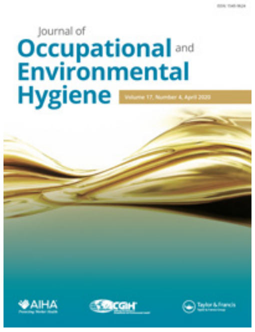
Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20



Comparison between OSHA-NIOSH Heat Safety Tool app and WBGT monitor to assess heat stress risk in agriculture

Danielle Dillane & Jo Anne G. Balanay

To cite this article: Danielle Dillane & Jo Anne G. Balanay (2020) Comparison between OSHA-NIOSH Heat Safety Tool app and WBGT monitor to assess heat stress risk in agriculture, Journal of Occupational and Environmental Hygiene, 17:4, 181-192, DOI: 10.1080/15459624.2020.1721512

To link to this article: https://doi.org/10.1080/15459624.2020.1721512

Published online: 27 Feb 2020.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2020, VOL. 17, NO. 4, 181–192
https://doi.org/10.1080/15459624.2020.1721512

Comparison between OSHA-NIOSH Heat Safety Tool app and WBGT monitor to assess heat stress risk in agriculture

Danielle Dillane[a] and Jo Anne G. Balanay[b]

[a]Department of Public Health, Brody School of Medicine, East Carolina University, Greenville, North Carolina; [b]Environmental Health Sciences Program, Department of Health Education and Promotion, East Carolina University, Greenville, North Carolina

ABSTRACT
Agricultural workers are exposed to heat stress due to spending significant amount of time outdoors. Risk information from mobile apps is more readily available for timely advice on risk management that is crucial in preventing severe acute illnesses and deaths, but its reliability is unknown. The purpose of this study was to determine the reliability of the OSHA-NIOSH Heat Safety Tool mobile app in providing accurate risk information to prevent heat-related illnesses among agricultural workers in eastern North Carolina. Wet bulb globe temperature (WBGT) indices were datalogged at two agricultural sites using heat stress monitors from April–August 2019 and were assigned to risk levels (minimal, low, moderate, high, extreme) by workload (light, moderate, heavy, very heavy) based on the ACGIH® Threshold Limit Values (TLVs®). Hourly heat index (HI) and its corresponding risk level were obtained using the app. Hourly HI-based risk level assignments were time-matched to their corresponding WBGT-based risk level assignments (682 pairs) and analyzed using cross-tabulation by determining the percentage of hourly WBGT-based risk level assignments ("gold standard") with the same hourly HI-based risk level assignments under different workloads, with a higher percentage indicating higher app reliability. Results showed that the app correctly identified 60–100% of minimal risk conditions, depending on workload type, but its reliability decreased as the heat stress risk condition and workload became more severe. The app identified the majority of low risk conditions for a moderate workload (74%) and moderate risk conditions for a light workload (94%) only, indicating limited use in these specific conditions, while the app identified 0% of either the high risk or extreme risk conditions at any workload type. It is concluded that the performance of the OSHA-NIOSH app in assessing occupational risk to heat stress is not protective of workers particularly for heavy and very heavy workloads, and that the use of the app for the assessment of occupational heat stress risk in agricultural settings is not recommended.

KEYWORDS
Agriculture; heat index; occupational exposure; outdoor workers; risk assessment; WGBT

Introduction

Agricultural workers are at risk of heat-related illness (HRI) or death due to the outdoor nature of their work. Heat is the leading cause of weather-related deaths with agriculture, ranking number one from 2000–2010 in average annual heat-related fatality rate; North Carolina (NC) ranked number six in the top-ten United States (US) states with the highest occupational heat-related death rates occurring in July (Gubernot et al. 2015). The Centers for Disease Control and Prevention (CDC) estimates that farmworkers' risk for heat-related death is nearly 20 times greater than that of other outdoor workers (CDC 2008). Castro et al. (2017) found that farmworkers who exceed 90 min of moderate to vigorous activity per day are at a higher risk to HRI. Despite such high risk, many agricultural workers do not fully understand how to prevent or treat HRI nor feel that they can openly complain about unsafe working conditions (Arcury et al. 2015). It is important for workers to know the extent of their heat exposure and its associated health risk so that they can take appropriate necessary preventive measures.

Wet bulb globe temperature (WBGT) is a weighted average of dry bulb, wet bulb, and globe temperatures, and incorporates the effects of all four environmental heat determinants (air temperature, relative humidity, air movement, and radiant heat). WBGT has been the preferred environmental heat metric for HRI

CONTACT Jo Anne G. Balanay balanayj@ecu.edu Environmental Health Sciences Program, Department of Health Education and Promotion, East Carolina University, 3407 Carol Belk Building, 300 Curry Ct, Greenville, NC 27858.

prevention in workplaces. The Occupational Safety and Health Administration (OSHA) recognizes that measuring WBGT at the worksite provides the most accurate information about the workers' heat exposure (CDC 2018). WBGT is advocated by the American Conference of Governmental Industrial Hygienists (ACGIH) and National Institute for Occupational Safety and Health (NIOSH) as part of occupational heat stress prevention programs (ACGIH 2019; NIOSH 2016). Recommended heat stress occupational exposure limits (OELs) published by NIOSH and ACGIH are based on WBGT and workload (ACGIH 2019; NIOSH 2016). Studies demonstrated that the OELs are highly sensitive for detecting hazardous heat stress in human volunteers (Garzon-Villalba et al. 2017) and in actual workers, particularly the identification of fatal heat stress and non-fatal HRI hospitalizations (Morris et al. 2019; Tustin et al. 2018), and therefore should be used for occupational assessment of heat hazard (Morris et al. 2019).

However, the WBGT may not always be readily available for workplace heat stress assessment due to various reasons, including lack of financial resources to procure appropriate instruments and/or hire trained personnel, which may be an issue in agricultural worksites. Heat index (HI), which is an "apparent' temperature that combines air temperature and relative humidity to quantify how hot it really feels ("feels like") to the typical human (NWS 2019a; Steadman 1979), has been identified as an alternative environmental heat metric. The HI was originally designed for use by the general public, based on algorithms that modeled a person wearing light clothing and walking in a shaded area with light wind (Steadman 1979). The HI equation used by the National Weather Service (NWS 2019b) is derived from either a multiple regression analysis by Rothfusz (1990) or a simpler formula by Steadman (1979), depending on the temperature and relative humidity values. The HI does not address the effects of direct sunlight, wind speed and strenuous activities (Tustin et al. 2018). Due to these limitations, no HI-based OELs have been published by either NIOSH or ACGIH (Morris et al. 2019). However, despite these limitations, HI information is often more readily available than WGBT to employers from publicly broadcasted weather reports or forecasts (Tustin et al. 2018), creating interest in using HI for establishing OEL or risk threshold for heat stress assessment (Garzon-Villalba et al. 2019; Morris et al. 2019). When WBGT is not available, the HI has been recommended for use in outdoor workplaces, particularly for setting specific HI alert thresholds, to identify potentially hazardous occupational heat exposures (Bernard and Iheanacho 2015; Morris et al. 2019; Tustin et al. 2018). OSHA (2019) published HI-based heat stress guidance for employers, in which HI risk thresholds were adapted from the National Oceanic and Atmospheric Administration (NOAA) HI chart but modified for use at worksites.

