



Published in final edited form as:

Am J Physiol Regul Integr Comp Physiol. 2025 June 01; 328(6): R703–R717. doi:10.1152/ajpregu.00004.2025.

Heat exposure, heat strain, and off-work recovery of Guatemalan sugarcane workers

Lyndsay Krisher^{1,2}, Karely Villarreal Hernandez¹, Yaqiang Li^{1,2}, Jaime Butler-Dawson^{1,2}, Diana Jaramillo¹, Hillary A. Yoder³, Kevin E. Miller⁴, Evan C. Johnson⁵, Katherine A. James^{1,2}, Miranda Dally^{1,2}, Elizabeth J. Carlton², Daniel Pilloni Alessio⁶, Alex Cruz⁶, Joshua Schaeffer⁷, John L. Adgate^{1,2}, Lee S. Newman^{1,2}

¹Centers for Health, Work and Environment, Colorado School of Public Health, University of Colorado Anschutz Medical Campus, Aurora, Colorado, United States

²Department of Environmental and Occupational Health, Colorado School of Public Health, University of Colorado Anschutz Medical Campus, Aurora, Colorado, United States

³Department of Kinesiology, New Mexico State University, Las Cruces, New Mexico, United States

⁴Department of Exercise Science, University of Providence, Great Falls, Montana, United States

⁵Division of Kinesiology and Health, University of Wyoming, Laramie, Wyoming, United States

⁶Grupo Pantaleon, Guatemala City, Guatemala

⁷Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, Colorado, United States

Abstract

Agricultural workers are at high risk for heat-related illnesses when performing heavy labor in hot conditions. Occupational heat strain, the physiological response to heat stress, is hypothesized to be common in this worker population but has rarely been measured objectively through core body temperature (T_c). The objective of this study was twofold: 1) evaluate workday heat strain and 2) examine the trajectory of heat exposure and T_c from the workday through the off-work hours to advance understanding of the recovery process and conditions of heat-exposed agricultural workers. Among 55 male Guatemalan agricultural workers, individual heat exposure (using

Licensed under Creative Commons Attribution CC-BY-NC 4.0.

Correspondence: L. Krisher (Lyndsay.krisher@cuanschutz.edu).

AUTHOR CONTRIBUTIONS

L.K., J.B.-D., and L.S.N. conceived and designed research; L.K., K.V.H., and D.J. performed experiments; L.K., Y.L., and K.E.M. analyzed data; L.K., K.V.H., Y.L., J.B.-D., H.A.Y., E.C.J., M.D., and E.J.C. interpreted results of experiments; L.K. and Y.L. prepared figures; L.K. drafted manuscript; L.K., K.V.H., Y.L., J.B.-D., D.J., H.A.Y., K.E.M., E.C.J., K.A.J., M.D., E.J.C., D.P.A., A.C., J.S., J.L.A., and L.S.N. edited and revised manuscript; L.K., K.V.H., Y.L., J.B.-D., D.J., H.A.Y., K.E.M., E.C.J., K.A.J., M.D., E.J.C., D.P.A., A.C., J.S., J.L.A., and L.S.N. approved final version of manuscript.

DISCLAIMERS

The contents of this manuscript are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention or the Department of Health and Human Services. Funders had no role in data analysis, interpretation of data, writing the manuscript, or the decision to submit the findings for publication.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

ambient temperature loggers) and T_c (via an ingestible pill) were measured across a 24-h period, including workday and off-work hours. Urine samples were collected to assess hydration status on and off-work. Workers reported off-work activities, hydration practices, sleep, and nutrition through a survey. Data were summarized using descriptive statistics and visualizations. Workers experienced excessive heat strain (44% with $T_c > 38.0^\circ\text{C}$, 16% with $T_c > 38.3^\circ\text{C}$, and 6% with $T_c > 38.5^\circ\text{C}$) during the workday. Approximately 29% achieved a higher maximal T_c during off-work hours than during the workday. Nearly 15% of workers reported sleeping <7 h. There is a need to understand off-work conditions, practices, and resources available to workers to mitigate heat strain and related illnesses. Heat stress and T_c monitoring should extend to postwork shift for assessment of workers' physiological recovery and to inform more comprehensive interventions to protect worker health.

NEW & NOTEWORTHY

This study examined the trajectory of heat exposure and core body temperature (T_c) across the workday into off-work hours among agricultural workers at risk of heat-related illness. Workday heat strain was common, and a significant proportion of workers experienced higher off-work T_c compared with their workday T_c . Survey and environmental data collected from workers provide insights into the off-work practices and conditions of the home environment that could influence the recovery of workers.

