Heat stress, heat strain, and productivity in Washington State tree fruit harvesters

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Abstract

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Background: Heat health effects are an important public health problem in outdoor workers, including agricultural workers. Outdoor agricultural workers who perform heavy physical labor in hot conditions are at increased risk for developing occupational heat-related illness. Heat stress, under certain environmental conditions, has been reported to reduce worker productivity. Climate models project future increases in the frequency, severity, and duration of heat waves.

Objectives: This study aimed to characterize heat stress and physiological effects of heat stress (heat strain) in outdoor tree fruit workers performing harvest activities in Yakima Valley, Washington, and to assess the relationship between heat exposure and productivity in these workers.

Methods: During the summer of 2015, 46 pear and apple harvesters from six orchards participated in a cross-sectional study in Yakima Valley, Washington for one work shift each during warmer periods in August (n=34 pear harvesters) and cooler periods in September (n=12 apple harvesters). All participants were paid by the amount of fruit harvested (piece-rate). Heat stress and strain were characterized using American Conference of Governmental Hygienist (ACGIH) guidelines, which recommend thermal Action Limits and Threshold Limit Values based on several factors, including environmental conditions, metabolic rate of task, and clothing ensembles. Heat exposure was measured near individual workers using hand-held Wet Bulb Globe Temperature (WBGT) monitors, metabolic rate was estimated using field observations and personal hip-mounted accelerometers, and research staff observed workers' clothing. Heart rate and core body temperature were monitored over the course of the work shift using heart rate monitors and wireless ingestible core body temperature sensors. A computer-assisted self-interview survey instrument captured other relevant demographic, individual, and work factors. The total weight of fruit bins collected per time worked was used to assess productivity. Effect estimates of the association between maximum work shift WBGT and productivity were estimated using linear mixed effects models with a random intercept for orchards, using Kenward-Roger methods for small sample sizes, adjusted for relevant confounders.

Results: Surveys of workers indicated that 24 (52%) had experienced symptoms of heat strain and heat-related illness, and only 13 (28%) received training on working in the heat. Of the 34 participants who worked in pear harvest in August, 25 (74%) exceeded the ACGIH Action Limit ($WBGT_{effective}$ 25° C), and 21 (62%) exceeded the Threshold Limit Value ($WBGT_{effective}$ 28° C) for the moderate work task (300 Watts) of harvesting. Using personal accelerometer data to estimate metabolic rate (n=39), 12 (31%) participants exceeded the Action Limit and four (10%) exceeded the Threshold Limit Value. Of the 12 participants exceeding the Action Limit, based on accelerometer data, nine (75%) exceeded the maximum heart rate (180-age beats per minute), and five (42%) exceeded the maximum internal core body temperature of 38.5°C recommended by ACGIH. There was a trend of a decrease in productivity with increasing maximum daily WBGT, but this association was not statistically significant.

Conclusions: Current summer tree-fruit harvesters in Yakima Valley, Washington are laboring in thermal environments hazardous to health. Payment schemes may provide incentives for workers to not slow down, and increase the risk of HRI. Acclimatization practices, HRI training, and orchard management practices could be improved to increase biological adaptation to heat stress and prevent HRI. The relationship between heat exposure and productivity in tree fruit harvesters is complex and likely affected by monetary factors and orchard and harvest characteristics. The effects of heat stress on heat strain and productivity in outdoor workers should be considered in future planning, given the projected increase in frequency, severity, and duration of heat waves.

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INTRODUCTION

Occupational heat-related illness

Heat-related illness (HRI) is an important public health problem in outdoor workers. Gubernot *et al's* analysis of Bureau of Labor Statistics data identified 359 occupational heat-related deaths between the years of 2000 and 2010 in the US (2015). This analysis identified agriculture as the industry with the highest heat-related mortality rate with 3.06 per 1 million workers (Gubernot, Anderson, & Hunting, 2015). Heat exposures also contribute to other poor health outcomes in the workplace. Studies have demonstrated associations between exposures to high temperatures and decreased cognitive function (Griffiths & Boyce, 1971; Hancock, & Vasmatzidis, 2003; Ramsey, 1995; Tamm, Jakobson, Havik, Timpmann, Burk, Oopik, & Kreegipuu, 2015) and increased cardiovascular stress (Bernard & Iheanacho, 2015; Sahu, Sett, & Kjellstrom, 2013; Wright Beatty, Hardcastle, Boulay, Flouris, & Kenny, 2015). Decreased cognitive function may lead to increased injury rates in the workplace (Adam-Poupart et al., 2015). Exposure to increasingly warm temperatures and resulting health effects degrade the ability for a worker to be productive to their full potential (Kjellstrom, Holmer, & Lemke, 2009)

The core temperature of the human body functions optimally around 37° Celsius (Kurz, 2008). Thermoregulatory receptors in the body detect variations in temperatures and provide feedback to the hypothalamus to regulate core body temperature (Kurz, 2008). Through vasoconstriction and vasodilation of arteries, the body regulates blood flow to ensure optimal core body temperature (Kurz, 2008). The thermal steady state of the human body occurs when heat loss into the environment equals metabolic heat production. The human body's primary mechanism to reduce body temperature is through evaporation of sweat into the environment. The dissipation of heat into the environment requires a temperature and humidity gradient from the body to the environment. Hot-humid environments and personal protective equipment that does not allow dissipation of heat through sweating limit the ability to lose excess heat into the environment. In addition, internal metabolic heat is generated during physical exertion.

Heat strain is the physiological response of the body to heat stress conditions. If a worker is continually exposed to warm thermal environments and internal heat generated through physical work, this can lead to the development of adverse health outcomes, including heat rash, heat cramps, heat syncope, heat exhaustion, and heat stroke (Center for Disease Control and Prevention [CDC], 2016). Heat stroke is classified as either classical heat stroke or exertional heat stroke (National Institute of Occupational Safety and Health [NIOSH], 2016). Exertional heat stroke occurs in athletic, military, and workplace settings (NIOSH, 2016).

Risk factors for heat-related illness

There are many risk factors for HRI in working populations. Environmental (including heat and humidity exposure), clothing, workplace (including rest breaks, shade, physical exertion, hydration, and piece rate pay) (Spector, Krenz, & Blank, 2015), and individual (including certain medication use and chronic diseases such as obesity) factors affect the development of HRI.

The physical fitness and health status of an individual impacts their ability to sweat and dissipate heat into the environment. Trained athletes sweat at greater rates than sedentary individuals, which allows for an improved ability to thermo-regulate under heat stress conditions (Buono & Sjoholm, 1988). Individuals with cardiovascular disease and the elderly (Kenny, Yardley, Brown, Sigal, & Jay, 2010) have a reduced ability to acclimate to extreme environmental temperatures (Sawka, Leon, Montain, & Sonna, 2011). Diseases and medications that inhibit vasodilation or sweating increase the risk of HRI (Charkoudian, 2010).

Acclimation of workers to thermal environments prior to performing physical labor is recommended to reduce the risk of HRI. The US Occupational Safety and Health Administration (OSHA) recommends five days of heat acclimation prior to performing a full eight-hour workday in the heat (OSHA, 2015). Physiological adaptations from acclimation to repeated heat exposures occur quickly, with between 75-80% of adaptations occurring in the first four to seven days of exposure (Pandolf, Burse, & Goldman, 1977; Shapiro, Moran, & Epstein, 1998)

Wet-Bulb Globe Temperature

The Wet Bulb Globe Temperature (WBGT) is a heat index developed by the United States Army and Marine Corps (Budd, 2008). WBGT is calculated from measurements from three different thermometers. A black bulb temperature is measured using a thermometer placed inside a black body. The black bulb thermometer absorbs radiant heat from the sun or hot objects emitting radiation. A natural wet bulb, in the form of a thermometer engulfed in a wet wick, measures temperature with humidity as a contributing factor. Finally, a dry thermometer measures the temperature of the dry air. One of two equations is used for the final calculation of WBGT, depending on whether the heat exposure occurs outside in the sun or indoors. Outdoor WBGT ($WBGT_{out}$) is calculated using the equation $WBGT_{out}=0.7T_{nwb}+0.2T_g+0.1T_{db}$, where T_{nwb} is the temperature of the natural wet bulb, T_g is the temperature of the black globe thermometer, and T_{db} is the temperature of the dry bulb (Budd, 2008).

Current US occupational heat regulations

Federal OSHA does not have any specific regulations protecting workers from environmental heat. The legal premise on which an employer must provide a safe working environment falls under the OSHA General Duty Clause (OSHA, 1983). In recent years, OSHA has released guidelines for educating employers and employees to recognize hazardous thermal environments (OSHA, 2015). The guidelines use the heat index rather than the WBGT. Heat index is calculated using humidity and dry bulb temperature (National Oceanic and Atmospheric Administration, [NOAA], 2015). As shown in *Table 1*, this approach does not take into account the type of work being performed or clothing worn by the worker. California and Washington are currently the only two states that have enacted legislation intended to protect outdoor workers from extreme thermal conditions (California Code of Regulations, 2015; Washington Administrative Codes [WAC], 2016).

Table 1. Risk levels of developing heat-related Illness using heat index. Source: OSHA, 2015.

Heat Index	Risk Level	Protective Measures
Less than 91°F	Lower (Caution)	Basic heat safety and planning
91°F to 103°F	Moderate	Implement precautions and heighten awareness
103°F to 115°F	High	Additional precautions to protect workers
Greater than 115°F	Very High to Extreme	Triggers even more aggressive protective measures

Washington Heat Rule

Washington Administrative Code (WAC) 296-62-095 through 296-62-09560 and 296-307-097 through 296-307-09760 are intended to protect workers from outdoor heat exposure (2016). The Washington Heat Rule for work in outdoor environments is only in effect from May 1^{st} through September 30^{th}. The Rule uses dry bulb air temperatures and takes into account the type of clothing being worn. Different clothing worn by workers corresponds to different temperatures at which preventative measure must be implemented. For example, the threshold for implementing preventative measures is 52° F for a worker wearing non-breathable clothing, 77° F when wearing double-layer woven clothing (coveralls, jackets, and sweatshirts), and 89° F for more breathable clothing (long-sleeve shirt, and jeans).

The rule requires employers to maintain an accident prevention program addressing heat exposures. Employees must be encouraged to frequently drink water or other acceptable beverages. However, employees must monitor themselves for risks of HRI. The employer must provide specific quantities of potable water per employee at a nearby location. All employees must be trained on the recognition of HRI. The burden of taking rest breaks falls on the employee.

American Conference of Governmental Industrial Hygienist guidelines

The American Conference of Governmental Industrial Hygienists (ACGIH) put forth recommendations on work/rest cycles for employees in hot thermal environments (ACGIH, 2015). The guidelines provide a step-wise method for assessing heat stress and strain, as shown in F*igure 1* (2015). A clothing-adjustment factor is used to estimate an effective WBGT ($WBGT_{eff}$), as shown in *Table 2.* Workload is classified into metabolic rate categories ranging from light to very heavy. Light labor refers to labor where an individual is sitting or standing in one area with light arm work. Very heavy labor is considered very intense activity at fast to maximum pace. Light work corresponds to 180 Watts and very heavy corresponds to 520 Watts, as shown in *Table 3*. Controls for preventing HRI in the workplace include clothing, administrative, and certain engineering controls, which may be difficult to implement in outdoor environments where climate control interventions are not realistic.

ACGIH recommends Actions Limits and Threshold Limit Values for different levels of energy expenditure during a work task. When $WBGT_{eff}$ exceeds Action Limits, ACGIH recommends continual monitoring of the environmental conditions of the worksite (2015). General practices should be considered to limit exceedances of the Action Limit including potential administrative or engineering controls (2015). If $WBGT_{eff}$ exceeds Threshold Limit Values, these conditions are considered hazardous to health and exposures should cease. Individual physiological heat strain monitoring of workers should occur at temperatures above Threshold Limit Values including heart rate and core body temperature monitoring. Finally, any symptom of heat-related illness must never be ignored in the workplace.

Figure 1. Heat stress and strain decisions flow chart. Source: From ACGIH TLV Handbook, 2015.

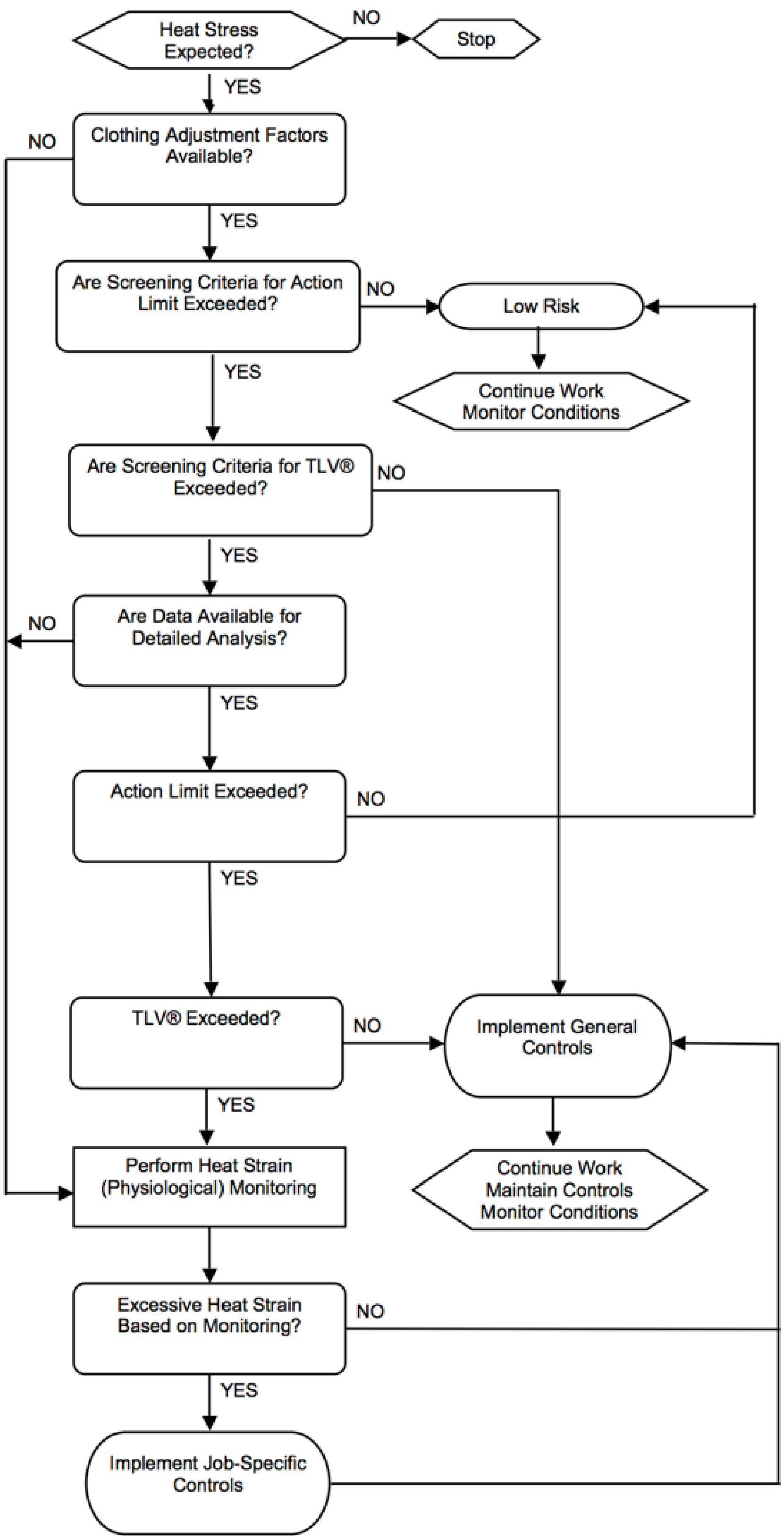


Table 2. Clothing adjustment factor for calculating effective Wet Bulb Globe Temperature. Source: ACGIH TLV Handbook, 2015.

