_{out} = 0.7\,WB + 0.2BG + 0.1\,DB$.
*Study sample is limited to measurements at times when NOS dry air temperature ≥ 80°F/26.7°C.

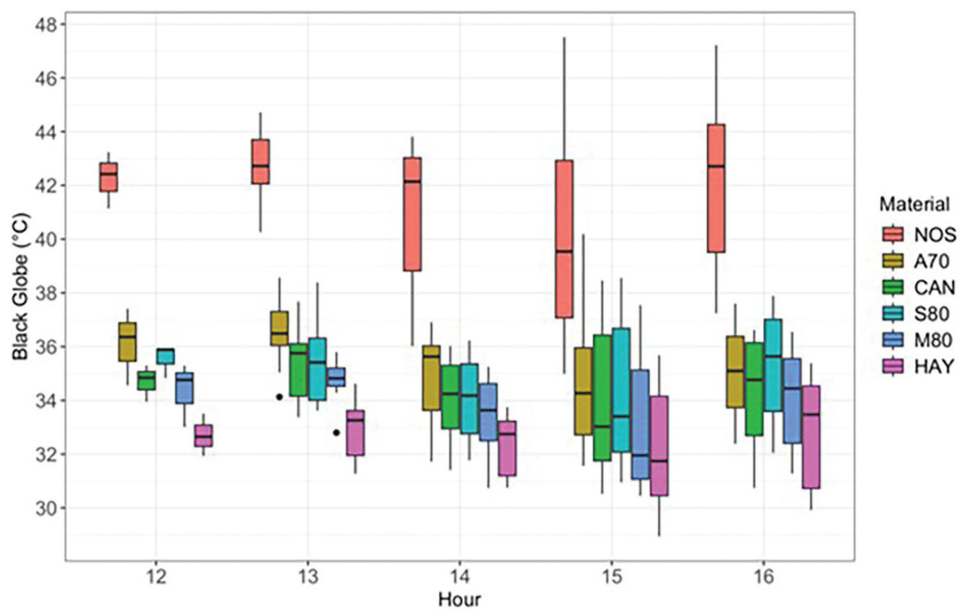

Figure 3. Black globe temperature (BG) per hour by shade material, averaged across all three sampling days in the study sample ($N = 284$)*.
A70 = Aluminet®; CAN = canopy cover; DB = dry air temperature; HAY = hay tarp; M80 = monofilament shade cloth; NOS = no shade; S80 = SilviShade.
*Study sample is limited to measurements at times when NOS dry air temperature ≥ 80°F/26.7°C; intermittent clouds present at hours 14, 15, and 16

$WBGT_{out}$, respectively, over time by material, across sampling days in the study sample. Across all study days, the mean (SD) NOS DB was 28.3 (1.3)°C, the mean (SD) of the daily maximum NOS DB was 30.0 (1.7)°C, and the mean wind speed was 2.2 (0.4) m/s. The mean (SD) BG was highest for the NOS condition 41.4 (3.3)°C and lowest for HAY 32.6 (1.7)°C (Table 1). HAY had the highest mean RH (24.6%) and NOS the lowest (20.6%) (Table 1). As shown in Figures 3 and 4 and Table 1, BG and $WBGT_{out}$ were lower among shade conditions relative to NOS. Specifically, mean BG was highest for NOS, followed by A70, S80, CAN, M80, and HAY, while mean $WBGT_{out}$ was highest for NOS, followed by A70, CAN, S80, M80, and HAY. In general, increased variability in