Keywords

agricultural workers; heat stress; home environment; recovery

INTRODUCTION

Heat stress, dehydration, intense physical labor, and exposure to toxins and toxicants are some of the occupational hazards experienced by agricultural workers in Latin America (1-9). Since agricultural workers frequently labor outdoors, they are at high risk of morbidity and mortality due to heat exposure. The projected rise in global temperatures due to climate change will further increase workers' susceptibility to excessive heat exposure (10). Often, workers have limited access to potable water and adequate nutrition at the worksite, are unable or disincentivized to take rest breaks, and have limited training and awareness of heat-related adverse health outcomes (11). Such working conditions put workers at a higher risk for heat-related illnesses (HRI) and have prompted researchers and policymakers to consider how to modify work practices to mitigate HRI. However, less is known about how heat exposure and social determinants of health faced by workers in their off-hours—outside the workplace—may contribute to the overall risk of HRI. Among the many socioeconomic disparities they experience, agricultural workers worldwide frequently live in housing without air conditioning or adequate ventilation needed for recovery from the heat and exertion during their workday (12-17).

Environmental as well as occupational risk factors contribute to the heat stress, or net heat load, experienced by workers. Environmental factors include heat, humidity, and solar radiation, whereas exertional heat stress results from metabolic heat that is generated

internally through physical activity, such as that performed in agricultural work settings (7, 18). During such physical activity in hot environments, the body dissipates heat by increasing skin blood flow and sweat rate; however, the metabolic heat production can sometimes exceed these heat loss mechanisms. In such situations, heat stress is considered uncompensable, where core body temperature (T_c) will continue to rise (19, 20), increasing the risk of heat-related illnesses and injuries, mortality, and lost productivity (18). Repeated bouts of heat strain, the physiological response to heat stress, and elevated T_c further increase the risk for HRI (21) and are associated with long-term adverse physical and mental health effects (22).

Current guidelines that address heat exposure in occupational settings include the National Institute for Occupational Safety and Health's (NIOSH) *Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments* (18). Meanwhile, off-work heat exposure, including temperature related to living conditions in the home environment, has been evaluated only minimally among agricultural workers, primarily in the United States (23) and more recently in a sample of sugarcane workers in Nicaragua (24). Agricultural workers may be exposed to high temperature and humidity levels during their off-work hours, which inhibit the normal decrease in T_c that occurs naturally during sleep (25), thus limiting their ability to fully recover from the heat and exertion of their workday.

Despite the recognition of the short- and long-term health and economic impacts of heat stress, occupational heat exposure continues to cause morbidity and mortality among agricultural and other workers (26, 27). Although agricultural workers have frequently reported symptoms of HRI (3, 28-30), few studies have examined heat strain objectively in this population through measurement of T_c during work. Furthermore, the trajectory of agricultural workers' T_c off-work will be useful for evaluating workers' response to heat stress, for example, by examining the pattern and recovery of T_c at the end of the workday and overnight. Our central hypothesis is that some workers are unable to cool off, and therefore recover, after their workday, creating a cumulative effect of heat stress and exertion that increases the risk for adverse health outcomes and HRI. The information presented in this paper is helpful for informing the next steps for understanding the cumulative burden of heat stress in this high-risk population that can ultimately lead to the development of more effective interventions that are needed to better address the effects of heat on workers.

The primary objective of this paper is to characterize heat exposure and physiological response (T_c), both on and off-work, among a group of male Guatemalan sugarcane workers considered to be at particularly high risk of work- and off-work-related heat stress. We will describe the continuous trajectory of core body temperature from the workday through the off-work recovery period, that is, until the start of the following workday (24 h). To characterize workers' temperature exposure over a full 24-h period, we examined the variability of ambient environmental temperature using heat index (HI) measurements as well as individual ambient temperature loggers worn at work and home. Finally, we describe workers' off-work recovery practices reported in a survey and through urinary hydration measurement.

METHODS

Study Population

This study was conducted with male sugarcane cutters who were employed for either the 2021–2022 or 2022–2023 6-mo harvest season by the agribusiness Pantaleon in southwest Guatemala. These workers represent a subset of study participants whom were recruited as part of the “CKDu Heat and Air Pollution” (CHAP I) Study (Grant R01 ES31585) focused on occupational exposures and practices during the work shift. All participants were at least 18 yr old at the time of recruitment and were residing in local communities in the coastal lowland region surrounding the sugarcane fields. The sugarcane harvest lasts from November to May. During their work shift, sugarcane cutters manually cut and stack cane in the fields for approximately 8 h/day with 2 h of interspersed rest, roughly from 0700 to 1700, and each man cuts on average six tons of cane daily (31). Rest breaks include two 30-min breaks, taken in the shade, including one in the morning around 1000 and one in the afternoon around 1430, as well as a 1-h break for lunch at noon. Workers are provided with free access to purified water directly in the field and, in addition, receive at least 5 L of electrolyte solution daily. Other details of the work setting and practices have been published previously (5). When these workers have completed their work shift, they return home to their communities each evening on non-air-conditioned buses. This commute can take from 30 min up to 2 h, each way, to their worksite and back, depending on the daily field location. Workers return to homes in the communities that lack air conditioning or other cooling mechanisms, such as fans, with limited ventilation. As a pilot ($n = 9$), we assessed the conditions of the home environment that may contribute to heat exposure among a subset of workers involved in this study. Additional details will be described in DISCUSSION.