Clothing type	WBGT addition*
Work clothes (long-sleeved shirt and pants)	0
Cloth (woven material) overalls	0
Double-layer woven clothing	3
SMS polypropylene coveralls	0.5
Polyolefin coveralls	1
Limited-use vapor-barrier coveralls	11

* These values must not be used for completely encapsulating suits, often called Level A clothing. Clothing adjustment factors cannot be added together for multiple layers. The values for coveralls assume that only modesty clothing is worn underneath, not a second layer of clothing.

Table 3. Metabolic work-rate categories for various levels of activity. Source: ACGIH TLV Handbook, 2015.

Category	Metabolic Rate (W)*	Examples
Rest	115	Sitting
Light	180	Sitting with light manual work with hands or hands/arms, and driving. Standing with some light arm work and occasional walking.
Moderate	300	Sustained moderate hand and arm work, moderate arm and leg work, moderate arm and trunk work, or light pushing and pulling. Normal walking.
Heavy	415	Intense arm and trunk work, carrying, shoveling, manual sawing; pushing and pulling heavy loads; walking at a fast pace.
Very Heavy	520	Very intense activity at fast to maximum pace.

** The effect of body weight on the estimated metabolic rate can be accounted for by multiplying the estimated rate by the ratio of actual body weight divided by 70 kg (154 lb).*

Heat exposure and worker productivity

Few studies have assessed the relationship between worker productivity and environmental temperatures. Sahu *et al.* performed a productivity analysis of rice harvesters in India while monitoring WBGT levels (2013). Sahu *et al.* found that the amount of rice harvested significantly decreased at WBGT levels exceeding 26°C (2013). Kjellstrom *et al*. reported greatly reduced work capacity at WBGT levels exceeding 26°C-30°C (2009). A recent paper by Zander *et al.* attempted to calculate an economic cost of reductions in productivity due to heat in Australia over the 2013-14 summer from a sample of 1,726 employed Australians (2015). The authors estimated this cost to be US$655 per person (2015). Across all of Australian employees, that amounts to an over US$6.2 billion economic burden (Zander, Botzen, Oppermann, Kjellstrom, & Garnett, 2015). The Intergovernmental Panel on Climate Change (IPCC) projects future global surface mean temperatures to increase with increasing concentrations of greenhouse gases emitted into Earth's atmosphere (Intergovernmental Panel on Climate Change [IPCC], 2007). A projected increase in frequency, severity, and duration of heat waves may continue to impact worker productivity losses (Dunne, Stouffer, & John, 2013). Dunne *et al.* predicted work capacity to be reduced to 80% in mid-latitude developing countries by the year 2050 (2013).

Context of climate change in the Pacific Northwest

The Climate Impacts Group at the University of Washington has been adapting global climate change models specifically to the Pacific Northwest. Mote *et al.* examined 20 different climate change prediction models under two different CO_2 emission scenarios (2010). All models predicted increases in temperatures in coming years. In addition to expected increases in average temperatures, the frequency, severity, and duration of extreme weather events, such as heat waves, is also expected to increase (IPCC, 2007). Climate Impacts Group projections indicate that the greatest temperature increases will occur during the summer months in the Pacific Northwest. Under the two separate emission conditions, Mote *et al.* projects average dry air temperature increases of 2.17° C and 2.83° C, under a conservative and less conservative emission scenario, respectively, from 2030-2059 (2010). These increases in dry air temperature may play a role in the ability for a tree fruit harvester to labor in the fields, particularly if under current conditions they are already experiencing heat stress and strain. If temperature trends continue in their increasing pattern, greater heat exposures and morbidity from HRI will occur.

Increases in temperatures of this magnitude have the potential to transition workers from heat exposures below recommended guidelines to new exposures known to have serious health risks.

STUDY GOALS, SPECIFIC AIMS, AND HYPOTHESES

The purpose of this study was to characterize heat stress and strain and to assess the association between heat exposure and productivity in tree fruit harvesters in Washington State. Few studies have examined the relationship between heat exposure, heat stress, heat strain, and productivity using individual-level measures. This study attempts to contribute to the knowledge of the effects of heat on workers during the summer months of tree fruit harvest.

The specific aims of this study were to:

1) Perform a descriptive analysis of heat stress and strain in 46 tree-fruit harvesters in Yakima Valley, Washington during the hot summer month of August and cooler month of September 2015 using American Conference of Governmental Industrial Hygienist (ACGIH) methods.
   Hypothesis 1: Washington tree fruit harvesters are exposed above the ACGIH heat stress Threshold Limit Value.
2) Estimate associations between WBGT and productivity in a cross-sectional sample of 46 tree fruit workers in the Yakima Valley during the 2015 harvest season.
   Hypothesis 2: Increases in WBGT are associated with decreases in productivity.

We anticipated that the results of this study could help inform planning for heat health and productivity impacts in agricultural workers in future climate conditions, with an ultimate goal of reducing the risk of HRI while optimizing productivity in the future.

METHODS

Study population and design

An observational cross-sectional study was conducted during August and September 2015 in Yakima Valley, Washington. These two months were selected to provide variability in environmental conditions. A convenience sample of orchards and adult (age 18 or older) tree fruit harvest participants was recruited through University of Washington Pacific Northwest Agricultural Safety and Health Center (PNASH) contacts. Only harvesters receiving compensation through a piece-rate payment scheme were recruited to participate. Participants provided informed consent the day prior to their participation. Participating tree-fruit harvesters were monitored during one day of harvest each. A maximum of four harvesters were monitored daily, for a total of 46 participants (34 in August during pear harvest and 12 in September during apple harvest). Participants received $50 for their time participating in the study. All data analyses took place at the University of Washington. Study procedures were reviewed and approved by the University of Washington Institutional Review Board. Additional methods by specific aim are described below.

***Specific Aim 1**: Perform a descriptive analysis of heat stress and strain in 46 tree-fruit harvesters in Yakima Valley, Washington during the hot summer month of August and cooler month of September 2015 using American Conference of Governmental Industrial Hygienist (ACGIH) methods.*

Hypothesis 1: Washington tree fruit harvesters are exposed above the ACGIH heat stress Threshold Limit Value.

A. Participant characteristics

Personal factors including demographic factors, medical history and medications, reported heat-related symptoms, height and weight to calculate body mass index (BMI), and work experience were assessed using an audio computer-assisted self-interview survey instrument on tablet computers. The tablet questionnaire assessed factors over the participants' previous two-weeks. Physical measurements were performed, including height and weight, to calculate BMI.

B. Heat stress assessment

Effective WBGTs were determined using the Threshold Limit Value for Chemical Substances and Physical Agents booklet produced by ACGIH (2015). ACGIH takes into account human health in developing Threshold Limit Values and Action Limits (ACGIH, 2015). The limits were developed to allow a typical worker to work 40-hours a week over a working lifetime without suffering any occupational disease (ACGIH, 2015). ACGIH standards do not take into consideration economic feasibility. ACGIH guidelines were selected as means for evaluating heat stress and strain in orchard harvesters in this study for the following reasons. The ACGIH guidelines provide a more comprehensive assessment and recommendations than the Washington Heat Rule (WAC, 2016). The International Standard Organization thermal heat stress standards require purchasing six different standards (ISO 7243, ISO 7726, ISO 7933, ISO 8996, ISO 9886, and ISO 9920) and include a separate analysis of sweat rate that was not practical in our study (McNeill & Parsons, 1999; Parsons, 2013). There are no federal regulations that specifically assess heat stress and strain in the United States. ACGIH and National Institute for Occupational Safety and Health (NIOSH) guidelines are very similar, with ACGIH being more protective at lower temperatures and workloads than NIOSH (NIOSH, 2016). The differences between various guidelines are shown in *Table 4.*

Table 4. Comparison of WBGT exposure limits for acclimatized workers. Source: From NIOSH Occupational Exposure to Heat and Hot Environments, 2016.

Workload	ACGIH	AIHA	OSHA	ISO	NIOSH
Resting		32.2°C (90°F) 100 kcal·h^{-1} (117 W)		33°C (91.4°F) ≤100 kcal·h^{-1} (117 W)	
Light	30°C (86°F) 100–200 kcal·h^{-1} (117–233 W)	30°C (86°F) 200 kcal·h^{-1} (233 W)	30.0°C* (86°F) 32.2°C† (90°F) <200 kcal·h^{-1} (233 W)	30°C (86°F) 100–201 kcal·h^{-1} (117–234 W)	30°C (86°F) <200 kcal·h^{-1} (233 W)
Moderate	26.7°C (80°F) 201–350 kcal·h^{-1} (234–407 W)	26.7°C (80°F) 300 kcal·h^{-1} (349 W)	27.8°C* (82°F) 30.6°C† (87.1°F) 201–300 kcal·h^{-1} (234–349 W)	28°C (82.4°F) 201–310 kcal·h^{-1} (234–360 W)	28°C (82.4°F) 201–300 kcal·h^{-1} (234–349 W)
Heavy			26.1°C* (79°F) 28.9°C† (84°F) >301 kcal·h^{-1} (350 W)	25°C* (77°F) 26°C† (78.8°F) 310–403 kcal·h^{-1} (360–468 W)	26°C (78.8°F) 301–400 kcal·h^{-1} (350–465 W)
Very heavy	25°C (77°F) 350–500 kcal·h^{-1} (407–581 W)			23°C* (73.4°F) 25°C† (77°F) >403 kcal·h^{-1} (468 W)	25°C (77°F) 401–500 kcal·h^{-1} (466–580 W)

*Low velocity; †high velocity; kcal·h^{-1} = kilocalories per hour.

NOTE: Unacclimatized workers would have greater heat expenditures during the same amount of work and temperature.

Adapted from the American Industrial Hygiene Association (AIHA) [2003].

Note: ACGIH exposure limits were calculated using the Threshold Limit Value equation (56.7-$\log_{10}$(Watts)) and maximum workload for category

Wet Bulb Globe Temperatures (WBGTs) were measured using a hand-held WBGT monitor (Extech HT30 WBGT Meter, Extech Instruments; Nashua, NH) in the orchards harvested. This instrument estimates natural wet bulb temperature using relative humidity to calculate WBGT and reports dry air temperature. WBGT measurements were taken regularly (~60 - 90 minutes), during working hours as near to the workers' locations as possible. Research staff noted whether WBGT measurements were taken in direct sunlight.

Photographs were taken of harvesters providing consent at the beginning of the day. Photographs of consenting workers (n=32) assessed the type and amount of clothing worn by a worker. Pictures were taken in the morning. The ACGIH clothing correction factor was determined using *Table 2* and used to calculate an effective WBGT ($WBGT_{eff}$) for each participant.

Workload and metabolic activity were assessed through research staff observation of tasks and accelerometer data. Research staff noted work start time, stop time, and lunch break times. Workers wore actigraphs (wGT3X-BT, ActiGraph; Pensacola, FL) during their work shifts. Using corresponding ActiLife software, the Freedson VM3 method was used to calculate hourly kcal/hour energy expenditure estimates (Williams, 1998). Kcal/hour was divided by 0.86 to provide a final output in Watts. Observational metabolic work categories were also determined as shown in *Table 3*. Perceived exertion was assessed using the OMNI scale. Perceived exertion was self-reported using tablet computers on a scale of 1-10, with 10 being the point of complete exhaustion and one being 100% alert and ready for work (Utter, Robertson, Green, Suminski, McAnulty, & Nieman, 2004).

C. Heat strain assessment

Heat strain was assessed using ACGIH methods and Moran *et al's* Physiological Strain Index (PSI) (1998). Workers' core body temperatures and heart rates were monitored using CorTemp™ sensors (HQ Inc; Palmetto, FL) and Polar® chest band monitors (Polar Inc; Lake Success, NY), respectively. CorTemp™ sensor systems consist of small FDA registered and cleared (510K, No. 880639) ingestible thermometer 'pills'. Continuous core temperature and heart rate data were wirelessly transmitted to data recorders worn by workers. Body temperatures were also measured using tympanic thermometers (Braun; Kronberg, Germany). Core temperature data less than measured tympanic temperature were excluded, as core temperature is typically greater than measured aural temperatures (Huggins, Glaviano, Negishi, Casa, & Hertel, 2012). Core temperature values greater than 40°C were excluded, as this would constitute a medical emergency of heat stroke with accompanying clinical symptoms and signs, which were not observed during the study (Bouchama & Knochel, 2002; Hassanein, Razack, Gavaler, & Van Thiel, 1992).

Heart rate and core temperature data were collected every 20 seconds and summarized as rolling medians over 200 seconds. Missing values for heart rate and core temperature were imputed using the median of the previous and future 100 seconds. As CorTemp™ sensors do not equilibrate immediately, morning pre-work tympanic temperature measurements were used to impute baseline core body temperature values after applying an adjustment factor of +0.27°C to account for differences between core temperature and tympanic temperature (Huggins Glaviano, Negishi, Casa, & Hertel, 2012). Baseline heart rates were calculated using the mean of the lowest 10 observed values during the work shift monitoring period.

Per ACGIH methods, heat strain is a concern when the maximum sustained heart rate for several minutes is above 180 beats per minute minus the age of the worker, or recovery heart rate at one minute after peak work is greater than 120. Thresholds for core temperatures are 38.5°C for acclimatized workers (individuals who have been laboring in hot conditions for greater than two weeks) and 38.0°C for unacclimatized workers, per ACGIH. If any of these criteria are met, or the worker exhibits sudden heat strain symptoms, the worker is considered exposed to excessive heat and exposure to heat stress should be immediately discontinued. All of the participants were assumed to be acclimatized workers as 100% purported to have begun working the 2015 Washington tree-fruit harvest at some point after the month of June.

The Physiological Strain Index (PSI) is another tool used to quantitatively assess heat strain based on heart rate and core body temperatures. This method requires baselines for both heart rate (HR_0) and core temperature (T_0). The equation $5(T_x - T_0) \cdot (39.5 - T_0)^{-1} + 5(HR_x - HR_0) \cdot (180 - HR_0)^{-1}$ is used to calculate the PSI at time x. The severity of heat strain is expressed on a scale from 0-10 with five as "moderate" heat strain, seven as "high" heat strain, and 10 as "very high" physiological strain, as shown in *Table 5* (Moran, Shitzer, & Pandolf, 1998).

Table 5. Calculated Physiological Strain Index (PSI) using the equation $PSI=5(T_x-T_0)*(39.5-T_0)^{-1}+5(HR_x-HR_0)*(180-HR_0)^{-1}$, where T_x is current core temperature, T_0 is baseline core temperature, HR_x is current heart rate, and HR_0 is baseline heart rate. Source: Moran, 1998

PSI	Physiological Strain
0	none
1	minimal
2	
3	low
4	
5	moderate
6	
7	high
8	
9	very high
10	

Specific Aim 1 Analyses

A. Description of the study population

Age, sex, BMI, years of experience, and antihypertensive cardiovascular medication and self-reported heat-related symptoms were summarized using descriptive statistics. Participating orchard acreage, type of tree fruit, month of participation, number of participants, days of observations, and heat exposure characteristics were also described.

B. Heat stress assessment

The day was divided into four sections: early-morning (5 am-8 am), morning (8 am-11 am), midday (11 am-2 pm), and afternoon (2 pm-5 pm), and mean WBGT, $WBGT_{effective}$, dry air temperature, and relative humidity were determined for these periods, by month. A time-weighted average (TWA) WBGT was calculated for the entire day. To calculated the TWA WBGT, each WBGT field measurement was weighted by time of work spent for that interval. All weighted WBGT measurement were divided by total work shift time to calculate the TWA WBGT. WBGT and metabolic workload (assessed using actigraphs and field observations) were plotted against the ACGIH Action Limit ([°C-WBGT] = 59.9 - 14.1 log10 M [Watts]) and Threshold Limit Value ([°C-WBGT]= 56.7 - 11.5 log10 M [Watts], where M is metabolic activity of the worker (2015). Perceived exertion was summarized by section of the day.