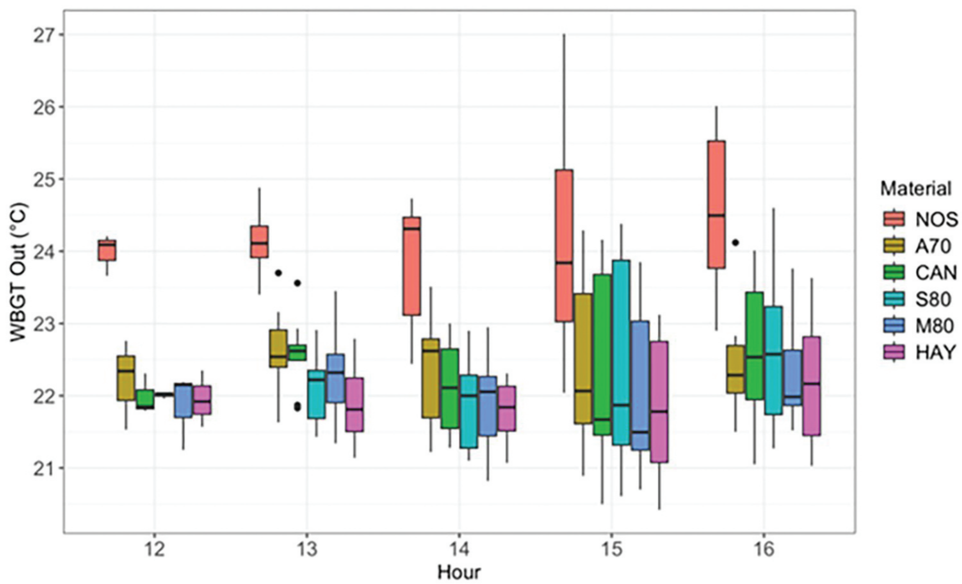

Figure 4. $WBGT_{OUT}$ per hour by shade material, averaged across all three sampling days in the study sample ($N = 284$)*.
A70 = Aluminet®; CAN = canopy cover; DB = dry air temperature; HAY = hay tarp; M80 = monofilament shade cloth; NOS = no shade; S80 = SilviShade.
*Study sample is limited to measurements at times when NOS dry air temperature ≥ 80°F/26.7°C; intermittent clouds present at hours 14, 15, and 16.

BG and $WBGT_{out}$ was observed later in the afternoon (Figures 3 and 4), consistent with intermittent cloud cover later in the day. Heat exposure metrics summarized by day are presented in Supplementary Table 1, and BG and $WBGT_{out}$ time-series plots in Supplementary Figures 1 & 2.

Inferential results

Results from our linear mixed-effects models of BG and $WBGT_{out}$ by material show significantly lower BG and $WBGT_{out}$ in all shade conditions compared to no shade (Table 2). The largest reduction in BG (−8.81 °C) was seen for HAY (95% Confidence Interval [CI]: −9.39, −8.23) followed by M80 (−7.68°C; 95%CI −8.27, −7.10), with the smallest reduction for A70 (−6.10°C; 95% CI: −6.68, −5.53). The magnitude of the effect of shade material on temperature was generally smaller for $WBGT_{out}$ than for BG.

Secondary analyses identified a marginally higher BG temperature for A70 (1.58°C; 95% CI: 1.07, 2.09; $p \leq .001$) and S80 (1.00°C; 95% CI: 0.50, 1.51; $p \leq .001$), compared to M80, suggesting only a small difference in sun blockage between aluminized versus monofilament materials. BG was slightly lower for 80% material S80 (−0.58°C, 95% CI: −1.08, −0.07; $p = .025$), compared to 70% material A70, suggesting only a very small difference in BG in these shade percentage ratings. Finally, $WBGT_{out}$ was slightly lower for HAY (−0.56°C, 95% CI: −0.78, −0.34; $p \leq .001$), compared to A70, suggesting only a very small difference between non-porous and porous materials.

Inferences were similar when we substituted $WBGT_{out}$ with $WBGT_{in}$ and after accounting for intermittent cloud cover in sensitivity analyses (Supplementary Methods & Supplementary Table 2).

Table 2. Multivariable linear mixed-effects models of black globe and $WBGT_{out}$ by shade material.

Effect		BG Estimate (Standard Error; 95% Confidence Interval)	$WBGT_{out}$ Estimate (Standard Error; 95% Confidence Interval)
Condition	NOS	Ref	Ref
	A70	−6.10 (0.29; −6.68, −5.53)*	−1.66 (0.11; −1.88, −1.44)*
	CAN	−7.00 (0.30; −7.58, −6.41)*	−1.78 (0.11; −2.00, −1.55)*
	HAY	−8.81 (0.30; −9.39, −8.23)*	−2.22 (0.11; −2.44, −2.00)*
	M80	−7.68 (0.30; −8.27, −7.10)*	−2.07 (0.11; −2.29, −1.84)*
	S80	−6.68 (0.29; −7.26, −6.10)*	−1.94 (0.11; −2.16, −1.71)*

*$p \leq .001$.
BG = black globe temperature; $WBGT_{out}$ = wet bulb globe temperature (outdoor).