OSHA and NIOSH developed, released, and recently updated the OSHA-NIOSH Heat Safety Tool application (app) for mobile devices that enables workers and supervisors to monitor the HI at worksites (CDC 2018). The app provides hourly HI and obtains ambient temperature and relative humidity directly from land-based NOAA observation stations for a specific location to calculate the HI. The app categorizes HI values into five risk levels (minimal to extreme), similar to those in the OSHA heat stress guidance (OSHA 2019), and also provides immediate precautions based on risk category. The potential of the app as a heat stress risk mitigation and educational tool for agricultural workers has been recognized and recently investigated (Luque et al. 2019a; 2019b).

The relationship between WBGT and HI has been investigated at varying scenarios. Bernard and Iheanacho (2015) conducted a theoretical study that quantified the relationship between WBGT and HI under the assumptions of light wind and no radiant heat, and concluded that HI can be a useful surrogate for WBGT to screen for potentially hazardous heat exposures. Given that the assumptions in the study did not represent a wide range of hazardous heat stress scenarios in the workplace, Morris et al. (2019) expanded Bernard and Iheanacho's (2015) study across a wider range of realistic meteorological conditions (i.e., full or partial sun, varying wind speed) using simulated weather data, and found that HI and WBGT, although strongly correlated, lacked a one-on-one consistent relationship (i.e., a scenario with higher HI does not always have a higher WBGT). Although studies on the correlation between WBGT and HI values have been conducted, no study that compares risk levels derived from these two environmental heat metrics has been published. Moreover, to the authors' best knowledge, there are currently no published studies that compare risk information from an HI-based mobile app to WBGT-based risk information derived from onsite instrumentation-obtained exposure measurements for occupational heat stress.

Daily risk information from mobile apps can be more readily available for worker protection compared to instrumentation-derived risk data, but their accuracy is unknown. Specifically for heat stress prevention, additional risk factors must also be taken into consideration when managing worker risk, even when the heat index is lower (OSHA 2019). Some of these risk factors, including exposure to direct sunlight and prolonged or strenuous work, affect agricultural workers. OSHA states that the OSHA-NIOSH Heat Safety Tool app is advisory in nature and informational in content, and that OSHA cannot guarantee that calculations accurately reflect the conditions at a specific worksite (CDC 2018; OSHA 2019). Therefore, it is important to assess if the HI-based risk advisory provided by the app is applicable to the agricultural workforce and does not either underestimate or overestimate their risks. Obtaining such baseline information is important to determine if the app is reliable to be used as an alternative risk assessment method that is cheaper and readily available to agricultural and other outdoor workers for HRI prevention.

The main purpose of this pilot study was to determine the reliability of the OSHA-NIOSH Heat Safety Tool app in providing accurate heat stress risk information for agricultural workers in eastern NC. This study specifically aimed to: (1) assess the heat stress exposure of agricultural workers using WBGT indices as compared to the ACGIH Threshold Limit Values (TLVs) and action limits; (2) determine the correlation between WBGT and heat index; and (3) compare the HI-based risk levels obtained from the OSHA-NIOSH Heat Safety Tool app to WBGT-based risk levels derived from heat stress monitor measurements.

Methods

Monitoring sites

In consultation with the Pitt County Cooperative Extension Center, two agricultural sites in the rural parts of eastern NC within or near Pitt County were selected and recruited as monitoring sites. Occupational exposure to heat stress at these agricultural sites was assessed by area monitoring. One site was in Ayden, NC in Greene County bordering the southwest edge of Pitt County. The other site was in Tarboro, NC at the northwest edge of Pitt County bordering Edgecombe County. Pitt County is comprised of over 400,000 acres, with more than 40% of these acres being used as farmland to grow the following major crops: peanuts, tobacco, corn, cotton, soybeans, and sweet potatoes (Pitt County Development Commission 2019). In comparison, Greene and Edgecombe counties are 59.5% and 39.2% farmland, respectively (Criner 2006a; 2006b; NASS 2014a; 2014b). The straight-line distance between the two monitoring sites, which was determined using Google Earth (version 7.3, Google, Mountain View, CA), was approximately 19.8 miles.

Heat stress monitoring

Heat stress monitoring was conducted by deploying two heat stress monitors (QUESTemp°34, 3 M, Oconomowoc, WI), one at each monitoring site on the same days. Each heat stress monitor was positioned at a height of 3.5 ft from the ground using a tripod. The heat stress monitors were factory-calibrated within 2 months prior to the start of the data collection. A trial run for a side-by-side comparison of monitor readings was also conducted on April 12, 2019 from 11:00 AM–3:00 PM, showing similar 1-min readings with an average difference of 0.04 °C. For each monitoring day, the dry bulb, wet bulb, and globe temperatures (°C), outdoor WBGT index (°C), and relative humidity (%) were datalogged every minute for 7–11 hr within the working period of 8:00 AM–7:00 PM. Monitoring was conducted for 44 days within the period of April 16–August 9, 2019 to cover most of the summer season. The hourly mean WBGT indices were calculated and compared to the ACGIH TLVs and action limits for heat stress exposure (ACGIH 2019).

Comparison of WBGT with ACGIH TLVs and action limits

The screening criteria for ACGIH TLV and action limit for heat stress exposure considers the workload and the work allocation in a work/recovery cycle (ACGIH 2019). Tasks performed by agricultural workers may encompass all workload categories: light work performed by agricultural workers may include driving a tractor, other heavy machinery or work truck/vehicle, casual walking, labeling, shelving, and counting grains; moderate work may include pesticide application, transplanting, picking vegetables or fruits, walking with tools, weeding or hoeing; heavy work may include manually lifting and carrying crops or water, manually plowing, and digging soil, and very heavy work may include heavy shoveling or digging (Nag et al. 1980; OSHA 2019). Hourly mean WBGT indices were compared to the TLVs and action limits to determine if these exposure limits were exceeded at any time throughout the day. Since worker assessment

Table 1. WBGT index range (°C) used to assign heat stress risk level by workload and corresponding metabolic rate.

Risk Level	Workload [Metabolic Rate, W]* Light [180]	Moderate [300]	Heavy [415]	Very Heavy [520]
Minimal	<28.1	<25.0	<23.0	<21.6
Low	28.1–28.6	25.0–25.7	23.0–24.1	21.6–23.0
Moderate	28.7–30.7	25.8–28.1	24.2–26.5	23.1–25.4
High	30.8–31.0	28.2–28.8	26.6–27.5	25.5–26.6
Extreme	≥31.1	≥28.9	≥27.6	≥26.7

*Adapted from ACGIH, 2019

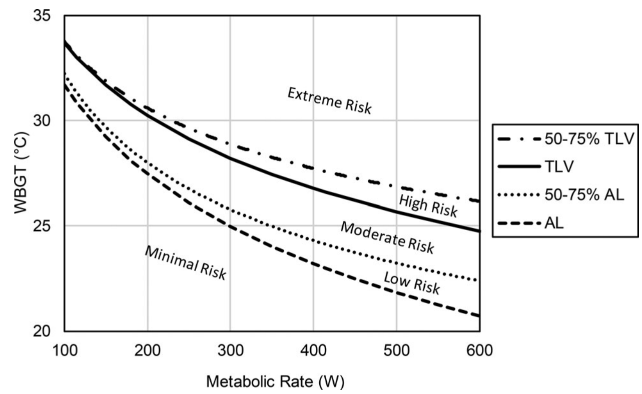


Figure 1. Risk level zones for heat stress adapted from ACGIH TLV and Action Limit (AL).

was not conducted in this study, assumptions on the workload and work allocation were made. Assuming that the workers' work allocation based on a 2-hr work/recovery cycle was within the 50–75% category, the TLVs and action limits used for comparison are 31.0 °C and 28.5 °C for light workload, 29.0 °C and 26.0 °C for moderate workload, and 27.5 °C and 24.0 °C for heavy workload, respectively (ACGIH 2019).