C. Heat strain assessment

Individual workers deemed to have exposures exceeding the ACGIH Action Limit were further analyzed for heat strain. Core temperature and heart rate data were summarized as percentages of the total time data was collected during the work shift that exceeded thresholds (>38.5°C for core temperature and 180-age beats per minute for heart rate). Heat strain was also presented as percentage of time spent in PSI categories of moderate, high, and extreme and plotted over time.

Specific Aim 2: *Estimate associations between environmental heat exposure and productivity in a cross-sectional sample of 46 tree fruit workers in the Yakima Valley during the 2015 harvest season. Hypothesis: Higher WBGTs are associated with lower productivity.*

A. Exposure

The maximum daily WBGT ($WBGT_{max}$) for each individual worker on the day of observation was used in the analyses as the primary exposure.

B. Outcome

Data on the amount of fruit harvested for the specific day of participation in the study for each participant were obtained. Workers use a punch card system to keep track of the number of bins of fruit harvested daily, and this is the basis of payment for piece-rate workers. Field research staff obtained information from these cards for the complete workday. Productivity was calculated using average bin weights reported by growers for apples and pears. The mean weight of pear bins was reported to be 950 pounds and of apple bins was reported to be 750 pounds. For individuals indicating they received help filling their bins (n=12), the total bin count was divided by the number of assisting individuals. The number of bins collected during the work shift was multiplied by the corresponding bin weight. The total number of pounds collected was converted to kilograms and divided by total shift time to yield an average hourly productivity rate.

Specific Aim 2 Analyses

A. Descriptive analyses:

Mean $WBGT_{max}$, mean productivity, and mean perceived exertion values were summarized by month. Mean $WBGT_{max}$ and mean productivity were also summarized by orchard. The relationship between age and work experience was explored using descriptive statistics. Bivariate relationships between $WBGT_{max}$ and productivity and between productivity and crop, age, gender, BMI, price per bin, and shift duration were explored using scatter plots and box plots.

B. Inferential analyses

The association of $WBGT_{max}$ with productivity was modeled using linear mixed effects models with intercept random effects for worksites, using the Kenward-Rogers method for small samples (Kenward & Roger, 1997; Halekoh, & Højsgaard, 2014). Work experience, gender, price paid per bin, BMI, and shift duration were considered to be potential confounders, as they were hypothesized to be related to both heat exposure and the productivity outcome. Work experience (<1 [reference category], 1-2, 3-5, 6-9, >9 years) and price paid per bin ($15/bin [reference category], $19/bin, and ≥$21/bin) were coded as dummy variables. Gender was coded as binary (0=male, 1=female). Shift duration and BMI were coded as continuous variables.

We developed the sequence of models, from unadjusted to adjusted for all potential confounders, shown in *Figure 2:*

Figure 2. Models of the association of productivity with Wet Bulb Globe Temperature

$$(1)\ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N(\beta_0 + b_{0i} + \beta_1 WBGT_{ij}, \sigma_e^2),$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \dots, 6$$

$$(2)\ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N(\beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, \sigma_e^2),$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \dots, 6$$

$$(3)\ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N\begin{pmatrix} \beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, \\ +\beta_4 BMI_{ij} + \beta_5 price/bin_{ij}, \sigma_e^2 \end{pmatrix},$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \dots, 6$$

$$(4)\ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N\begin{pmatrix} \beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, +\beta_4 BMI_{ij} \\ +\beta_5 price/bin_{ij} + \beta_6 duration_{ij}, \sigma_e^2 \end{pmatrix},$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \dots, 6$$

RESULTS

Specific Aim 1

A. Participant & orchard characteristics

Personal characteristics of the study population are presented in *Table 6*. 84.8% of the participating harvesters were male, with a mean age of 39 (standard deviation=14) years. Mean body mass index was 28.9 (standard deviation= 5.8). The mean work shift duration was 6.8 (standard deviation=1.5) hours. 52.2% of all participants reported exhibiting heat-related symptoms of either dizziness/light-headedness or heavy sweating. 65.2% of participants had been working in agriculture for 10 or more years. 8.7% of all participants reported taking antihypertensive medication.

Table 6. Characteristics of study population (n=46)

Characteristic	Frequency (%) or mean (SD)
Male	84.8%
Age*	39.1 (14.1)
Body mass index	27.9 (4.2)
Daily hours worked	6.8 (1.5)
Reported heat-related symptoms*ᵠ	52.2%
Years worked*	
< 1	10.9%
1-2	6.5%
3-5	8.7%
6-9	8.7%
≥ 10	65.2%
Cardiovascular antihypertensive medication*	8.7%

*Self-reported responses

ᵠSelf-reported symptoms of dizziness/light-headedness or heavy sweating

Orchard characteristics are shown in *Table 7.* A total of six orchards participated in the study, during Bartlett pear harvest (n=5) and during Red Delicious apple harvest (n=1). Size of the orchards ranged from 5 – 20 acres, with a range of participating harvesters from 3 – 14. The mean participant productivity for Orchard C was less than for other participating orchards. Orchard F was the only participating orchard in the month of September.

Table 7. Characteristics of participating orchards (n=6)

Orchard	Acreage	Fruit	Harvest month	# of participants	# of days participating	Hours worked by participants (mean (SD))	$WBGT_{max}$ (mean (SD))	Productivity of participants in kg/hr (mean (SD))
A	9	Bartlett	August	5	2	6.0 (0.9)	28.1 (2.0)	397.2 (90.9)
B	20	Bartlett	August	14	4	7.6 (0.8)	26.1 (1.7)	323.7 (51.0)
C	5	Bartlett	August	8	2	7.2 (0.8)	32.0 (1.3)	258.2 (53.2)
D	10	Bartlett	August	4	1	4.6 (0.1)	22.0 (0.0)	349.0 (42.7)
E	12	Bartlett	August	3	2	8.3 (0.6)	27.3 (1.1)	380.1 (175.8)
F	10	Red delicious	September	12	3	6.4 (1.9)	21.2 (1.7)	383.1 (76.6)

B. Heat stress assessment

Effective WBGT means and standard deviations are presented in *Table 8.* WBGT and dry air temperature generally increased during the day. Mean WBGT peaked in the hours between 11am and 2pm. Mean dry air temperatures continued to increase through the afternoon, peaking between the 2pm and 5pm. August temperatures were higher than September temperatures. Relative humidity decreased throughout the day, a known phenomenon related to the ability of increased air temperatures to hold more water (Davis, McGregor, & Enfield, 2016).

Table 8. Heat and humidity exposures (mean[SD])[1]

Time of day	WBGT	Effective WBGT[2]	Dry air temperature (°C)	Relative humidity (%)
Early morning 5am-8am (n=46)	12.6 (4.6)	13.8 (4.3)	15.4 (6.4)	65.5 (18.0)
August (n=34)	14.7 (3.2)	15.9 (2.9)	18.3 (4.8)	57.6 (14.1)
September (n=12)	6.6 (1.5)	8.1 (1.9)	7.3 (1.7)	87.7 (1.4)
Morning 8am-11am (n=46)	20.7 (4.1)	22.0 (4.1)	24.0 (4.3)	44.7 (10.7)
August (n=34)	22.6 (2.7)	23.8 (2.7)	26.0 (2.7)	42.7 (8.2)
September (n=12)	15.4 (2.9)	16.9 (3.0)	18.3 (2.3)	50.4 (14.7)
Midday 11am-2pm (n=38)	25.3 (4.5)	26.3 (4.3)	29.6 (4.6)	38.7 (13.4)
August (n=29)	27.3 (2.9)	28.2 (2.7)	31.4 (3.7)	39.7 (14.7)
September (n=9)	18.8 (1.1)	20.2 (1.6)	23.7 (1.1)	35.7 (7.5)
Afternoon 2pm-5pm (n=9)	22.3 (3.2)	24.0 (4.3)	30.0 (2.9)	30.5 (9.0)
August (n=3)	26.1 (3.1)	29.1 (3.1)	31.7 (2.4)	33.1 (2.9)
September (n=6)	20.4 (0.1)	21.4 (1.5)	29.2 (2.9)	29.3 (10.9)

[1]*Measurements taken near participants at the times indicated*

[2]*WBGT corrected for clothing adjustment factors*

Perceived exertion results are presented, stratified by month, along with WBGT exposure and productivity data, in *Table 9.* The self-reported exertion of workers increased throughout the day, except at the end of the lunch break. Workers in August reported greater perceived exertion in the morning than workers in September on the OMNI scale. However, workers in September had higher reported perceived exertion at the end of the shift compared to workers in August.

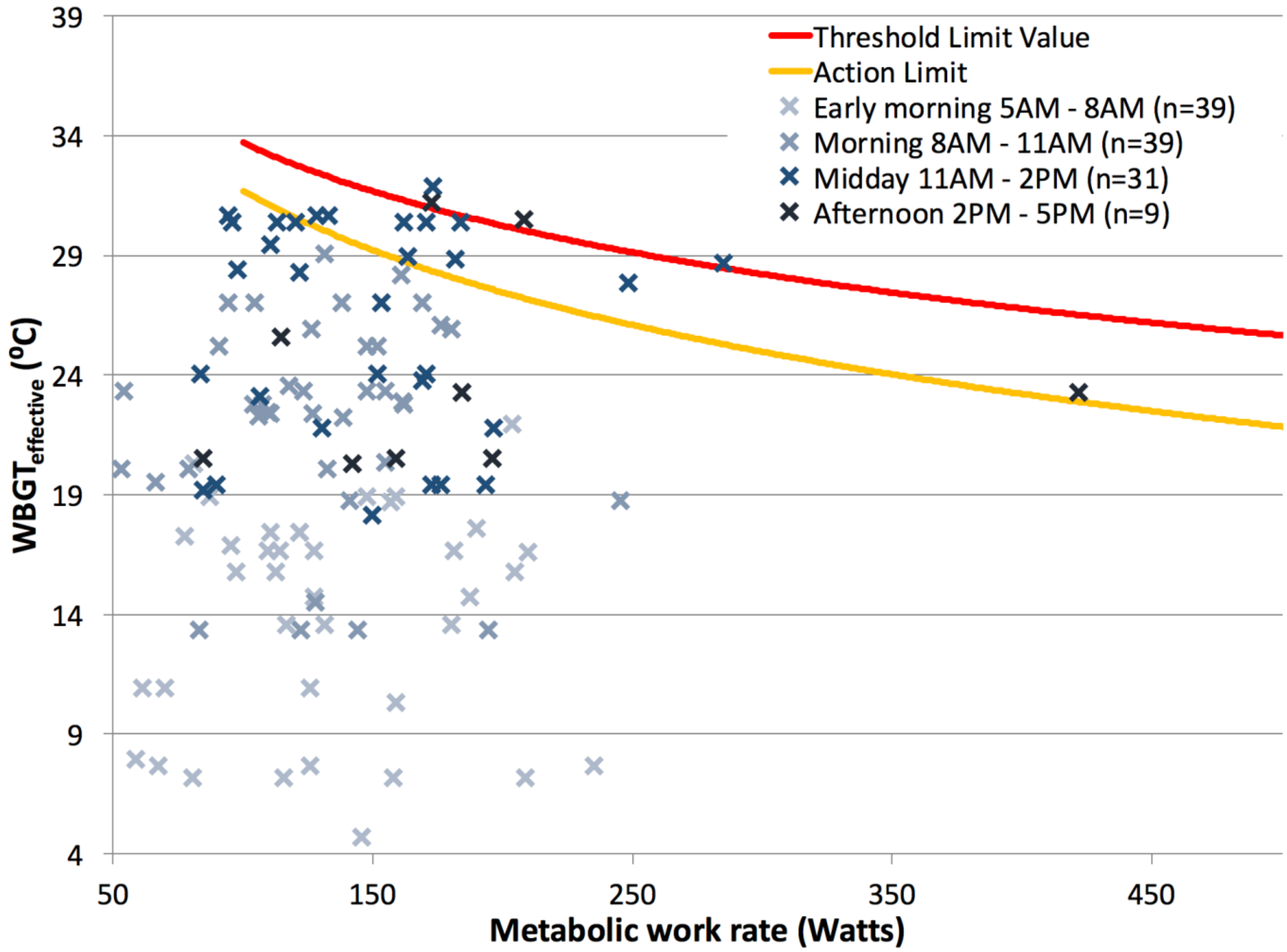
Table 9. WBGT exposure, productivity outcome, and perceived exertion

Characteristic	Mean (SD)
Hours worked	6.8 (1.5)
August	7.0 (1.3)
September	6.4 (1.9)
Total kilograms harvested per hours worked	340.7 (84.2)
August	327.0 (82.9)
September	383.1 (76.6)
$WBGT_{max}$	25.8 (4.1)
August	27.4 (3.4)
September	21.2 (1.7)
$WBGT_{full\text{-}shift\ time\text{-}weighted\ average}$	20.6 (3.7)
August	22.3 (2.6)
September	15.7 (1.1)
Perceived Exertion	
Start work (n=46)	1.3 (1.7)
Before lunch (n=38)	2.8 (1.6)
After lunch (n=38)	2.5 (1.6)
End work (n=46)	5.8 (2.7)
Perceived Exertion (August)*	
Start work (n=34)	1.5 (1.8)
Before lunch (n=28)	2.5 (1.6)
After lunch (n=28)	2.2 (1.5)
End work (n=34)	5.5 (2.4)
Perceived Exertion (September)*	
Start work (n=12)	0.7 (1.2)
Before lunch (n=10)	3.7 (1.3)
After lunch (n=10)	3.3 (1.4)
End work (n=12)	6.6 (3.4)

*Perceived exertion was self-reported on a scale of 1-10, with 10 complete exhaustion and 1 being 100% alert and ready for work

Metabolic workload, calculated from actigraph data, versus effective WBGT, stratified by three-hour periods of the work-shift, is plotted in *Figure 4.* Twelve participants exceeded the ACGIH Action Limit and four participants exceeded the ACGIH Threshold Limit Value. The periods of day when guidelines were exceeded were all either midday or afternoon.

Figure 3. Individual metabolic workload and average effective Wet Bulb Globe Temperature ($WBGT_{eff}$) stratified by time of day in comparison to American Conference of Governmental Industrial Hygienist's Threshold Limit Values and Action Limits (n=118)



C. Heat strain assessment

The twelve participants that exceeded the ACGIH Action Limit based on actigraph data in *Figure 3* underwent heat strain assessment. *Table 10* presents exceedances of ACGIH Action Limits and Threshold Limit Values stratified by month and how work activity level was assessed. Using ACGIH categorical classification of the work task as moderate, or 300 Watts, instead of actigraph data, 25 participants exceeded the Action Limit of 25°C WBGT and 20 of those 25 participants exceed the Threshold Limit Value of 28°C WBGT. One participant exceeded the Action Limit in the month of September using actigraph data. Exposures in the month of September were below the Action Limit when using the moderate category of workload.