Qualitative assessment

Qualitative results are reported by encounter, as some respondents encountered the research booth as individuals and others as groups. We recorded a total of 40 encounters (individual or group), which included 94 individuals. Crop and job title categories were not mutually exclusive (i.e., some groups contained individuals in more than one category). The majority of encounters involved employees in tree fruit ($n = 33$), followed by hops ($n = 6$), with only a few ($n = 3$) involving employees in blueberries and vineyards (**Supplementary Table 3**). The majority of encounters involved manager/supervisors ($n = 18$) or general laborers ($n = 11$), with fewer involving mechanics ($n = 5$), pesticide sprayers ($n = 6$), tractor drivers ($n = 3$), or human resources/administrative/office employees ($n = 8$). Among encounters ($n = 40$) reporting shade preferences, the most common preference was for mobile shade trailers movable by vehicles. Mobile shade trailers are often fitted with bench seats and have a fixed overhead roof made of solid materials like sheet metal. The next most commonly reported shade preferences were monofilament material, canopy, and hay tarp. Across worker job titles of general laborers, pesticide sprayers, mechanics, and tractor drivers, preferences were for shade mobility (e.g., ability to move the shade to where workers are working), followed by ease of use (e.g., not too labor intensive or time intensive to take up and put down) and effectiveness in protecting from heat and sun. Among encounters that included managers/supervisors, preferences included ease of use, followed by mobility and effectiveness in protecting from heat, sun protection, material breathability (e.g., ability to withstand wind), durability, and cost. Workers named additional preferences to accompany shade such as cool drinking water, seating, restrooms and handwashing stations that are not too far away, sufficient shaded space, and air conditioning.

Discussion

In our study evaluating different shade materials, we found that all evaluated materials significantly reduced BG and $WBGT_{out}$ compared to no shade. However, there were minimal differences in mitigation of BG and $WBGT_{out}$ between most of the studied materials. Workers and supervisors provided different perspectives about shade approaches. Our qualitative results indicated that factors such as ease of use and shade mobility may influence shade implementation decisions in the workplace.

The studied shade materials reduced BG by an average 6.1–8.8°C and $WBGT_{out}$ by an average 1.7–2.2°C, depending on the material, compared to no shade. This magnitude of effect is consistent with studies compiled in a literature review of heat stress alleviation practices among dairy cows, which reported reductions in BG temperature from 2°C to 11°C under different artificial shade materials compared to no shade.[28] A previous study, at the same location as the current study, of pop-up shade canopies with the CAN material, compared to open areas without shade, reported a 5.1–6.2°C lower $WBGT_{out}$.[17] The difference in magnitude of the decrement in $WBGT_{out}$ in shade compared to the present study may be attributed to the sunnier and hotter conditions in the previous study compared to the current study (mean dry air temperature 31°C [88°F] versus 28°C [82°F], respectively). Previous studies comparing shaded conditions among dairy cattle with no shade have reported the greatest effect of shade on heat exposure during the hottest and sunniest times of day.[29] Our estimates of mitigation by shade materials of BG and $WBGT_{out}$ may therefore be underestimates compared to shade mitigation in hotter and sunnier settings and climates.

The magnitude of $WBGT_{out}$ (total heat exposure) mitigation by shade materials, compared to no shade, was generally lower than for BG. $WBGT_{out}$ is a weighted sum of WB (70%), BG (20%), and DB (10%).[2] WB and DB did not vary considerably between materials, so differences in $WBGT_{out}$ mitigation were driven by differences in BG. Despite the relatively low weighting (20%) of BG in computing $WBGT_{out}$, we still observed reductions in our linear mixed-effects models of $WBGT_{out}$ for all materials compared to no shade. There is potential practical significance, depending on the scenario, of the observed magnitude of $WBGT_{out}$ mitigation in conditions exhibited by shade materials compared to no shade. For example, based on National Institute for Occupational Safety & Health (NIOSH) methods[2] and mean $WBGT_{out}$ measurements from Table 1, assuming work in double layer clothing (+3°C WBGT clothing adjustment factor), the time-weighted average WBGT exposures can be computed for a scenario with a 30 min shaded versus unshaded 110 Watt metabolic rate lunch break (25% of a 2-h period) in the middle of a -90 min 250 Watt unshaded work period (75% of a 2-h period). Exposure during unshaded work and an unshaded break is 24.1°C + 3°C = 27.1°C WBGT and during shaded breaks is 21.9°C to 22.5°C + 3°C = 24.9°C to 25.5°C WBGT. The time-weighted average exposure of unshaded work and an unshaded break is 27.1°C, and the time-weighted average exposure of unshaded work and a shaded break is 26.6°C to 26.7°C, depending on the shade material. In this scenario, the condition of unshaded work and an unshaded break exceeded the NIOSH heat stress Recommended Alert Limit (RAL) of 27.0°C, but unshaded work plus a shaded break did not.