Use of mobile app

The OSHA-NIOSH Heat Safety Tool app (version 3.1) was used to collect data on current hourly ambient temperature (°C), relative humidity (%), HI (°C), and associated risk levels from 8:00 AM to 6:00 PM. The app categorizes HI values into five risk levels: minimal (≤79 °F; <26.1 °C), low (80–90 °F; 26.7–32.2 °C), moderate (91–103 °F; 32.8–39.4 °C), high (104–115 °F; 40.0–46.1 °C), and extreme (≥116 °F; ≥46.7 °C) risk (CDC 2018). App data was recorded at the start of every hour during the monitoring day. Zip codes (28513 for Ayden and 27886 for Tarboro) were used in the app to obtain data that were specific to the location of the monitoring sites. The straight-line distances between the agricultural site and its corresponding NOAA regional weather station, from which the location-specific app data was obtained, were 6.82 and 6.26 miles for the Tarboro and Ayden locations, respectively.

Assignment of TLV-based risk levels to WBGT indices

Table 1, which specifies ranges of WBGT indices for each risk level by workload and its corresponding metabolic rate, was developed for this study to assign risk levels to the hourly mean WBGT indices obtained from heat stress monitoring. The risk level categories (minimal to extreme) used in Table 1 were the same as those used in the OSHA-NIOSH Heat Safety Tool app for easier comparison. The WBGT index criteria in Table 1 were derived from Figure 1 that shows the five risk level zones by WBGT index and metabolic rate. Figure 1 was adapted from the ACGIH TLV and action limit for heat stress (ACGIH 2019) and a study by Morris et al. (2019). The solid line represents the ACGIH TLV for heat stress (ACGIH 2019) that is meant for workers who are acclimatized to heat (Morris et al. 2019; NIOSH 2016; OSHA 2017), and serves as the lower border of the "high risk" zone. The dashed line represents the action limit (ACGIH 2019) that is meant for unacclimatized workers (Morris et al. 2019; NIOSH 2016; OSHA 2017), and serves as the lower border of the "low risk" zone. The dash-dotted and dotted lines represent the TLVs and action limits, respectively, for light, moderate, and heavy workloads under the "50–75%" work allocation (ACGIH 2019), which are proposed in this study to serve as the lower borders of the "extreme risk" and "moderate risk" zones (Figure 1). The "minimal risk" zone is similar to zone 1 in the Morris et al. (2019) study, which indicates insignificant heat hazard (i.e., heat stress is below the exposure limits for all workers). The combined "low risk" and "moderate risk" zones are equivalent to zone 2 (i.e., intermediate level of heat stress that is above the exposure limits for unacclimatized workers but below those for acclimatized workers) while the combined "high risk" and "extreme risk" zones are equivalent to zone 3 (i.e., hazardous level of heat stress that is above the exposure limits for all workers) in the Morris et al. (2019) study.

Comparison between heat stress monitoring and app data

Two types of comparison were conducted between data obtained from heat stress monitoring and the app: (1) hourly mean WBGT vs. hourly HI; and (2)

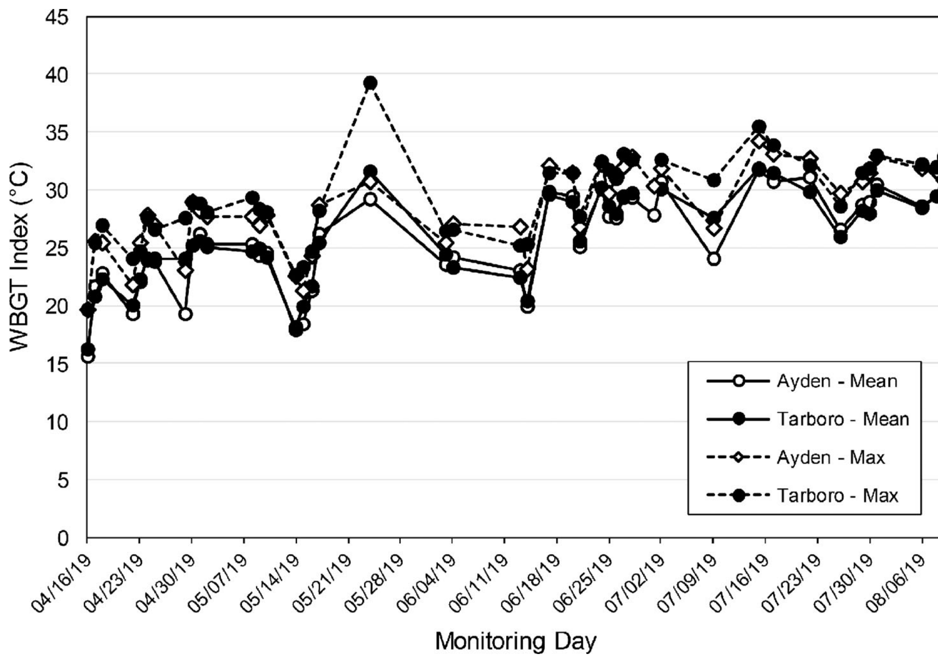


Figure 2. Daily mean and maximum WBGT Index (°C) by monitoring day and site.

hourly WBGT-based risk vs. hourly HI-based risk for heat stress. Only data pairs (e.g., WBGT/HI) that were time-matched (i.e., same day, same hour, same location) were used for comparison. The time-matched hours used were between "8:00 AM" and "6:00 PM", and the number of hours per day ranged from 7–11 hr. The hourly mean instrument-obtained WBGT indices and app-obtained HI were compared by day and time and assessed for correlation. Considering the WBGT index as the preferred metrics or "gold standard" for occupational heat stress assessment, the reliability of the app in assessing workplace risk to heat stress was determined by the percentage of hourly WBGT-based risk levels, under different workloads, that had the same hourly HI-based risk levels assigned by the app. The aim was to compare the similarity between assigned risk levels from WGBT/heat stress monitoring and from the app, with a higher percentage of agreement on risk assignments indicating higher app reliability.

Data analysis

The daily mean, minimum, maximum, and standard deviation of both hourly WBGT and HI were determined. Analysis of variance (ANOVA) was conducted to compare both daily mean WGBT and HI matched by monitoring day between monitoring sites. The Pearson correlation test was conducted to determine the correlation between WBGT and HI. Cross tabulation was used to analyze the relationship between risk level categories based on instrumentation-obtained WBGT indices and those obtained from the app. The Statistical Package for Social Sciences (SPSS version 25, IBM, Armonk, NY) was used to analyze the data. Statistically significant results were identified when $p < 0.05$.