Table 10**.** Prevalence of heat stress from effective Wet Bulb Globe Temperatures in harvesters using American Conference of Governmental Industrial Hygienists' guidelines for heat exposure

Characteristic	**August (n=34)**	**September (n=12)**
Exceeding ACGIH guidelines at moderate workload (300 W)		
Action Limit n(%)	25 (73.5%)	0 (0.0%)
Threshold Limit Value n(%)	21 (61.8%)	0 (0.0%)
Exceeding ACGIH guidelines using actigraph metabolic data (n=39)		
Action Limit n(%)	11 (40.7%)*	1 (8.3%)
Threshold Limit Value n(%)	4 (14.8%)*	0 (0.0%)

*n=27 participants with complete actigraph data

The 12 individuals exceeding the ACGIH Action Limit using actigraph data are described further in *Table 11*. The mean age was 35 (standard deviation=14) years and mean BMI 30 (standard deviation=4) kg/m^2. 67% of participants self-reported experiencing heat-related symptoms. Four of the participants answered ‘yes’ to having received formal HRI training.

Table 11. Individual characteristics of participants exceeding ACGIH Action Limit.

Participant	Date of participation	Age	BMI	Anti-hypertensive medication	Reported heat-related Symptoms	Acclimatized at beginning of season*	Received HRI training
1	8/1/15	25	27.2	No	No	No	No
3	8/1/15	61	26.7	Yes	No	No	Yes
4	8/1/15	25	33.7	No	Yes	No	No
10	8/4/15	34	25.3	No	No	Yes	Yes
11	8/4/15	43	31.0	No	Yes	No	*n/a*
14	8/5/15	29	26.9	No	Yes	No	No
21	8/12/15	32	29.9	No	Yes	No	No
22	8/12/15	27	31.2	No	Yes	No	No
32	8/19/15	42	28.6	No	Yes	Yes	Yes
35	8/19/15	19	29.4	No	No	*n/a*	Yes
36	8/20/15	23	26.6	No	Yes	Yes	No
39	9/23/15	63	40.2	No	Yes	No	No

*Acclimatization was assessed through a survey question asking if the worker gradually increased shift duration over the course of two-weeks to a an eight hour day

Table 12 presents the ACGIH heat strain evaluation of the 12 individuals exceeding the ACGIH Action Limit. Nine of the 11 participants (81%) exceeded recommended maximum heart rates. Participant three, a 61-year-old at worksite *A,* spent 89% of the shift in exceedance of the max heart rate. Participant 3 responded 'yes' to taking antihypertensive medication. Participant 21, a 32-year-old at worksite *C*, spent 37% of the shift in exceedance of the maximum heart rate. Participant 14, a 29-year-old at worksite *B*, had a core body temperature exceeding 38.5°C for nearly 32% of the shift.

Table 12. Heat strain summary of individuals exceeding American Conference of Governmental Industrial Hygienists Action Limit

Date	Participant	Orchard	Age	Max heart rate (180-age)	% time core temp >38.0°C	% time core temp >38.5°C	% time heart rate >heart $rate_{max}$
8/1/2015	1	A	25	155	38.0	13.8	*n/a**
8/1/2015	3	A	61	119	28.3	5.0	88.6
8/1/2015	4	A	25	155	0.0	0.0	0.0
8/4/2015	10	B	34	146	22.8	0.0	17.5
8/4/2015	11	B	43	137	13.6	0.0	1.1
8/5/2015	14	B	29	151	92.0	31.9	7.6
8/12/2015	21	C	32	148	54.4	0.1	37.4
8/12/2015	22	C	27	153	*n/a**	*n/a**	19.0
8/19/2015	32	E	42	138	0.0	0.0	0.3
8/19/2015	35	E	19	161	0.1	0.0	0.0
8/20/2015	36	E	23	157	14.2	0.0	0.1
9/23/2015	39	F	63	117	25.6	1.0	3.6

*Data was missing for participants

Moran *et al's* physiological strain index was used to evaluate the 12 participants exceeding the ACGIH Action Limit (*Table 13)* (1998). Participants 3, 10, 14, and 21 spent more than 43% of the work shift in a state of moderate heat strain. Participant 3 spent 17% of the work shift in a state of high heat strain. No participants exhibited extreme heat strain. Participants 1 and 22 did not have complete physiological data collected to calculate PSI.

Table 13. Physiological strain index heat strain summary of individuals exceeding American Conference of Governmental Industrial Hygienists Action Limits

Participant	Age	Baseline core temperature (°C)	Baseline heart rate (BPM)	Total time with complete PSI data (hours)	% time moderate heat strain	% time high heat strain	% time extreme heat strain
1	25	*n/a**	*n/a**	*n/a**	*n/a**	*n/a**	*n/a**
3	61	36.0	63.6	6.1	64.3	16.5	0.0
4	25	35.6	65.5	1.2	0.4	0.0	0.0
10	34	36.0	62.3	7.4	75.7	2.7	0.0
11	43	36.5	73.6	6.7	9.5	0.0	0.0
14	29	37.4	94.3	6.5	53.2	0.1	0.0
21	32	37.2	68.7	6.4	43.7	0.4	0.0
22	27	36.2	62.3	n/a*	n/a*	n/a*	n/a*
32	42	36.4	67.5	8.0	0.0	0.0	0.0
35	19	37.1	83.6	7.0	0.0	0.0	0.0
36	23	37.0	84.1	8.3	0.1	0.0	0.0
39	63	36.6	66.0	7.4	0.0	0.0	0.0

*Data not available

Figures 4-10 present continuous PSI for the 10 participants with complete physiological data exceeding the ACGIH Action Limit. Moderate heat strain, high heat strain, and extreme heat strain are plotted for reference across the entire day of collected physiological data. WBGT is also plotted on the secondary axis. In general, PSI tended to increase with increases in WBGT. On observation days when WBGT approached or exceeded 30°C, participants exhibited greater increases in PSI.

Figure 4. Continuous physiological strain index over the course of the work shift for participants 3 & 4

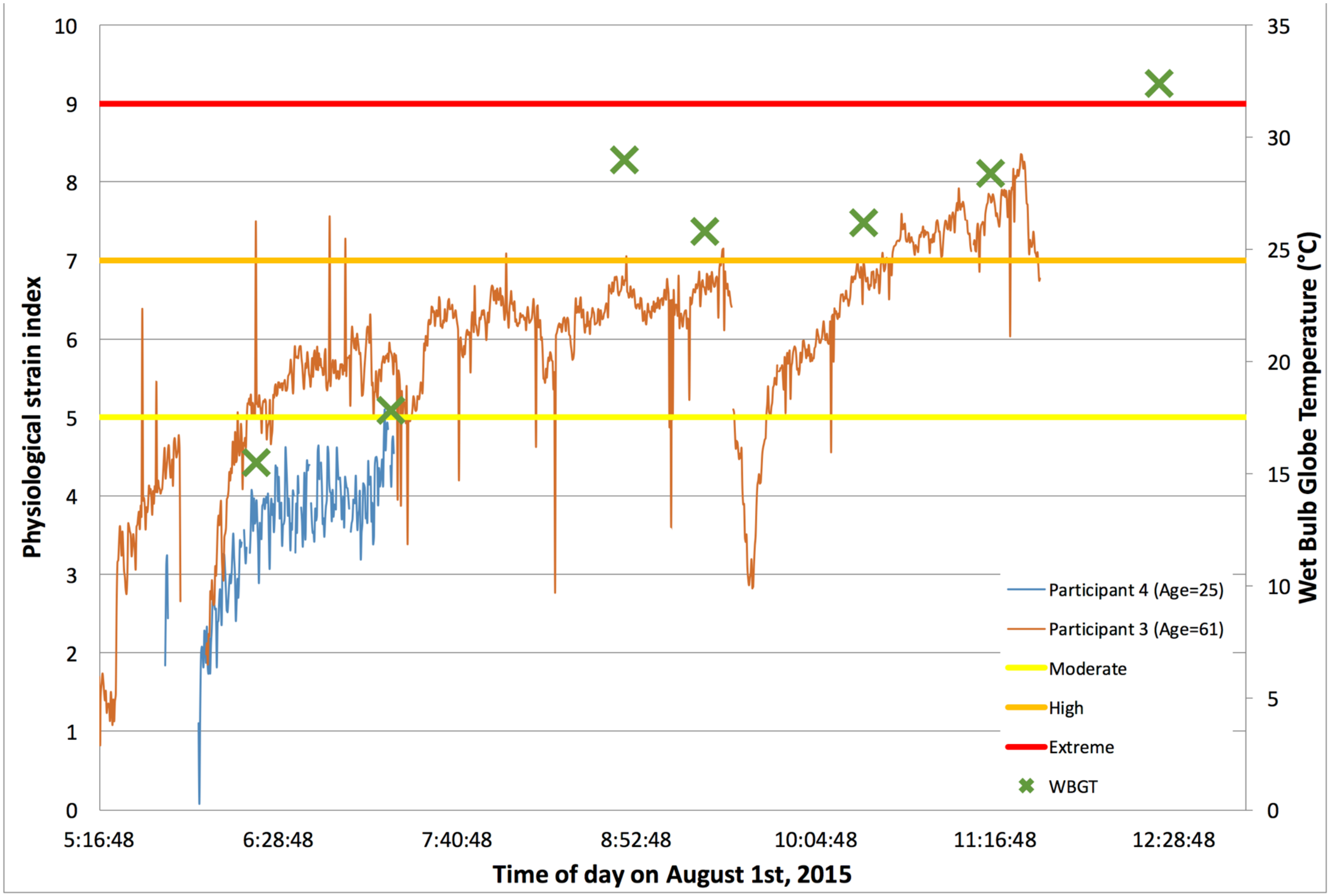


Figure 5. Continuous physiological strain index over the course of the work shift for participants 10 & 11

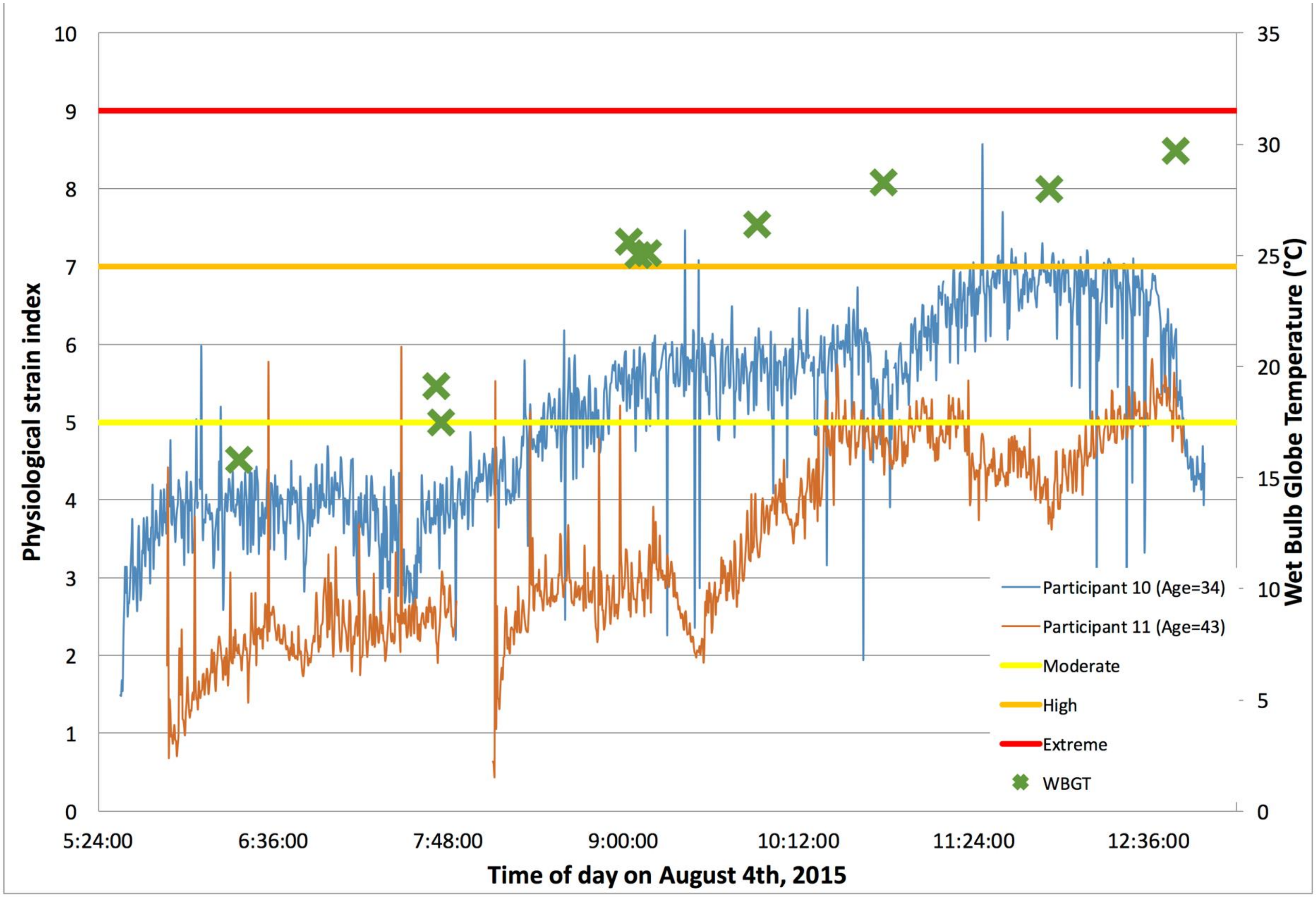


Figure 6. Continuous physiological strain index over the course of the work shift for participant 14

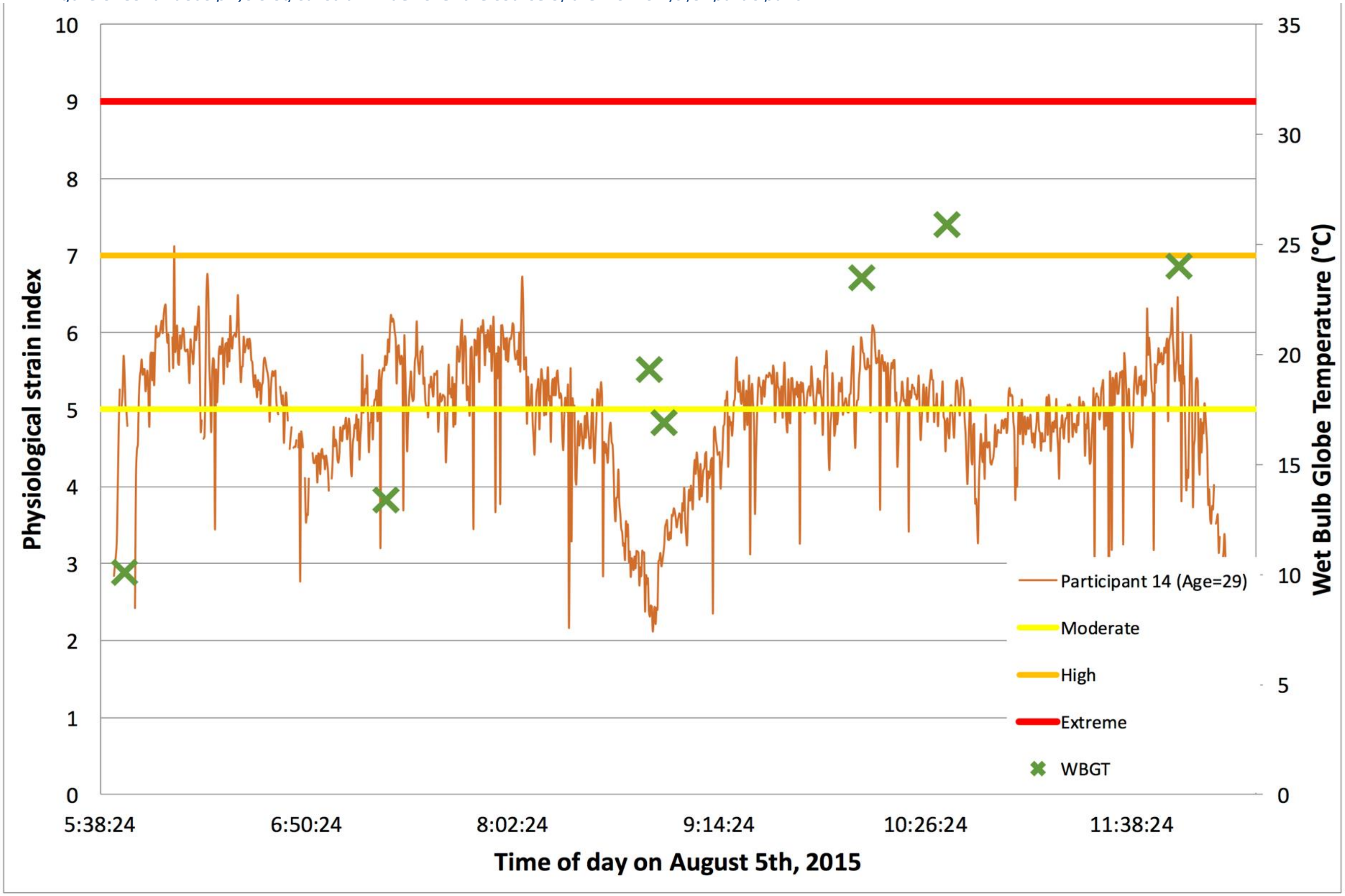


Figure 7. Continuous physiological strain index over the course of the work shift for participant 21