We did not find substantial differences in BG and $WBGT_{out}$ between different shade materials. This finding is consistent with an urban study of different tent shade materials, including mylar (polyester), tarp, and bedsheet, that reported a substantial difference in mean radiant temperature between shaded and non-shaded tents but no substantial differences between the different shade materials during the day.[20] Compared to all other studied materials, hay tarp (HAY) exhibited a lower BG, indicating mitigation of solar radiation. The effect of HAY on $WBGT_{out}$, a measure of net heat exposure, was similar to 80% monofilament (M80), and both materials exhibited better heat exposure mitigation through a lower $WBGT_{out}$ than all of the other materials. However, both HAY and M80 were heavier and more difficult to transport and maneuver than other materials. In terms of solar radiation, we found only a < 2°C BG difference between the reflecting aluminized flat tape (A70 and S80) and light-absorbing black monofilament (M80) materials. When comparing the aluminized flat tape materials, we found only a <1°C BG difference in their shade percentage ratings (S80 versus A70). Finally, in terms of heat exposure mitigation and the potential effects of wind speed, we found only <1°C difference in $WBGT_{out}$ between non-porous (HAY) compared to the most-porous (A70) materials.

Given only small differences in quantitative effectiveness between studied shade materials, other practical considerations should be incorporated into decision-making about which materials to implement in specific circumstances. Research has shown that solutions based on farmworker input provide better outcomes.[30] For example, supervisors in our qualitative study indicated that decision-making about shade considers ease of use, mobility, material breathability, durability, and cost. These considerations may inform decisions about permanent versus temporary shade, such as mounting shade materials on posts versus pop-up shade canopies, selection of specific shade materials based on weight, ability to withstand local weather conditions (e.g., durability in windy conditions), and fixed versus mobile shade, depending on the degree to which crop layout and tasks dictate worker movement around the workplace. Workers provided additional information that may inform successful shade implementation, including preferred features of a shaded "cooling station" approach that includes cool drinking water, seating, and restrooms and handwashing stations that are not too far away.

Strengths & limitations

This study has several strengths, including testing of materials of interest to the agricultural community that are available in our region and that could meet the definition of shade in the WA outdoor heat exposure rule and proposed federal OSHA heat rule.[9,14] We included materials readily available on the farm that may have farm uses beyond shade for workers. In addition, materials were tested in fields that mimic real-world agricultural environments. Our approach to quantify shade's effect on heat exposure, combined with information about practical considerations to inform decision-making about materials, could be translated to other highly heat-exposed industries such as construction. Given worker and supervisor preferences for mobile shade, the solid shade materials used in mobile shade trailers, and the integration of a built-in place to sit, rest, and eat within mobile shade trailers, further study of the practicality and effectiveness of mobile shade trailers is warranted.

This study also has several important limitations. Our study conditions included unexpected intermittent clouds. However, sensitivity analyses accounting for “sunny” versus cloudy conditions did not result in substantial changes in primary or secondary model interpretations. Our findings indicate that, even with unpredictable intermittent clouds, shade materials still mitigated BG and $WBGT_{out}$ and therefore should still be made available to workers in these and similar conditions. Second, we did not examine how shade materials are mounted or their safety but rather focused on the materials themselves. This study also has limited generalizability, as it was conducted in one location over 3 days in moderate heat conditions. Third, occupational heat stress consists of multiple components, but this study only addressed shade, which directly impacts solar radiation, and only measured exposure at fixed points. Finally, we were not able to interview or evaluate shade approaches at the level of individuals. Future studies should evaluate the feasibility, acceptability, and sustainability of co-developed shade approaches and their effects on WBGT, thermal comfort, and physiological heat strain experienced by actual workers. Other important factors to consider are heat load under shade structures that may hold different amounts of heat, depending on size and occupancy, structure, headspace, and design. Future studies should also systematically characterize factors affecting employer decision-making about shade, facilitators and barriers to trying new approaches, how worker and supervisor preferences about types of shade compare by crop, setting, and use type (e.g., work versus lunch area), and how employer perceptions of shade relate to their investment in shade resources.

Conclusions

In this study, shade materials significantly reduced Black Globe (BG) and $WBGT_{out}$ temperature compared to no shade. We did not observe substantial differences between specific shade materials on mitigation of BG and $WBGT_{out}$, although findings should be confirmed in settings with extreme heat and humidity and minimal cloud cover. Our qualitative findings identified practical shade considerations, such as ease of use and mobility, in addition to effectiveness in reducing heat exposure. Workplace decision-making about shade approaches that are likely to be adopted and sustained should consider worker and supervisor preferences and practical considerations, combined with information about the effectiveness of different shade approaches in reducing heat exposure.

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Disclosure statement

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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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