Results

WBGT indices

The hourly mean WBGT indices for the entire study period ranged from 9.7–37.8 °C, with an overall mean of 25.6 ± 4.2 °C (n = 823), while the daily mean WBGT indices ranged from 15.6–31.8 °C, with an overall mean of 25.3 ± 3.9 °C (n = 78). Comparing the same days for both monitoring sites, the overall daily mean WBGT index for Ayden (25.3 ± 4.0 °C, range = 15.6–31.8 °C, n = 39) was not statistically different (F = 0.03, $p = 0.86$) from that for Tarboro (25.4 ± 3.9 °C, range = 16.2–31.8 °C, n = 39). Similarly, the overall mean of daily maximum WBGT index for Ayden (28.0 ± 3.6 °C) was not statistically different (F = 0.83, $p = 0.37$) from that for Tarboro (28.8 ± 3.9 °C). The highest hourly mean WBGT index (37.8 °C) was measured at Tarboro on May 24, 2019 at 5 PM, while the highest daily mean WBGT index (31.8 °C) was measured at Tarboro on July 15, 2019. Figure 2 shows the daily mean and maximum WBGT indices by monitoring day for both sites and demonstrates an increasing trend in WBGT indices from April to August.

Table 2. Estimated number and percentages of hourly mean WBGT index exceeding ACGIH Threshold Limit Values (TLV)[a] and Action Limits (AL)[A] for heat stress exposure based on workload assumptions by month and time of day.

		Light Workload				Moderate Workload				Heavy Workload			
		>TLV		>AL		>TLV		>AL		>TLV		>AL	
Parameter	No. of Hours	n	%	n	%	n	%	n	%	n	%	n	%
Month													
April	173	0	0.0	0	0.0	0	0.0	10	5.8	2	1.2	51	29.5
May	200	4	2.0	17	8.5	13	6.5	54	27.0	21	10.5	118	59.0
June	230	5	2.2	87	37.8	72	31.3	128	55.7	112	48.7	174	75.7
July	160	31	19.4	106	66.3	83	51.9	146	91.3	125	78.1	157	98.1
August	60	0	0.0	45	75.0	37	61.7	54	90.0	50	83.3	58	96.7
Time of Day[B]													
Morning	226	2	0.9	37	16.4	23	10.2	84	37.2	61	27.0	118	52.2
Noon	170	10	5.9	63	37.1	53	31.2	82	48.2	72	42.4	122	71.8
Afternoon	326	21	6.4	120	36.8	106	32.5	177	54.3	138	42.3	251	77.0
Evening	101	7	6.9	35	34.7	23	22.8	49	48.5	39	38.6	67	66.3
Total	823	40	4.9	255	31.0	205	24.9	392	47.6	310	37.7	558	67.8

[A]ACGIH TLV and AL for work allocation in work/recovery cycle of 50-75%
[B]Morning – 8 AM to 11 AM; Noon – 11 AM to 1 PM; Afternoon – 1 AM to 5 PM; Evening – 5 PM to 7 PM

Comparison of WBGT with ACGIH TLVs and action limits

Table 2 shows the number and percentage of hourly mean WBGT indices that may potentially exceed the TLVs and action limits by month and time of day, assuming three different workload categories. Overall, 4.9, 24.9, and 37.7% of WBGT indices exceeded the TLVs for light, moderate and heavy workloads, respectively, while 31.0, 47.6, and 67.8% exceeded the actions limits for light, moderate, and heavy workloads, respectively. By month, July had the highest percentage of TLV exceedance for light workload (19.4%), while August had the highest percentage for moderate (61.7%) and heavy workloads (83.3%). In April, none of the WBGT indices exceeded the TLVs for light and moderate workloads, and 1.2% exceeded the TLV for heavy workload (Table 2). By time of day, evening and afternoon had the highest percentage of TLV exceedance for light workload (6.9 and 6.4%, respectively), afternoon had the highest percentage for moderate workload (32.5%), and noon and afternoon had the highest percentage for heavy workload (42.4 and 42.3%, respectively). Morning had the lowest TLV exceedance percentages regardless of the workload, ranging from 0.9–27.0%.

The highest percentages of action limit exceedance were found in the months of June to August, ranging from 37.8–75.0% for light, 55.7–91.3% for moderate, and 75.7–98.1% for heavy workload (Table 2). The action limits for moderate and heavy workloads were exceeded during all months monitored at varying magnitude, ranging from 5.8–91.3% and 29.5–98.1% exceedances, respectively. By time of day, noon and/or afternoon had the highest percentages of WBGT indices exceeding the action limits for all workloads (37.1% for light, 54.3% for moderate, 77.0% for heavy). Although morning had the lowest exceedance percentages (ranging from 16.4–52.2%), the action limits were exceeded during all times of the day regardless of the workload.

Heat index from mobile app

The hourly HI and the corresponding heat stress risk level were obtained from the OSHA-NIOSH Heat Safety Tool app for both monitoring sites. The hourly HI for the entire study period ranged from 6.7–41.7 °C, with an overall mean of 27.6 ± 6.3 °C ($n = 941$), while the daily mean HI ranged from 15.4–38.0 °C, with an overall mean of 27.5 ± 5.2 °C ($n = 88$). Comparing the monitoring sites, the overall daily mean HI for Ayden (27.9 ± 5.2 °C, range = 16.4–38.0 °C, $n = 44$) was not statistically different ($F = 0.49$, $p = 0.49$) from that for Tarboro (27.1 ± 5.3 °C, range = 15.4–37.4 °C, $n = 44$). Likewise, the overall mean of daily maximum HI for Ayden (31.1 ± 5.2 °C) was not statistically different ($F = 0.32$, $p = 0.57$) from that for Tarboro (30.5 ± 5.3 °C). The highest hourly mean HI (41.7 °C) was measured at Tarboro on July 17, 2019 at 5 PM, while the highest daily mean HI (38.0 °C) was measured at Ayden on the same day.