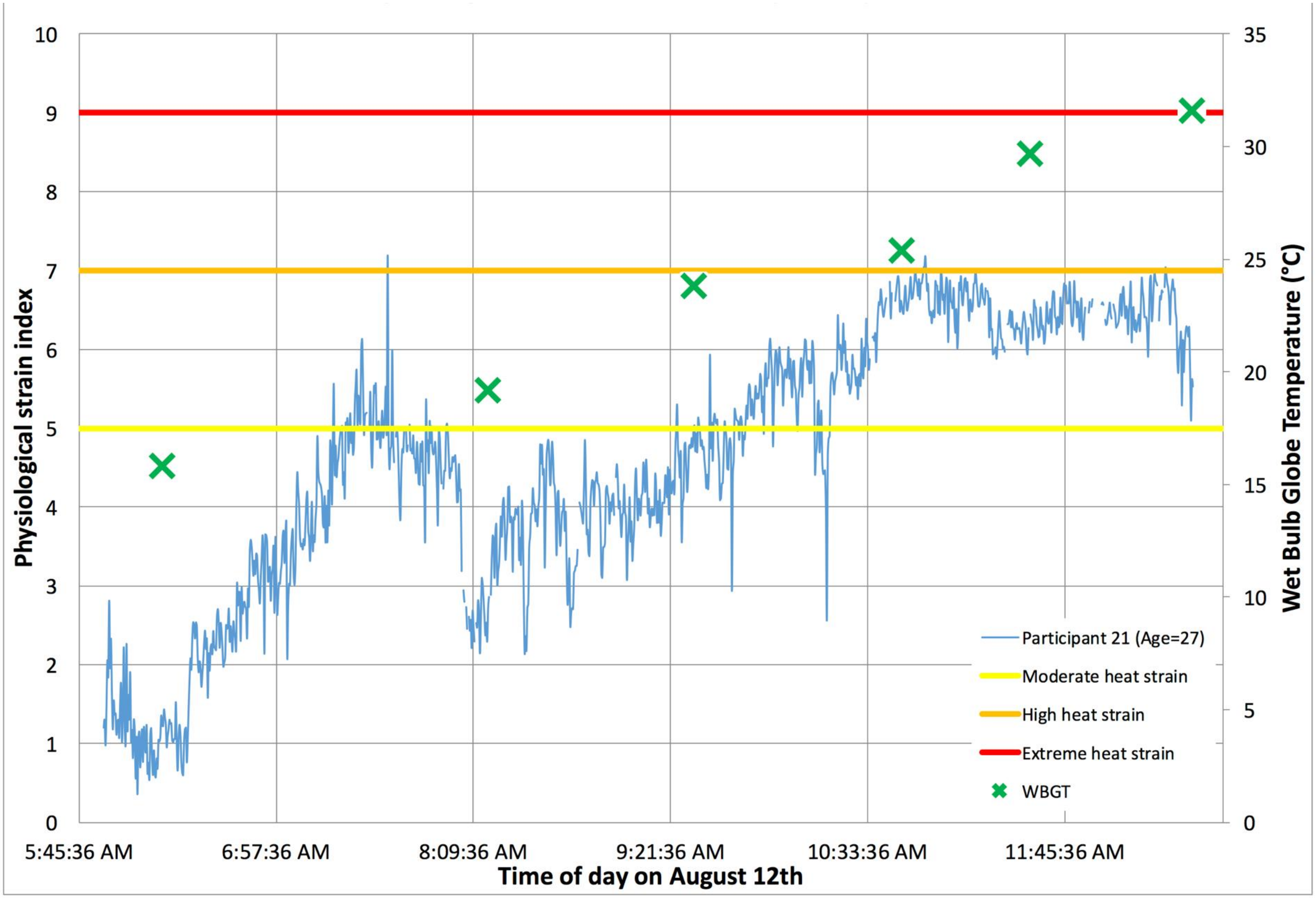


Figure 8. Continuous physiological strain index over the course of the work shift for participants 32 & 35

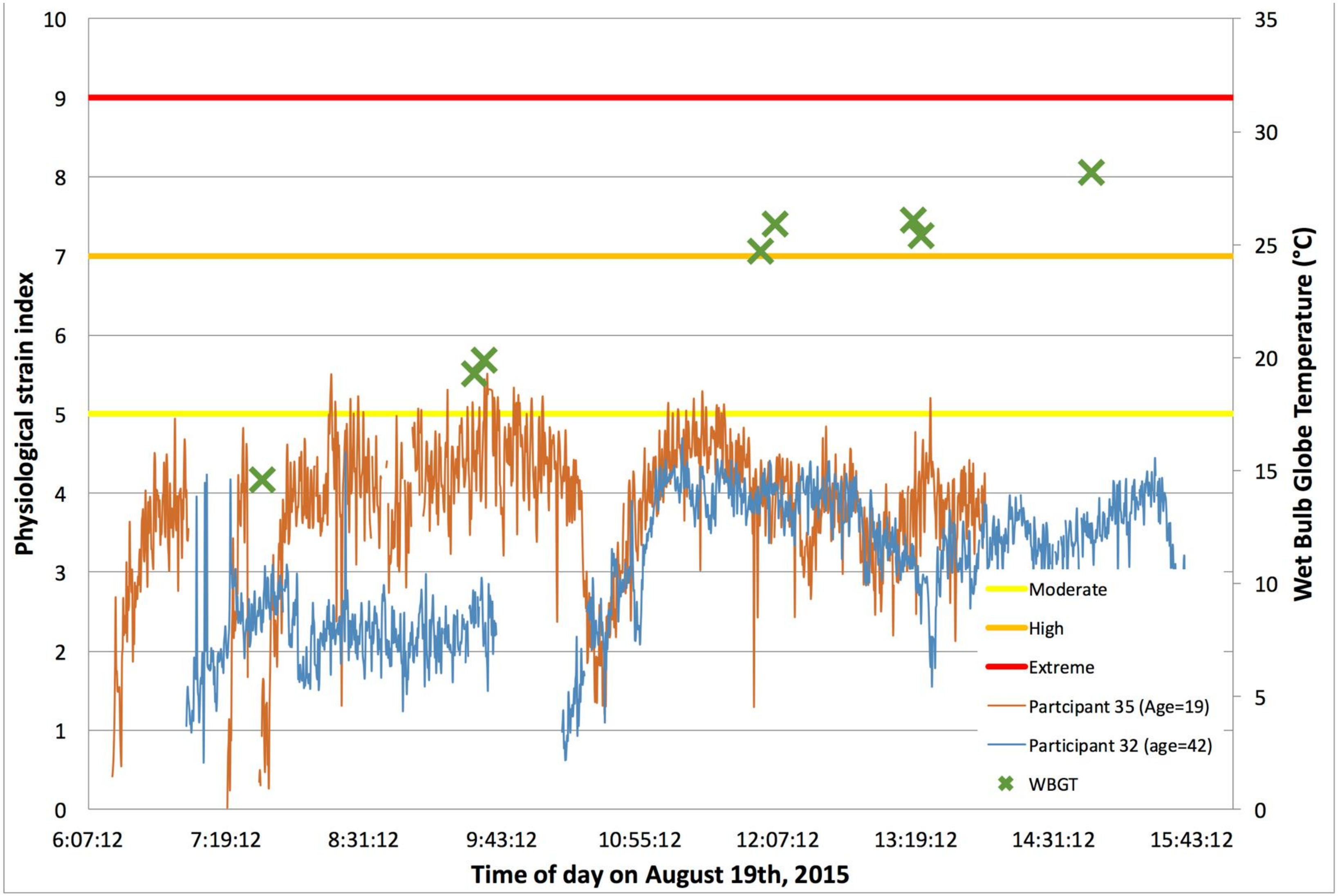


Figure 9. Continuous physiological strain index over the course of the work shift for participant 36

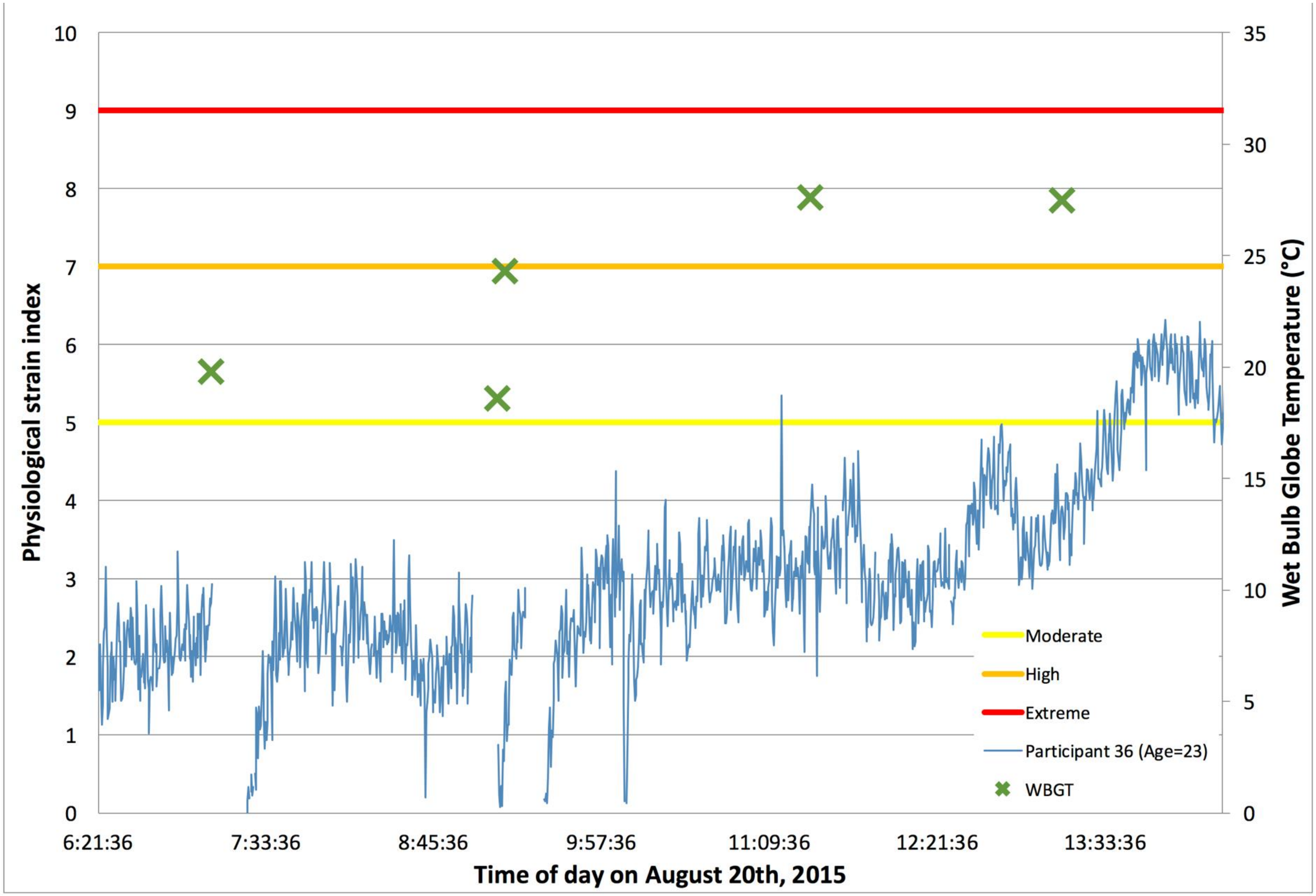
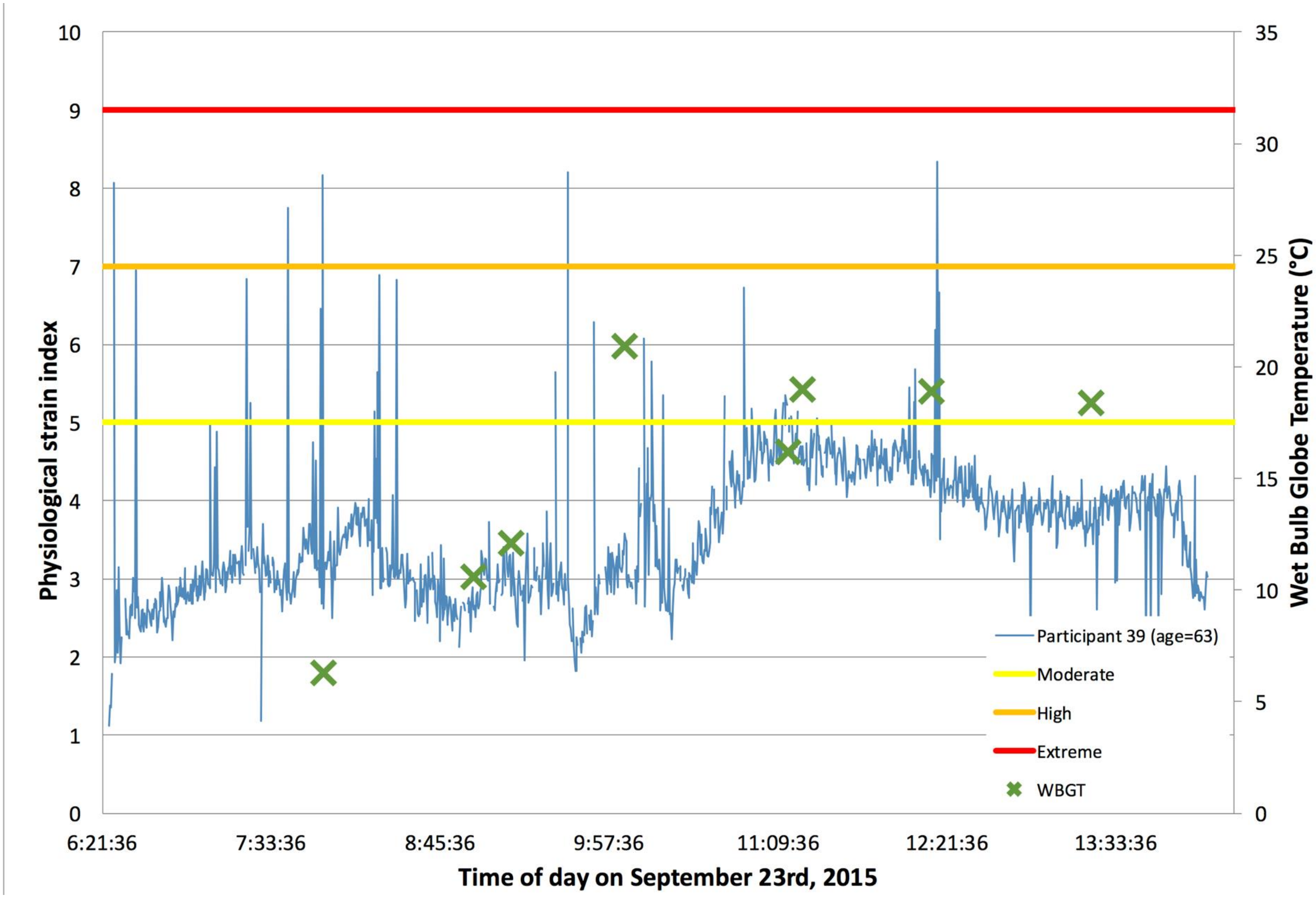