Correlation and comparison between WBGT and heat index

The hourly mean instrument-obtained WBGT indices and mobile app-obtained HI for both monitoring sites by date and time were compared in Figure 3. Figure 3A compares the two indices for the entire study period (April–August 2019), demonstrating an increasing trend. Figure 3B takes a closer look at the

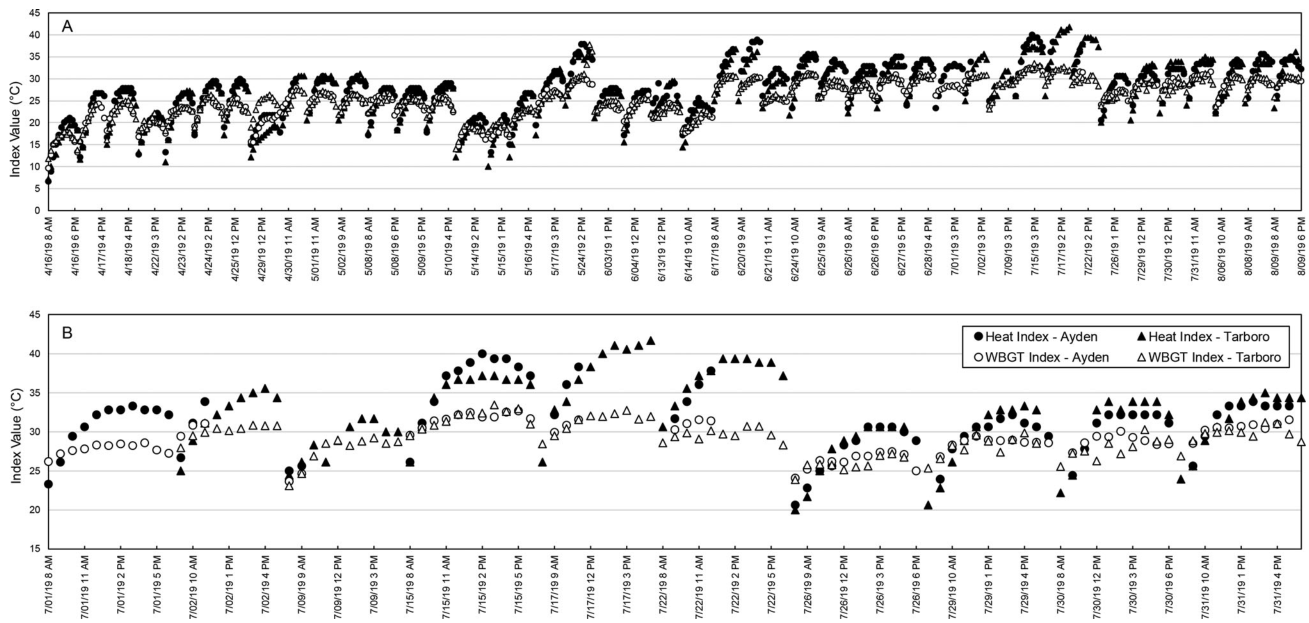


Figure 3. Hourly mean WBGT index and heat index (°C) by monitoring day, time and site for: A) the entire study period (April to August 2019), and B) the month of July 2019.

WBGT and HI during the month of July only, in order to have a clearer comparison of both indices. In both Figures 3A and 3B, each monitoring day showed similar patterns for the hourly indices, wherein the index values were lowest at the start of the day, highest at the middle of the day, and slightly decreased at the end of the day. Comparing the two index values, the HI had a larger range within the day compared to the WBGT index, as shown clearly in Figure 3B. Consequently, the WBGT index tended to be higher than the HI at low HI values (e.g., during 8–9 AM), while it tended to be lower than the HI at higher HI values (e.g., noon to evening).

The correlation between the hourly mean WBGT and HI were analyzed to determine if the HI could potentially be used as a proxy for WBGT index, and vice versa. Overall, the WBGT and HI had a statistically significant positive correlation ($p < 0.01$), meaning that they tended to increase together (Figure 4). The strength of the association was strong ($r = 0.89$, $r > 0.5$).

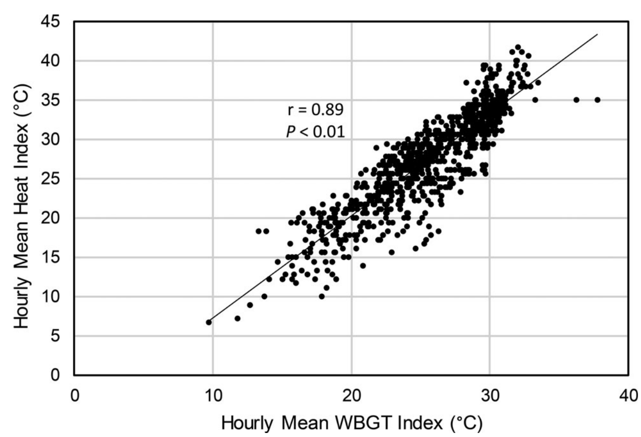


Figure 4. Correlation between hourly mean WBGT index (°C) and heat index (°C).

Comparison of WBGT-based and HI/app-based heat stress risks

Hourly mean WBGT indices (n = 823) were assigned to a heat stress risk level depending on the workload, and 682 of these WBGT indices had corresponding hourly HI to which they were paired. Figure 5 shows the percentage of each risk level categories assigned for WBGT indices by workload and for HI derived from the app. "Minimal risk" was the most common assigned risk level for WBGT indices under light, moderate, heavy and all workloads (77.6%, 52.9%, 33.0%, and 46.4%, respectively) and for HI (47.2%). "Extreme risk" was the most common risk level for WBGT indices under very heavy workload (29.0%), followed by "moderate risk" (24.5%) and "minimal risk" (22.0%). Comparing the four workload types, the percentages for the least severe risk level (e.g., minimal risk) decreased and the percentages for the more severe risk level (e.g., extreme risk) increased as the workload severity increased, which is due to the increasing stringency of the TLV associated with the increasing workload. The HI obtained had a similar percentage of "minimal risk" assignments (47.2%) as the WBGT indices under all workloads (46.4%) but were assigned much smaller percentages of "high risk" (0.1%) and "extreme risk" (0.0%) compared to those of WBGT (5.9% and 18.7%, respectively).

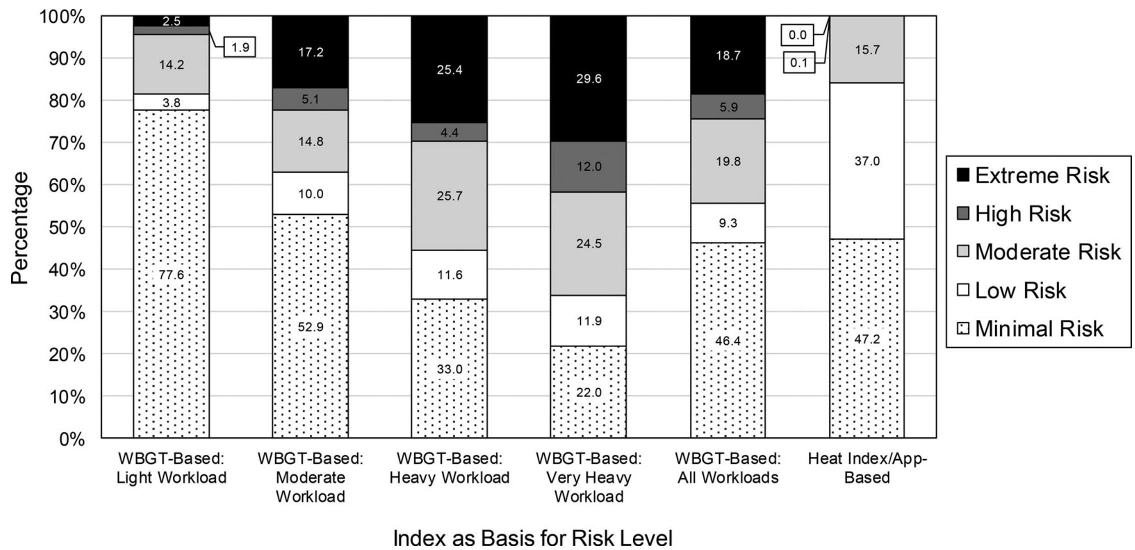


Figure 5. Percentage of assigned heat stress risk levels (n = 682) for WGBT index (by workload) and heat index (app-derived).