Figure 10. Continuous physiological strain index over the course of the work shift for participant 39



Specific Aim 2

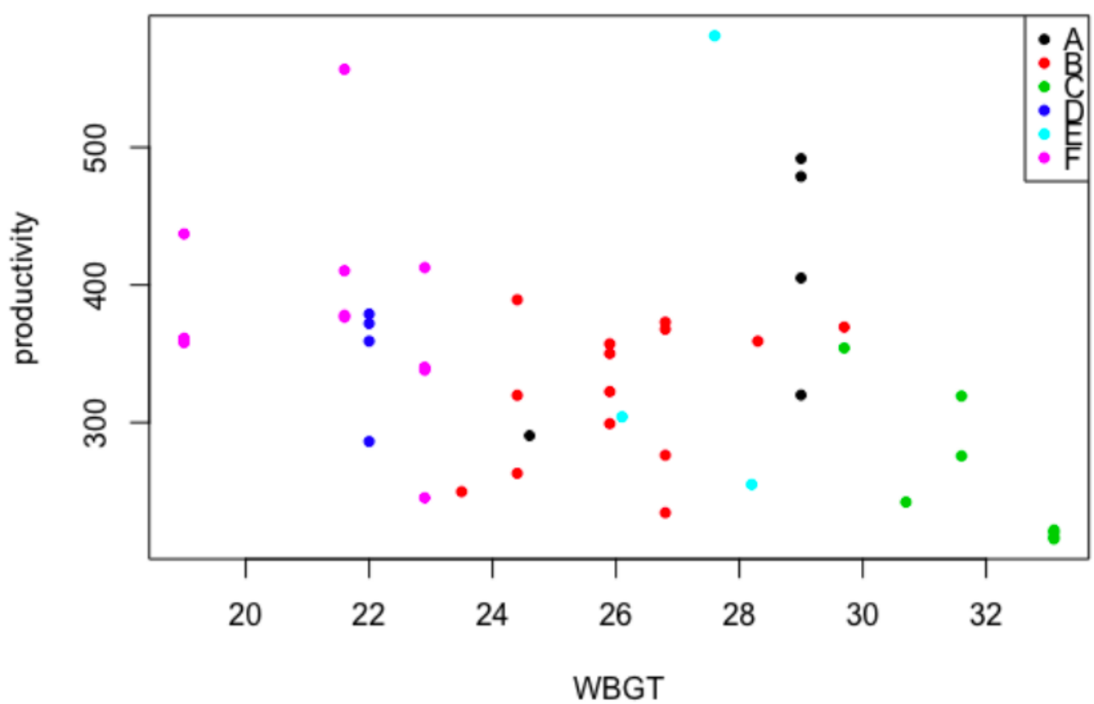
A. Results of descriptive analyses

A summary of mean maximum shift WBGT ($WBGT_{max}$) stratified by month is shown in *Table 9.* Mean $WBGT_{max}$ during the study was 25.9°C (SD=4.1). August (Bartlett Pear harvest) had a higher mean $WBGT_{max}$ of 27.4°C (SD=3.4) than September (Red Delicious Apple harvest; mean $WBGT_{max}$ of 21.2°C [SD=1.7]). *Table 7* summarizes mean $WBGT_{max}$ by participating orchard. Orchard C had the highest mean $WBGT_{max}$ of 32.0°C (SD=1.3). Orchard F had the lowest mean $WBGT_{max}$ of 21.2°C WBGT (SD=1.7). Orchard F was the only apple orchard, and workers from this orchard participated in September.

Mean productivity in the whole study sample was 340.7 kilograms per hour (SD=84.2) (*Table 9*). August had a lower productivity of 327.0 kg/hr (SD=82.9) than September 383.1 (SD=76.60). *Table 7* displays productivity stratified by orchard. Orchard A had the highest mean productivity of 397.2 kg/hr (SD=90.9). Orchard C had the lowest mean productivity of 258.2 kg/hr (SD=53.2). Productivity was generally higher during apple harvest than during pear harvest (*Figure 12*). *Figure 13* shows a scatter plot of $WBGT_{max}$ and productivity, stratified by orchard. Orchard C had the highest WBGT exposures and the lowest productivity outcomes.

Figure 11. Box plot of productivity (kg/hr) and type of crop

Figure 12. Productivity (kg/hr) versus maximum shift Wet Bulb Globe Temperature (degrees Celsius), stratified by orchard (A-F)



Age (<30, 30-45, and >45 years) and work experience (<1, 1-2, 3-5, 6-9, >9 years) were significantly associated, chi-square (8, *N*=46) = 18.12, *p*=0.02. There was no obvious relationship between age and productivity (*Figure 14*), but productivity appeared to increase with increasing work experience (*Figure 15*). Given the small sample size, experience was included in adjusted models of the association between $WBGT_{max}$ and productivity rather than age (see subsection B. Association between $WBGT_{max}$ and productivity, below).

Figure 13. Productivity (kg/hr) versus age (years), stratified by orchard (A-F)

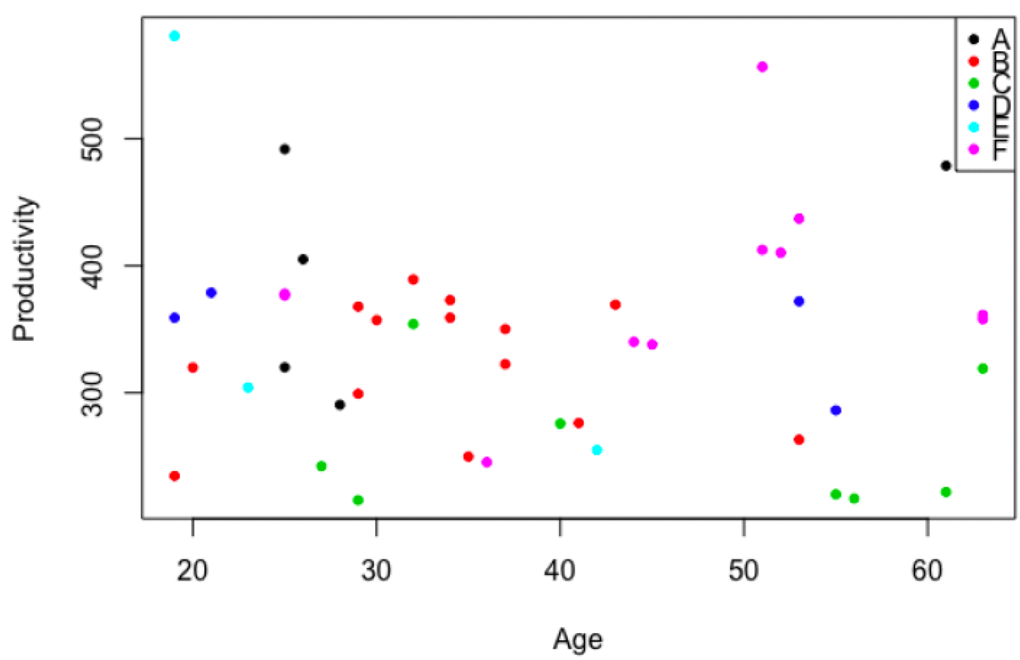
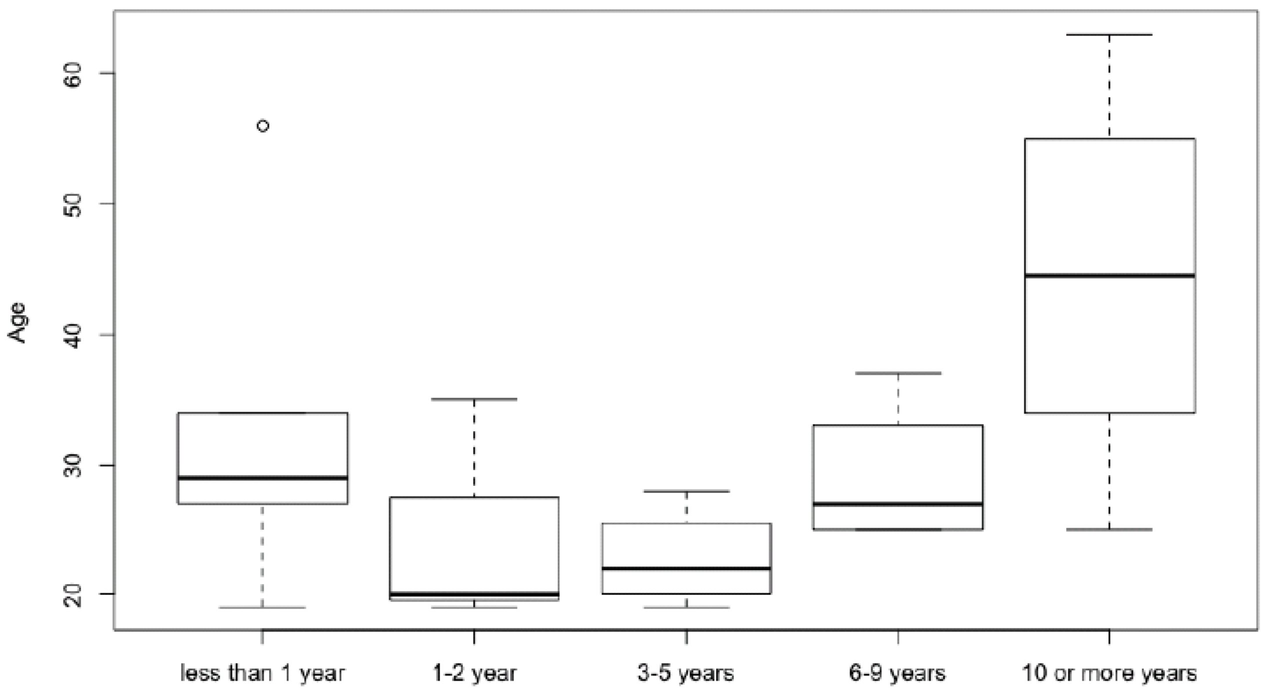


Figure 14. Box plot of age (years) and work experience (years)



Gender differences in productivity were explored. Of the 46 participants, seven (15.2%) were female. Of those seven female participants, five (71.4%) harvested Red Delicious apples during the September harvest, and one female participant was missing productivity data. Scatter plots of productivity versus $WBGT_{max}$ were stratified by gender and orchard, as shown in *Figure 16.* There appeared to be a trend of lower productivity with increasing $WBGT_{max}$ for both males and females. A scatter plot of BMI and productivity is shown in *Figure 15.* Individuals with a BMI between 25 and 30 kg/m^2 had the highest productivity.

Figure 15. Productivity (kg/hr) versus WBGT (degrees Celsius) in males and females, stratified by orchard (A-F)

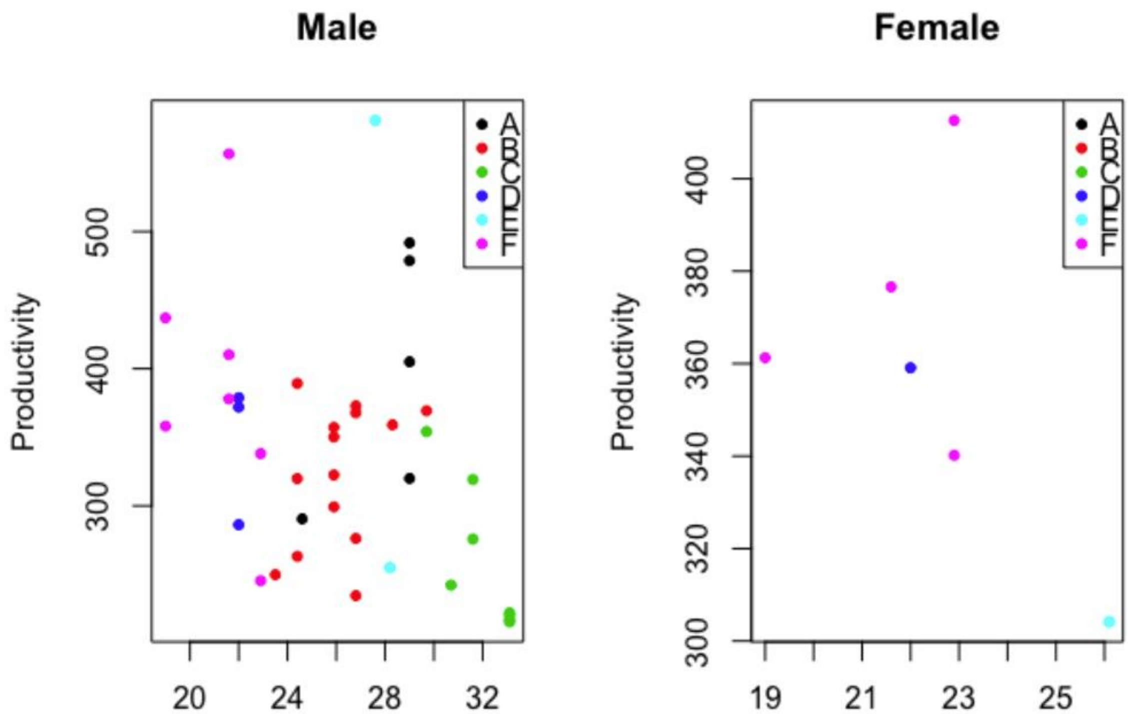
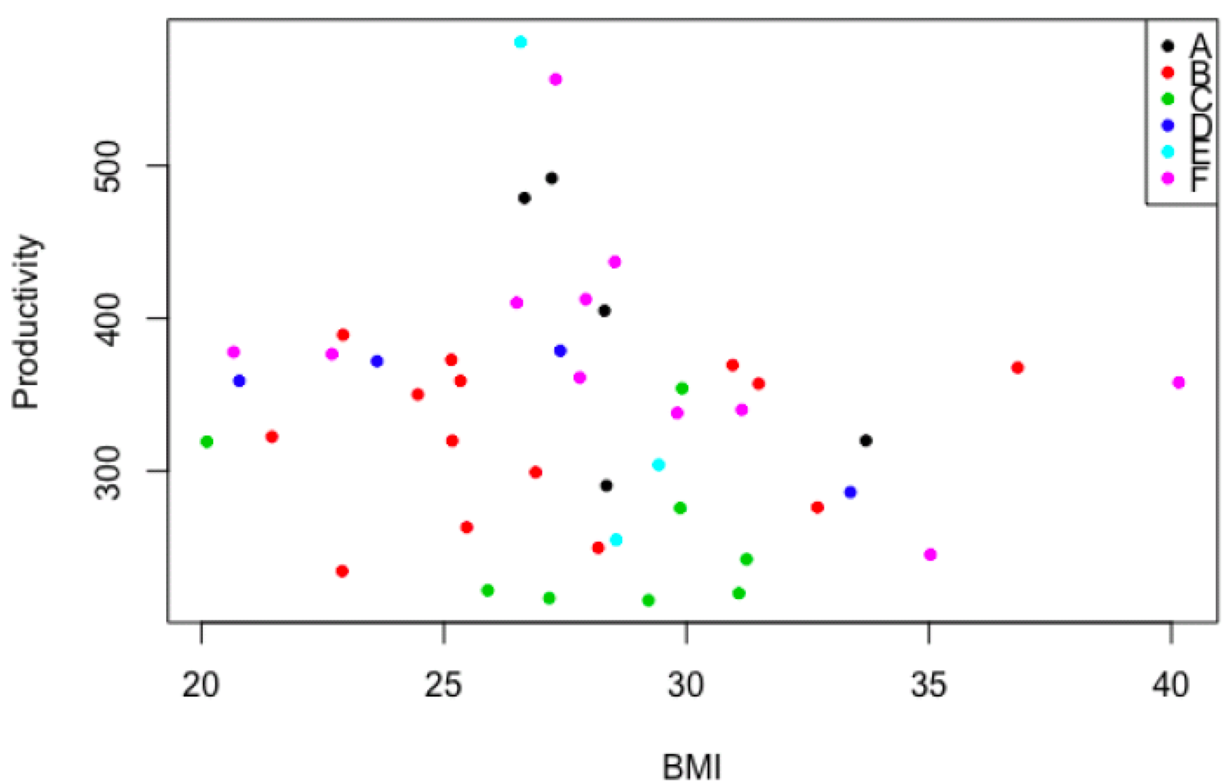


Figure 16. Productivity (kg/hr) versus body mass index (kg/m^2), stratified by orchard (A-F)



Price per bin varied between orchards. The range of prices paid per bin filled was $15 - $25. The orchard paying $25 per bin only had 3 participants, therefore it was combined with the $21 per bin orchard. As shown in *Figure 16*, the lowest price per bin was characterized by the highest mean productivity. The relationship between shift duration and productivity was explored in *Figure 17.* In general, longer shift times appeared to be related to lower productivity.

Figure 17. Box plot of productivity (kg/hr) by price per bin ($)

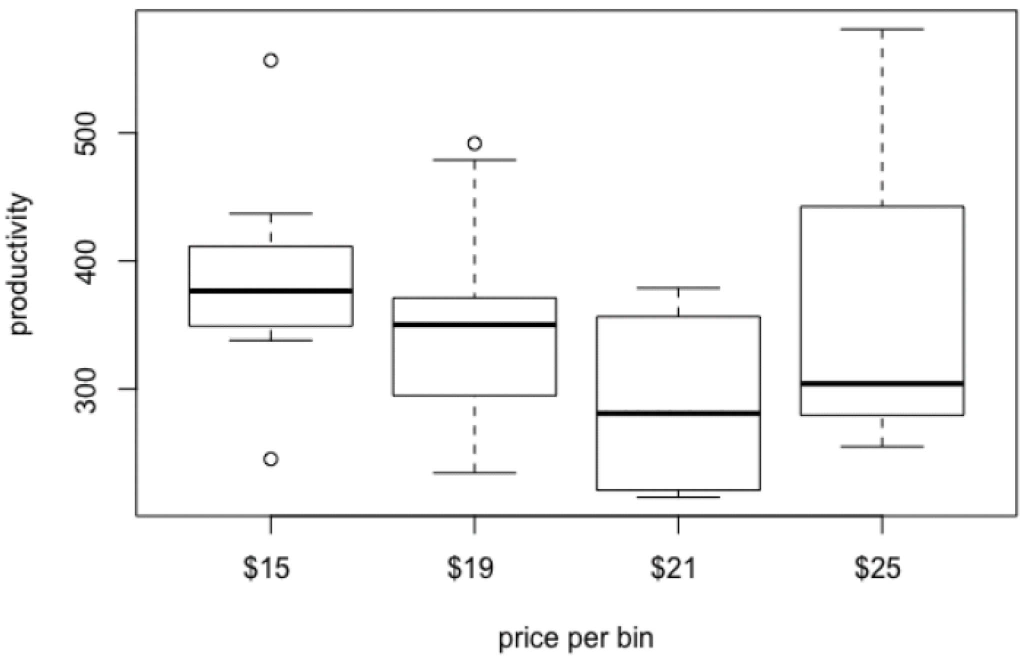
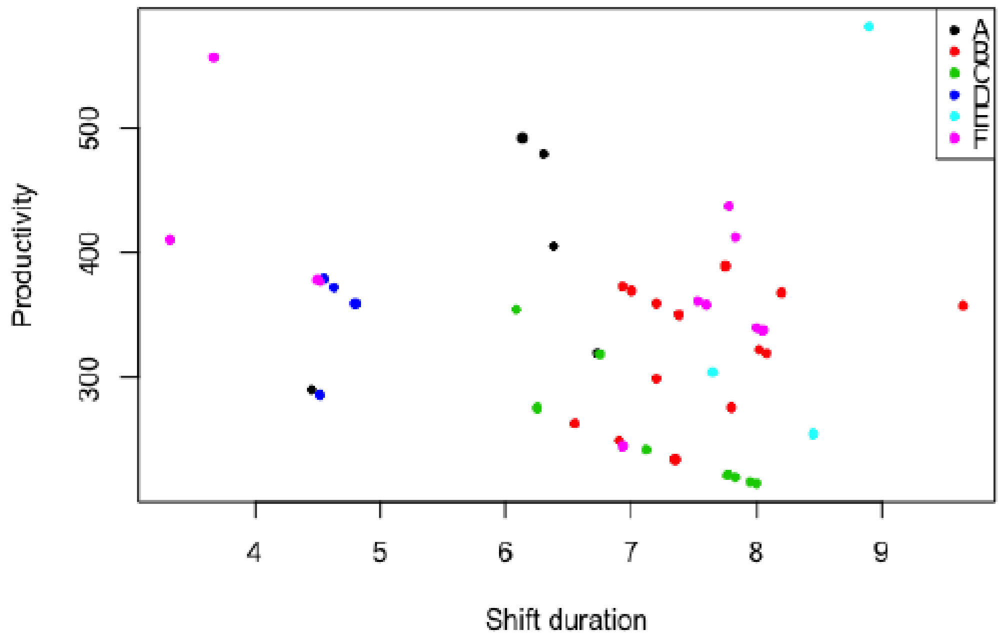


Figure 18. Productivity (kg/hr) versus shift duration (hr), stratified by orchard (A-F)



B. Association between $WBGT_{max}$ and productivity

Figure 20 shows unadjusted effect estimates from the linear mixed effects model of productivity with random effects for worksite. There was a trend toward a decrease in productivity with increasing $WBGT_{max}$, but this relationship was not statistically significant (coefficient for $WBGT_{max}$ -4.84, 95% confidence interval -16.31, 6.62). After adjustment for gender and experience, the effect estimate was similar and the estimate less precise (*Figure 21*; coefficient for $WBGT_{max}$ -6.13, 95% confidence interval -15.44, 3.18). After adjustment for BMI and price per bin, the effect estimate decreased substantially (*Figure 22*; coefficient for $WBGT_{max}$ -1.00, 95% confidence interval -18.07, 16.07). The coefficient for $WBGT_{max}$ was -0.70, 95% confidence interval -19.80, 18.93 after adjustment for all covariates *(Figure 23)*.

Figure 19. Effect estimate, 95% confidence interval, and *p*-value from unadjusted linear mixed effect model of productivity with random intercept for orchard

$$\text{(1) } Productivity_{ij}|b_{0i} \overset{independent}{\sim} N(\beta_0 + b_{0i} + \beta_1 WBGT_{ij}, \sigma_e^2),$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \ldots, 6$$

	N	estimate	95% C.I lower	95% C.I higher	p-value
(Intercept)		471.25	165.86	776.64	0.01
WBGT		-4.84	-16.31	6.62	0.35

Figure 20. Effect estimates and 95% confidence intervals from adjusted linear mixed effect model of productivity with random intercept for orchard, adjusted for gender and experience

$$\text{(2) } Productivity_{ij}|b_{0i} \overset{independent}{\sim} N(\beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, \sigma_e^2),$$
$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \ldots, 6$$

	N	estimate	95% C.I lower	95% C.I higher	p-value
(Intercept)		441.01	183.06	698.97	0
WBGT		-6.13	-15.44	3.18	0.15
Gender					
male	39	Ref			
female	6	-4.37	-89.45	80.72	0.92
Experience					
less than 1 year	5	Ref			
1-2 year	3	12.95	-121.46	147.35	0.85
3-5 years	4	102.51	-17.74	222.77	0.09
6-9 years	4	114.35	1.09	227.62	0.05
10 or more years	29	60.90	-22.20	143.99	0.15

Figure 21. Effect estimates and 95% confidence intervals from adjusted linear mixed effect model of productivity with random intercept for orchard, adjusted for gender, experience, body mass index, and price per bin

$$(3)\ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N\begin{pmatrix}\beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, \\ +\beta_4 BMI_{ij} + \beta_5 price/bin_{ij}, \sigma_e^2\end{pmatrix},$$

$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \ldots, 6$$

	N	estimate	95% C.I lower	95% C.I higher	p-value
(Intercept)		491.08	80.13	902.03	0.02
WBGT		-1.00	-18.07	16.07	0.89
Gender					
male	39	Ref			
female	6	-23.24	-103.08	56.60	0.56
Experience					
less than 1 year	5	Ref			
1-2 year	3	23.10	-106.93	153.13	0.72
3-5 years	4	106.9	-34.08	247.87	0.13
6-9 years	4	93.31	-18.03	204.64	0.10
10 or more years	29	55.35	-26.77	137.48	0.18
BMI		-4.75	-10.43	0.93	0.10
Price per bin					
$15	11	Ref			
$19	19	-36.74	-372.59	299.12	0.66
$21 and $25	15	-67.28	-316.14	181.58	0.43

Figure 22. Effect estimates and 95% confidence intervals from adjusted linear mixed effect model of productivity with random intercept for orchard, adjusted for gender, experience, body mass index, price per bin, and shift duration.

$$\text{(4)}\ \ Productivity_{ij}|b_{0i} \overset{independent}{\sim} N\begin{pmatrix}\beta_0 + b_{0i} + \beta_1 WBGT_{ij} + \beta_2 gender_{ij} + \beta_3 experience_{ij}, + \beta_4 BMI_{ij} \\ + \beta_5 price/bin_{ij} + \beta_6 duration_{ij}, \sigma_e^2\end{pmatrix},$$

$$b_{0i} \overset{iid}{\sim} N(0, \sigma_b^2), i = 1, \ldots, 6$$

	N	estimate	95% C.I lower	95% C.I higher	p-value
(Intercept)		489.47	43.35	935.59	0.04
WBGT		-0.70	-19.80	18.39	0.93
Gender					
male	39	Ref			
female	6	-22.71	-106.20	60.78	0.58
Experience					
less than 1 year	5	Ref			
1-2 year	3	22.94	-109.08	154.96	0.73
3-5 years	4	104.73	-42.06	251.52	0.15
6-9 years	4	92.00	-21.32	205.31	0.11
10 or more years	29	54.57	-28.96	138.09	0.19
BMI		-4.64	-11.04	1.77	0.15
Price per bin					
$15	11	Ref			
$19	19	-37.00	-488.63	414.62	0.69
$21 and $25	15	-67.94	-373.85	237.96	0.46
duration		-1.14	-27.03	24.76	0.93

DISCUSSION

Interpretation of results

A. Heat stress

In our study, harvest workers were observed to labor under heat stress conditions. Using field observations and ACGIH work-task categories to estimate metabolic heat production, over half of pear harvest participants in our study exceeded the ACGIH Threshold Limit Value for heat stress during the month of August. No apple harvest workers exceeded the Threshold Limit Value during the month of September. These exceedances generally occurred in the mid-day or afternoon, around the time that WBGT peaked. Similar findings have described peak WBGT occurring prior to later afternoon peak dry air temperatures (Farshad, Montazer, Monazzam, Eyvazlou, & Mirkazemi, 2014; Crowe, Wesseling, Solano, Umana, Ramirez, Kjellstrom, Morales, Nilsson, 2013). These peaks earlier in the day may be due to air's increased capacity to hold water at hotter temperatures (Davis, McGregor, & Enfield, 2016).

Using actigraph data to estimate metabolic workload may have under-estimated the magnitude of heat stress during harvest. Only fifteen percent of August pear harvest workers exceeded the Threshold Limit Value for heat stress using actigraph estimates of metabolic workload. Harvest is an upper-extremity intensive task. Although objective estimates of metabolic workload are appealing, the ActiGraph devices used in our study have only been validated on the hip, where they were mounted on our participants, and not on the wrist (ActiGraph, 2016). Better, validated methods for estimating metabolic workload for harvest tasks are needed.

We observed the allocation of work in the work cycle to be 75%-100% in participants, with breaks often being less than 15 minutes. At this allocation of work in the work cycle for moderate workloads, the ACGIH heat stress Threshold Limit Value is 28°C WBGT. Increased break time would have reduced exceedances of the ACGIH heat stress Threshold Limit Value. At 29°C WBGT for moderate work, the allocation of work in a work and recovery cycle would need to be 50 to 75% to avoid exceedances of the Threshold Limit Value (ACGIH, 2015). A shift duration of 6.8 hours would require 1.7 hours, or 102 minutes, of rest during a work cycle at temperatures greater than 29°C WBGT.

B. Heat Strain

The heat strain assessment for the 12 workers who exceeded the ACGIH Action Limit using actigraph estimates of metabolic workload revealed that five workers (42%) spent more than 10% of their shift time either exceeding the core body temperature (38.5°C) or the maximum heart rate (180-age) recommended by ACGIH. These findings are similar in other investigations in outdoor occupational settings. Meade et al. found in North American utility workers that six of the 12 manual pole workers performing strenuous tasks exhibited internal core body temperatures in excess of 38.5°C (2015). North American utility workers with other jobs tasks deemed less strenuous never exceeded the core body temperature threshold of 38.5°C (Meade, Lauzon, Poirier, Flouris, & Kenny, 2015).

The participant with the longest percent of his shift exceeding the recommended core body temperature (32%; 2.1 hours) was 32 years old at the time of harvest. Exertional heat stroke primarily affects younger healthy workers (NIOSH, 2016). A report from the United States

Armed Forces Health Surveillance Center reported the highest incident rate of heat injury in the age group <20 years old of 4.19 per 1,000 person years (2014).

The participant with the largest percent of his shift exceeding the recommended heart rate (89%; 5.4 hours) was over 60 years old. Participant 3 indicated taking antihypertensive medication. Individuals older than 60 years old are at greater risk of heat strain (Kenny, Yardley, Brown, Sigal, & Jay, 2010). Cardiovascular strain in aging working populations is especially concerning as the ability to vasodilate, dissipating heat through the skin, is significantly reduced (Sagawa, Shiraki, Yousef, & Miki, 1988). Kenney *et al.* found that hypertensive individuals have reduced capacity to increase blood flow to the forearm under thermal stress compared to normotensive individuals (1984).

Using Moran *et al's* PSI approach, 40% of workers without missing heat strain data (n=10) spent more than 40% of their work shift time in a state of moderate heat strain. Participant 3 spent 16.5%, or 1.0 hour, of his day in a state of high heat strain. Work shift trends in physiological strain generally increased during the work-shift as WBGT exposures increased and with decreases at the end of breaks. After breaks, the steepest slope of increasing physiological strain was observed, consistent with previous studies (Pilch, Szygula, Palka, Pilch, Cison, Wiecha, Tota, 2014). This may be due to the body storing heat in extremities, including thighs, which acts as a source of internal heat once activity is reassumed. Longer breaks or improved cooling practices during breaks may limit steep increases in physiological strain after a rest break.