The reliability of the OSHA-NIOSH app in assessing workplace risk to heat stress was determined by comparing the HI-based risk levels obtained from the app to the WBGT-based risk levels obtained from heat stress monitoring as the "gold standard." Figure 6 shows the percentage of hourly WBGT-based risk level assignments, by workload, that had the same hourly HI-based risk level assignments. Among the "minimal risk" assignments based on WBGT indices under the "light workload" assumption (n = 573), 59.7% were also assigned as "minimal risk" by the app, while the remaining 40.3% were assigned higher risk levels (38.9% as low risk and 1.4% as moderate risk). This made the app more conservative (i.e., more protective) when assigning risks for "minimal risk" conditions. As the workload increased, the percentage of "minimal risk" assignments by the app increased (from 77.6–100% for moderate to very heavy workloads) and became more similar with the WBGT-based "minimal risk" assignments (Figure 6A).

Among the WBGT-based "low risk" assignments under the "light workload" assumption (n = 46), 45.7% were also identified as "low risk" by the app, while 34.8% were assigned a higher risk level of "moderate" and 19.6% were assigned a lower risk level of "minimal," making the app less conservative (i.e., less protective) for "low-risk" conditions. Under moderate workload, 73.7% of the WBGT-based "low-risk" assignments (n = 76) were also assigned by the app as "low risk," demonstrating the best accuracy in risk assignment. However, as the workload increased from moderate to very heavy, the percentage of "low-risk" assignments by the app decreased, diverting further from the WBGT-based risk assignments. Moreover, the increase in workload from light to very heavy also resulted to an increase in the percentage of lower risk assignment of "minimal," making the app less protective than the WBGT indices (Figure 6B).

Among the WBGT-based "moderate-risk" assignments under the "light workload" (n = 187), 62.0% were also identified as "moderate risk" by the app, while the remaining were assigned lower risk levels, making the app even less conservative for "moderate-risk" conditions. Moreover, as the workload increased, the percentage of "moderate-risk" assignments by the app drastically decreased while the remaining majority of the WBGT-based assignments were assigned lower, less conservative risk levels. The worst-case scenario was found under very heavy workload wherein 0% of the WBGT-based "moderate-risk" assignments (n = 176) were assigned the same risk level by the app, while all were assigned lower risk levels (Figure 6C).

Among the WBGT-based "high-risk" and "extreme-risk" assignments under any workload type, none were identified in the same risk level assignment by the app and all were assigned to lower risk levels (Figures 6D and 6E). Among these lower-risk level assignments, as the workload increased, the percentage of the lowest risk level assignments (i.e., minimal risk) by the app also generally increased (from 0–29.2% and from 0–8.6% for WBGT-based high and extreme risk assignments, respectively), demonstrating that the app became less protective with increasing workload. Consequently, the percentage of "moderate-risk" assignments by the app among both WGBT-based "high-risk" and "extreme-risk" assignments decreased

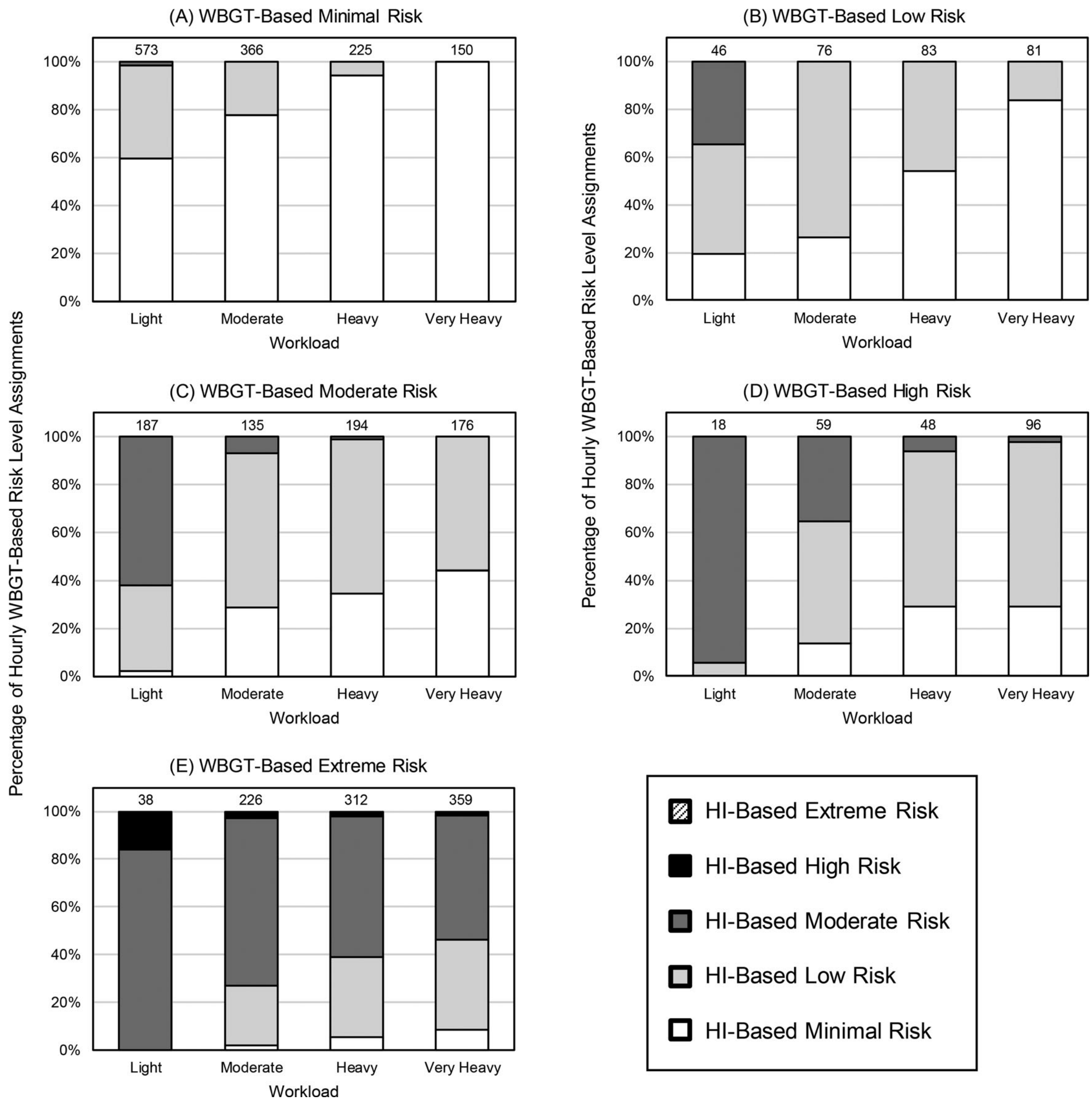


Figure 6. Percentage of hourly WBGT-based risk level assignments with the same hourly HI-based risk level assignments by workload.

as workload increased (from 94.4–2.1% and from 84.2–52.1%, respectively).

Overall, among all WBGT-based risk assignments (n = 862), 55.6% (n = 479) were assigned the same risk level by the app under the "light workload" assumption. As the workload increased, the percentage of having the same risk level assignments by the app decreased (40.5%, 29.2%, and 18.9% for moderate, heavy, and very heavy workloads, respectively).

Discussion

Results from this study indicated excessive heat exposures in agricultural settings in eastern NC during the afternoon for the summer months of June to August, as demonstrated by significant percentages of heat stress levels exceeding both the TLVs and action limits for occupational heat exposure. This finding is particularly important when the workload is either moderate or heavy, since TLV exceedance increases as workload increases. Results also showed that the action limits for moderate and heavy workloads were exceeded during all months monitored during the study and during all monitored parts of the day (morning, noon, afternoon, evening), although at varying magnitude. As expected, morning was the time of the day that had the lowest heat stress levels, but action limits were still exceeded during this period regardless of the workload. These findings are similar to those in a previous study on groundskeepers (Beck et al. 2018) and may indicate the need to implement preventive measures to reduce heat stress among workers even during the colder months (i.e., April) and times of the day (i.e., morning), particularly as the workload increases.

In this study, the reliability of the OSHA-NIOSH Heat Safety Tool app as an occupational risk assessment tool for agricultural settings was assessed by comparing the HI-derived heat stress risk levels provided by the app to the heat stress risk levels derived from WBGT indices measured by local heat stress monitors. The app was more reliable in identifying minimal risk conditions. For example, it agreed with the WBGT-based risk level assignments in 100% of very heavy workload scenarios in which the WBGT was judged to be minimal risk. However, the reliability of the app decreased as the heat stress risk condition became more severe. The app was found to be relatively reliable (>70%) in identifying low risk conditions at moderate workload but had lower reliability at light, heavy, and very heavy workloads (<50%), and was relatively reliable (>60%) in identifying moderate risk conditions at light workload but was not reliable at moderate, heavy, and very heavy workloads (<7%). Hence, the app may have some limited use in low and moderate risk conditions. Moreover, the app was shown to be unreliable in assessing high- and extreme-risk conditions at any type of workload (low to very heavy), with 0% of either the WBGT-based high-risk or extreme-risk assignments matching those identified by the app. Unfortunately, the app being reliable for minimal risk conditions is not very useful since this risk level is not one of utmost concern, but rather the more dangerous risk levels, such as high and extreme risks, are of greater concern wherein serious HRIs are more likely to occur.

Findings in this study demonstrated that the HI-based risk from the app did not correspond well with the WBGT-based risk derived from onsite heat stress measurements. There are several possible reasons for this finding. First, different parameters were used to calculate the HI and WBGT. While WBGT index takes air temperature, humidity, air movement, and radiant heat into account, HI considers air temperature and humidity only, thus, dismissing the cooling effect of higher wind speed and the hazardous effect of direct sunlight. A recent study showed strong correlation between HI and WBGT index but found that there is no one-to-one relationship between these two indices (Morris et al. 2019). Therefore, translating HI directly into a corresponding WBGT index is not straightforward. Similarly, Morris et al. (2019) stated that it is impossible to directly translate the current WBGT-based occupational exposure limits into HI equivalents. For use in risk assessment, there may be a need to supplement the HI with additional information (e.g., radiant heat, wind speed) to assess if the WBGT-based OELs are exceeded (Morris et al. 2019).

Secondly, HI was originally designed for use by the general public and not for workers. The assumptions on clothing and physical activity (i.e., workload) used in the original HI algorithm are invalid for many occupational groups, including agricultural workers who perform strenuous tasks. In contrast, WBGT-based OELs (e.g., TLVs) were established based on a given level of physical activity, wherein OEL decreases as workload increases. Recognizing this limitation, OSHA modified the HI risk thresholds from the NOAA Heat Index chart for use at worksites by narrowing down the HI range for "high risk" category from "103–124 °F" to "103–115 °F," and for "extreme risk" from "126–137 °F" to ">115 °F" (OSHA 2019). Although these changes made the criteria for more severe risk levels more stringent and protective, they are still not as protective as the WBGT-based risk criteria.

Thirdly, the local weather conditions at the agricultural sites may be different from those at the NOAA regional weather stations used by the app. The straight-line distances between the agricultural site and weather station were 6.82 and 6.26 miles for the Tarboro and Ayden locations, respectively. Cloud cover and wind speed, which may vary significantly by location, are potentially among the weather conditions that could have affected the differences in heat stress risks between the local worksite and the regional weather station. Mac et al. (2019) concluded that regional weather data may potentially provide good estimations of local worksite environmental heat conditions by comparing the calculated HI for both sites. Their finding may be attributed to the fact that HI only takes into account the air temperature and relative humidity, which may not significantly differ between the worksite and the nearest weather station. Studies comparing other environmental heat metrics (e.g., WBGT) between a local worksite and the regional weather station need to be conducted to further assess the role of other weather parameters on heat exposure.

Limitations

The findings of this study were limited to the two agricultural sites in eastern NC and may have limited generalizability to other agricultural sites. Further studies conducted on other parts of NC (e.g., mountainous regions) and other states with different meteorological conditions (e.g., temperature, humidity) is recommended. Actual agricultural workers were not observed in this study and assumptions were made on their workload (to create WBGT-based risk level assignments), their work/recovery allocation (i.e., 50–75%), and the times (i.e., hour) within the work day when agricultural workers perform their tasks. Moreover, clothing-adjustment factors were not considered in determining the acceptability of WBGT indices based on the TLVs and action limits. Lastly, a relatively narrow range of WBGT indices were obtained in this study and WBGT values above 35 °C were not well represented. The correlation between the WBGT and HI at these higher values was not feasible to assess in the study.

Conclusions

The OSHA-NIOSH Heat Safety Tool app was found to be most reliable in identifying minimal risk conditions, but its reliability decreased as the heat stress risk condition became more severe. The app had limited use for assessing risk in occupational settings performing low and moderate risk conditions as it identified the majority of these risk conditions for light or moderate workloads, but caution must be exercised. The app was very inaccurate in assessing high and extreme risks at any type of workload (low to very heavy), with 0% of the WBGT-based high and extreme risks matching those identified by the app.

Given the varying degree of reliability of the app depending on the risk conditions, the use of the app to assess occupational risk to heat stress in agricultural setting is not recommended. The performance of the app in assessing risk was demonstrated to not be protective of the workers particularly for heavy and very heavy workloads, which are likely performed by agricultural workers. There is still a need for more readily accessible and reliable information on heat stress risk and HRI prevention measures that may be used by agricultural workers and other similar outdoor workers, and a well-designed mobile app that provides WBGT-based risk information may fill this need.

Acknowledgments

The authors would like to thank the Pitt County Cooperative Extension center for their assistance in the identification and recruitment of agricultural sites for the study. This study was supported by a pilot grant from the National Institute for Occupational Safety and Health (NIOSH) through the Southeast Center for Agricultural Health and Injury Prevention (SCAHIP). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH or SCAHIP.