Other personal factors, including BMI and overall fitness levels, must be considered when evaluating HRI risk. Using actigraph data, the one participant exceeding the ACGIH Action Limits in September was participant 39. Participant 39 had the highest BMI of all participants in the study (40.2 kg/m^2). Obesity is a known risk factor for the development of HRI (Bar-Or, Lundegren, & Buskirk, 1969: Havenith, Coenen, Kistemaker, & Kenney, 1998). Henschel reported fatal heat stroke occurs 3.5 times more frequently in adults with overweight or obesity than in individuals of average body weight (1967).

The self-reported exertion of workers using the OMNI scale also increased throughout the day, except at the end of the lunch break. Workers in August, whose shifts started earlier in the morning than apple harvest workers in September because of differential sunrise times, reported greater perceived exertion at the start of the shift than workers in September. However, workers in September had higher reported perceived exertion at the end of the shift compared to workers in August. Although exertion may have been greater during apple harvest (mean productivity was higher during apple compared to pear harvest), exertion must be combined with other factors including environmental heat exposure, to influence heat strain.

Two thirds of the 12 participants exceeding the ACGIH Action Limit reported exhibiting heat-related symptoms of either dizziness/light-headedness or heavy sweating at work, and less than half reported gradually being exposed to heat at the start of the season or having had HRI training. Yet, the Washington Heat Rule requires HRI training for all employees prior to outdoor work exceeding dry air temperatures of 31.7° C (89° F) (WAC, 2015). If employees are required to wear jackets or sweatshirts the threshold temperature falls to 25°C (77°F) (WAC, 2015). Identification and recognition of HRI symptoms are vital to preventing heat stroke. Since HRI can manifest with altered cognition, it is especially important that nearby co-workers are capable of recognizing HRI. The discrepancy in the low prevalence of self-reported HRI training and high prevalence of heat strain in our study population is concerning.

C. Association between heat exposure and productivity

We found a trend of decreased productivity with increased WBGT, but this finding was not statistically significant. Sahu *et al* reported a negative association between productivity and WBGT in rice harvesters in India, where heat exposures were substantially higher than in our study. Participants in Sahu *et al*'s study were able to pace themselves, and the human body's natural response to heat stress is to slow down and rest. In contrast, all participants in our study were paid by the amount harvested (piece-rate). Piece-rate workers are incentivized to harvest quickly, and this monetary incentive is counter to the body's natural response to slow down in the heat. It is possible that, for this reason, workers in our study were less likely to reduce their productivity in the heat, placing them at greater risk for heat strain and HRI.

Other studies have attempted to explore the relationship of productivity and WBGT. Lundgren *et al.* found that in various occupations in Chennai, India, productivity could be reduced by about 50% in certain high heat occupations (2014). Sett et al. found that female brick workers in India had productivity losses of 2% for every increase of degree of air temperature (2014). However, these studies did not attempt to evaluate other potential confounding factors of the relationship between heat exposure and productivity.

Studies have attempted to project impacts on productivity under conditions of climate change. Dunne *et al's* analysis estimated current and future WBGT in Southeast Asia (2013). Dunne *et al* directly applied ACGIH guidelines for work-rest cycles to country level data (2013). Dunne *et al* estimated labor reductions of 80% in peak summer months of 2050 (2013). Kjellstrom *et al* similarly estimated losses in productivity in exceedance of 50% by the year 2050 for moderate and heavy work (2013). These studies did not assess individual factors related to productivity, including payment schemes or personal factors. Our study suggests individual and worksite factors have an effect on the association of WBGT and productivity.

In our adjusted models, it appeared that price paid per bin confounded the association of WBGT with productivity. The lowest price per bin ($15) was paid to apple harvesters in our study, who had the lowest heat exposures. A low price per bin was paid for Red Delicious apple harvest in our study because they are not easily bruised when harvested and the trees in apple orchard F were small and full of apples (Pablo Palmández, e-mail correspondence, May 3, 2016). Interestingly, there was a trend of decreasing mean productivity with increasing price paid per bin. One possible explanation for this trend is that workers target a particular amount of money to earn per day, and they need to fill less bins to reach this target if bins are priced higher.

Gender was associated with WBGT and productivity, as five of the seven female participants participated in apple harvest in September. The participating September orchard (F) had a high mean productivity compared to other orchards. Experience was associated with increased productivity, but there did not appear to be a clear relationship between BMI and productivity. Adjustment for gender and work experience did not influence effect estimates of the association between WBGT and productivity dramatically. Productivity decreased with increasing shift duration. One potential explanation for this observation is that workers who work longer hours have less easily available fruit to harvest and harvest becomes less efficient.

The mean work shift was longer during warmer pear than cooler apple harvest. Longer shift times during the hotter pear harvest may have also impacted productivity. Shift times with increased durations result in more time spent working in warmer environmental conditions in the afternoon. Maximum daily WBGT may have best represented exposure during these shifts, when Action Limits and Threshold Limit Values were exceeded.

Different crops have different sensitivities to bruising, and this may have implications for the amount of fruit harvested. Bartlett pears are less likely to bruise compared to Red Delicious apples (Pablo Palmández, e-mail correspondence, May 3, 2016). Therefore, workers may need to take less care when handling pears versus apples. This handling difference could result in a smaller amount of fruit harvested. Other factors affecting productivity differences between orchards may include fruit density on the tree, fruit volume, spacing of trees, harvesting practices, and distance to harvest bins.

Limitations

This study has several important limitations. We only analyzed productivity data from the end of the work shift. We did not have accurate productivity data during the course of the work shift. Such data would have given a more refined picture of how heat stress, heat strain, and productivity change during the course of a work shift. We also did not have individual weight measurements for bins collected at the end of shifts, and some workers shared their bins with family members. Although we accounted for shared bins, these issues could have resulted in misclassification of our productivity outcome. If non-differential, this misclassification may driven any true effect of WBGT on productivity towards the null.

Second, it was somewhat difficult to differentiate crop from orchard differences since there was only one participating apple orchard. There were also numerous orchard factors that we did not assess that could result in variability in productivity between orchards. These include differences in management practices, harvesting practices, distance from trees to bins, tree growth and condition, and terrain. At some of the participating orchards, owners preferred that harvesters pick every piece of fruit, including ripe fruit, pre-mature fruit, and fruit past the point of commercial consumption. Fruit not suitable for consumption would be discarded onto the ground. The practice of picking a tree clean could add significant time and effort to the work task while not contributing to the final weight of fruit placed into bins. Younger participating orchards had trees easily accessible by foot, as compared to participating orchards with older trees that required ladders to access the fruit. Bartlett pears are denser, and full bins harvested weighed 950 pounds. To fill these bins, harvesters made more trips to the bin than for apples, which had a mean bin weight was 750 pounds. Future studies with more participating orchards and that assess relevant orchard characteristics that we were not able to assess in our study are needed.

Third, the ACGIH heat stress TLV methods are not intended for use at the individual level, although individual heat strain assessments are recommended at exposures above the Action Limit. Yet, it is known that heat exposure varies within an orchard (Snyder, & Connell, 1993), and a job-based assessment does not take into account this variability. In addition, there is current debate about the role of intermittent versus continuous exposure on HRI risk. A recent NIOSH document reporting updated criteria for a recommended standard for occupational exposure to heat and hot environments indicates the following future research needs (NIOSH, 2016):

"Although there is general agreement that there is a relationship between heat stress and the health and safety risks for continuous exposure during an 8-hour workday, there is still uncertainty over acceptable levels of heat stress for intermittent exposure, where the worker may spend only part of the working day in the heat. Issues that need more information include:

- *Is a 1-hour, a 2-hour, or an 8-hour TWA required for calculating risk of health effects?*
- *How long are acceptable exposure times for various total heat loads?*
- *Are the health effects (heat-related illnesses) and risks the same for intermittent as for continuous heat exposure?"*

Fourth, we did not have continuous WBGT data. We used handheld WBGT monitors, which are more convenient and portable than classic WBGT monitors, which are stationary and log environmental conditions continuously throughout the day. Continuous data could have led to more accurate TWA exposure values in secondary analyses. For the secondary PSI analyses, we did not have reliable baseline core body temperature and heart rate values, as CorTemp™ pills were ingested at the worksite and took time to equilibrate, and subjects did not sit quietly for a sufficient period of time at the start of their shift to accurately measure a resting heart rate. However, we expect that PSI trends observed during the course of the work-shift would not have been affected by baseline values. Future studies could benefit from continuous WBGT data and more accurate baseline heart rate and core body temperature measures.

Fifth, the analysis of the association between WBGT and productivity was limited by a small sample size, with data collected during only one work shift per participant. It is difficult to determine whether the lack of statistical significance of the association between WBGT and productivity was the result of a small sample size or reflected a true absence of an association. Future larger studies with repeated measures are needed to further address this question. Future studies of interventions to improve productivity and prevent HRI in warm environments are also needed. A recent study in El Salvador reported that mandatory rest breaks each hour, along with hydration, above specific WBGT thresholds improved worker productivity (Bodin, Garcia-Trabanino, Weiss, Jarquin, Glaser, Jakobsson, & Wegman, 2016).

Sixth, a Supreme Court decision in the State of Washington filed July 16, 2015 ruled in favor or piece rate workers requiring employers to compensate employees during rest breaks (Demetrio & Paz v. Sakuma Brothers Farms, 2015). Our study did not assess whether rest break practices or compensation changed following this ruling in the month prior to the beginning of the study. The ruling may impact future piece-rate productivity.

Seventh, using energy expenditure data from actigraphs mounted on the hip may have underestimated harvesting activity energy expenditure. Harvesting of tree fruit requires constant upper-body exertion, and a hip mounted accelerometer may have not captured all of the activity performed during harvesting. Validated methods using wrist accelerometers may provide more accurate estimates of energy expenditures of workers.

Finally, findings from this study in Yakima Valley may not be generalizable to all agriculture workers. Many different climates are present within Washington State, and heat exposures in our study may not be representative of what is occurring in other areas of the Pacific Northwest and the United States. The participants in this study may be different from populations in other regions. Our study focused on pear and apple harvest and used a non-random method to identify participants. Cherry harvest workers may be exposed to even hotter conditions during the months of June and July.

Strengths

This study has several strengths. Recruitment of agricultural workers in research studies can be challenging. With support from the Pacific Northwest Agricultural Safety and Health Center, 46 harvesters from six different orchards were successfully recruited in this study. Of these 46 participants, 42 had complete individual physiological data collected, including heart rate and internal core body temperature using CorTemp^{TM} sensors. This is the first study that we are aware of that has reported results of individual heat stress and strain assessments in outdoor agricultural workers using these methods.

Our study used WBGT data directly measured in the field using handheld monitors. Similar studies have used nearby weather station data. In a secondary analysis, it was observed our measured WBGT was greater than calculated WBGT from nearby available weather station data using Liljegren *et al's* method (2008) (Appendix *Figure 23;* Sean Edward Hill, email correspondence January 25, 2016).

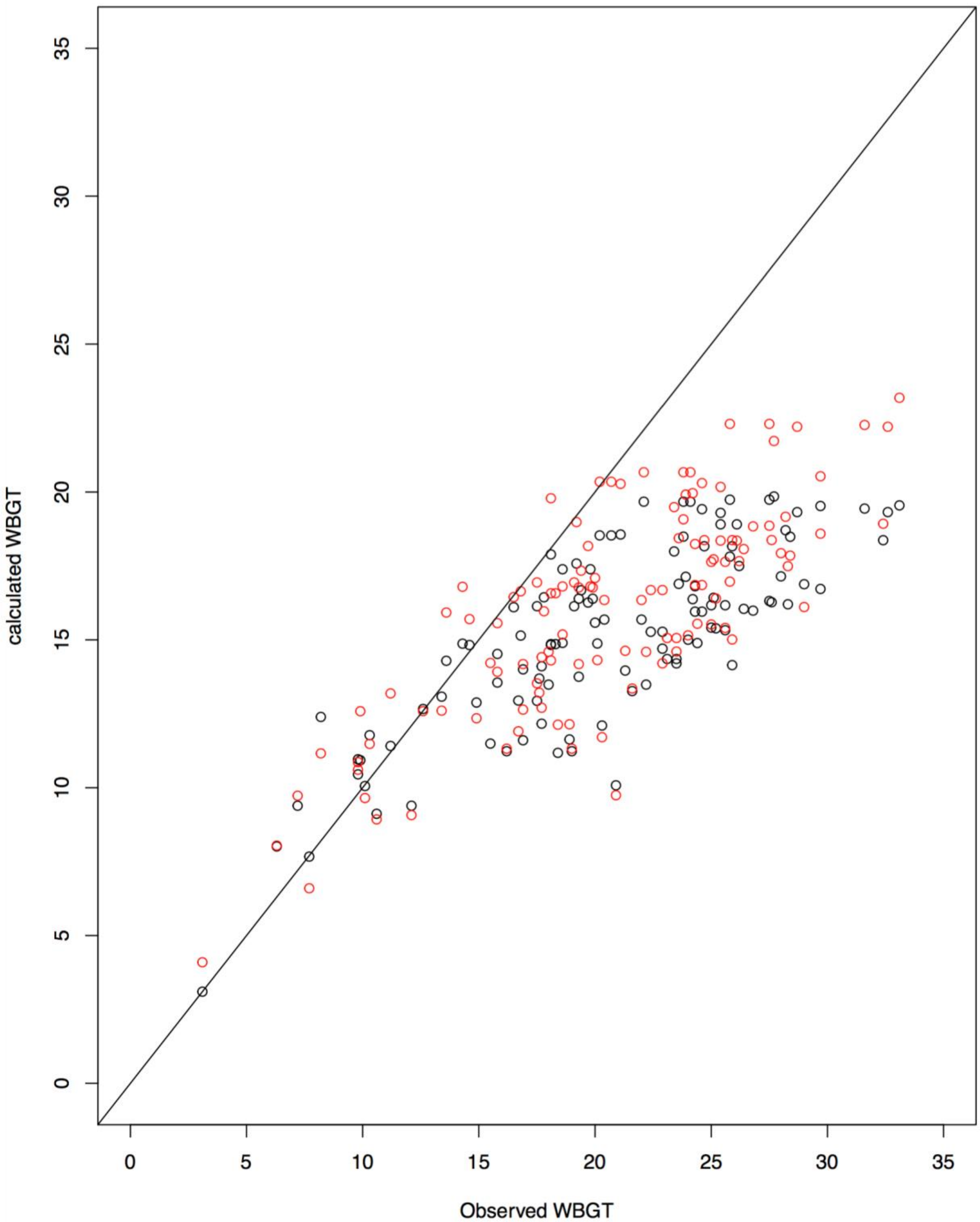
This study is one of few exploring the potential impacts of current climate conditions on productivity at an individual level (Sahu, Sett, & Kjellstrom, 2013; Sett, & Sahu, 2014; Crowe, Nilsson, & Kjellstrom, 2015; Bodin, Garcia-Trabanino, Weiss, Jarquin, Glaser, Jakobsson, & Wegman, 2016). We were able to capture factors related to payment and work shifts that influence the relationship between heat exposure and productivity. Assessment of such factors was essential in the interpretation of our results of the association between heat exposure and productivity.

CONCLUSION

Current summer tree-fruit harvesters in Yakima Valley, Washington are laboring in thermal environments hazardous to health. Payment schemes such as piece-rate pay may provide incentives for workers not to slow down when laboring in hot conditions and increase the risk of HRI in these workers. Acclimatization practices, HRI training, and orchard management practices could be improved to increase biological adaptation to heat stress and prevent HRI. The relationship between heat exposure and productivity in tree fruit harvesters is complex and likely affected by monetary factors and orchard and harvest characteristics. Future larger studies are needed to assess the relationship between heat exposure and productivity. The effects of heat stress on heat strain and productivity in outdoor workers should be considered in future planning, given the projected increase in frequency, severity, and duration of heat waves.

APPENDIX

Figure 23. Comparison of observed WBGT to calculated AgWeatherNet weather station WBGT data using the Liljegren method



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