References

American Conference of Governmental Industrial Hygienists (ACGIH)®. 2019. Heat Stress and Strain. In: 2019 TLVs® and BEIs®. Cincinnati (OH): ACGIH Signature Publications. p. 239–248.

Arcury TA, Summers P, Talton JW, Chen H, Sandberg JC, Johnson CR, Quandt SA. 2015. Heat illness among North Carolina Latino farmworkers. J. Occup. Environ. Med. 57(12):1299–1304. doi:10.1097/JOM.0000000000000552

Beck N, Balanay JG, Johnson T. 2018. Assessment of occupational exposure to heat stress and solar ultraviolet radiation among groundskeepers in an eastern North Carolina university setting. J. Occup. Environ. Hyg. 15(2):105–116. doi:10.1080/15459624.2017.1392530

Bernard TE, Iheanacho I. 2015. Heat index and adjusted temperature as surrogates for wet bulb globe temperature to screen for occupational heat stress. J. Occup. Environ. Hyg. 12(5):323–333. doi:10.1080/15459624.2014.989365

Castro J, Mitchell D, Armitage T, Schenker M. 2017. 0229 Risk of heat related illness in Latino agricultural workers: Core body temperature and work task. Occup. Environ. Med. 74(Suppl 1):A68–A69. doi:10.1136/oemed-2017-104636.182

Centers for Disease Control and Prevention (CDC). 2008. Heat-related deaths among crop workers – United States, 1992-2006. MMWR. 57(24):649–653. June 20, 2008; [accessed 2019 Oct 10]. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5724a1.htm.

Centers for Disease Control and Prevention (CDC). 2018. OSHA-NIOSH Heat Safety Tool [Mobile application software, version 3.1]. February 8, 2018; [accessed 2018 Aug 13]. https://apps.apple.com/us/app/osha-niosh-heat-safety-tool/id1239425102.

Criner AC. 2006a. Greene County. NCPedia; [accessed 2019 Sept 17]. https://www.ncpedia.org/geography/greene.

Criner AC. 2006b. Edgecombe County. NCPedia; [accessed 2019 Sept 17]. https://www.ncpedia.org/geography/edgecombe.

Garzon-Villalba XP, Ashley CD, Bernard TE. 2019. Benchmarking heat index as an occupational exposure limit for heat stress. J. Occup. Environ. Hyg. 16(8): 557–563. doi:10.1080/15459624.2019.1628348

Garzon-Villalba XP, Wu Y, Ashley CD, Bernard TE. 2017. Ability to discriminate between sustainable and unsustainable heat stress exposures—Part 1: WBGT exposure limits. Ann. Work. Expo. Health. 61(6):611–620. doi:10.1093/annweh/wxx034

Gubernot DM, Anderson GB, Hunting KL. 2015. Characterizing occupational heat-related mortality in the United States, 2000-2010: An analysis using the Census of Fatal Occupational Injuries database. Am J Ind Med. 58(2):203–211. doi:10.1002/ajim.22381

Luque JS, Becker A, Bossak BH, Grzywacz JG, Tovar-Aguilar JA, Guo Y. 2019b. Knowledge and practices to avoid heat-related illness among Hispanic farmworkers along the Florida-Georgia line. J. Agromedicine [Epub Ahead of Print, Sept. 23, 2019]. doi:10.1080/1059924X.2019.1670312

Luque JS, Bossak BH, Davila CB, Tovar-Aguilar JA. 2019. I think the temperature was 110 degrees!": Work safety discussions among Hispanic farmworkers. J.

Agromedicine. 24(1):15–25. doi:10.1080/1059924X.2018.1536572

Mac VVT, Hertzberg V, McCauley LA. 2019. Examining agricultural workplace micro and macroclimate data using decision tree analysis to determine heat illness risk. J. Occup. Environ. Med. 61(2):107–114. doi:10.1097/JOM.0000000000001484

Morris CE, Gonzales RG, Hodgson MJ, Tustin AW. 2019. Actual and simulated weather data to evaluate wet bulb globe temperature and heat index as alerts for occupational heat-related illness. J. Occup. Environ. Hyg. 16(1):54–65. doi:10.1080/15459624.2018.1532574

Nag PK, Sebastian NC, Mavlankar MG. 1980. Occupational workload of Indian agricultural workers. Ergonomics. 23(2):91–102. doi:10.1080/00140138008924724

National Agricultural Statistics Service (NASS). 2014a. 2012 Census of Agriculture County Profile, Greene County, North Carolina. Washington (DC): U.S. Department of Agriculture, NASS; [accessed 2019 Sept 17]. https://www.nass.usda.gov/Publications/AgCensus/2012/Online_Resources/County_Profiles/North_Carolina/cp37079.pdf.

National Agricultural Statistics Service (NASS). 2014b. 2012 Census of Agriculture County Profile, Edgecombe County, North Carolina. Washington (DC): U.S. Department of Agriculture, NASS; [accessed 2019 Sept 17]. https://www.nass.usda.gov/Publications/AgCensus/2012/Online_Resources/County_Profiles/North_Carolina/cp37065.pdf.

National Institute for Occupational Safety and Health (NIOSH). 2016. Criteria for a recommended standard: occupational exposure to heat and hot environments. By Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH. DHHS (NIOSH) Publication No. 2016-106. [accessed 2019 Aug 29] https://www.cdc.gov/niosh/docs/2016-106/pdfs/2016-106.pdf.

National Weather Service (NWS). 2019a. Heat Index. Silver Spring (MD): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, NWS; [accessed 2019 Oct 16]. https://www.weather.gov/safety/heat-index.

National Weather Service (NWS). 2019b. The Heat Index Equation. Silver Spring (MD): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, NWS; [accessed 2019 Oct 28]. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml.

Occupational Safety and Health Administration (OSHA). 2017. OSHA Technical Manual, Section III, Chapter 4: Heat Stress. Washington (DC): U.S. Department of Labor, OSHA; [accessed 2019 Sept 12]. https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html.

Occupational Safety and Health Administration (OSHA). 2019. Using the heat index: A guide for employers. Washington (DC): U.S. Department of Labor, OSHA; [accessed 2019 Oct 16]. https://www.osha.gov/SLTC/heatillness/heat_index/pdfs/all_in_one.pdf.

Pitt County Development Commission (PCDC). 2019. Ag and food products. Greenville (NC): PCDC; [accessed 2019 Sept 17]. http://locateincarolina.com/ag-and-food-products/.

Rothfusz LP. 1990. The heat index "equation" (or, more than you ever wanted to know about heat index). Fort Worth, TX: National Weather Service (NWS) Southern Region Headquarters. Technical Attachment SR 90-23. [accessed 2019 Oct 28]. https://www.weather.gov/media/ffc/ta_htindx.PDF.

Steadman RG. 1979. The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. J Appl Meteor. 18(7):861–873. doi:10.1175/1520-0450(1979)018 < 0861:TAOSPI

Tustin AW, Lamson GE, Jacklitsch BL, Thomas RJ, Arbury SB, Cannon DL, Gonzales RG, Hodgson MJ. 2018. Evaluation of occupational exposure limits for heat stress in outdoor workers - United States, 2011-2016. MMWR Morb Mortal Wkly Rep. 67(26):733–737. doi:10.15585/mmwr.mm6726a1