Study Design

This cross-sectional descriptive study characterized individual heat exposures for this group of agricultural workers, following them individually for 24 h to include both their workday (CHAP I study) and off-work exposures (substudy). For the substudy, the period of observation and data collection was extended to include time off work (~1700 to 0600 the next morning). Across the 2 years of fieldwork, the study design was integrated within CHAP I at one of the three time points during the 6-mo harvest. Over a 6-day period in February 2022 (*days 1–6*) and a 4-day period in April 2023 (*days 7–10*), measures of heat exposure and T_{c} response were collected during the workday and the off-work period. February represents the approximate midpoint of the harvest season, whereas April is closer to the end of the season, allowing us to sample workers who are acclimatized to the climate and work (18). A total of 55 workers were evaluated from 10 work groups. Data were collected from one work group (2–9 workers) each study day.

Briefly, to begin the 24-h monitoring period, workers and the research team arrived at the sugarcane field at ~0600 where workers provided a urine sample, had body mass measured, were given a T_{c} monitoring pill to ingest, and were equipped with an ambient temperature logger; a wet bulb globe temperature (WBGT) meter was set up in the field. At the end of work around 1700, researchers returned to the field to meet the workers, collect another urine sample, and provide a second pill. To end the 24-h monitoring period, another urine

sample and survey data were collected the following morning in the sugarcane field before the start of the next workday. Details about each measurement are provided below.

Ethics

The participants for this study were recruited and provided written informed consent in November 2021 and November 2022. Workers who could not sign their name provided a thumbprint with a witness present. This research was approved by the Colorado Multiple Institutional Review Board (COMIRB No. 20-0509) of the University of Colorado and the Comité de Ética Independiente ZUGUEME in Guatemala.

Heat Index

Environmental data were collected on heat exposure by two methods. During the workday, wet bulb globe temperature (WBGT) data were measured continuously in the sugarcane fields within ~1 km of all workers using the Kestrel 5400 (Kestrel Instruments, Boothwyn, PA). These data were used to calculate the heat index (HI), which was derived from dry temperature and humidity using the National Weather Service formula through the weathermetrics package in R (32, 33).

Personal Temperature Monitoring

Personal ambient temperature (T_{pa}) was collected for each individual worker in the fields during the workday and in those same individuals during off-work hours at home using a small, wireless temperature logger (Hygrochron iButtons, model DS1923, Maxim Integrated, California) set to record temperature once every 10 min. The temperature loggers were mounted to plastic key fobs and worn by workers on a running vest during the workday. At the end of the work shift, the temperature logger placement was moved from the vest to a bracelet around the wrist. The data were downloaded each day using the 1-Wire viewer software (Maxim Integrated, California).

Core Body Temperature

Core body temperature (T_c) was measured from the start of the workday through the next morning using a pill-sized ingestible telemetric sensor (Bodycap e-Celsius Performance, Caen, France) that measures and saves data. Ingestible telemetric temperature capsules are used to measure gastrointestinal temperature, particularly in field and occupational settings, and are considered both a valid and reliable surrogate indicator of T_c (34-36).

Study workers ingested the telemetric pill the morning of their monitored workday, shortly before starting their shift. The external wireless receiver (e-Viewer, BodyCap, Caen, France) for the telemetric pill was worn in a fanny pack around the waist by the workers to receive the data from the pill in real time (at work and off-work) before it was excreted (36). Pilot testing with the telemetric pills in this population revealed two main takeaways. First, if workers were provided with the pill the night before their workshift, many workers excreted the pill before work began the next morning, as other researchers have observed (37); therefore, the pill was given to workers shortly before the workshift. Second, although the pill records data, it was often excreted before meeting the research team at the end of the

workday. Therefore, to limit missing data, workers were equipped with wireless receivers to collect the data before excretion.

Because of the rapid excretion of the pill observed in pilot testing, workers were asked to take a second pill at the end of their work shift before returning home, a practice that had been cleared as safe by the pill manufacturer. The number of workers who could have their T_c monitored overnight on each of the 10 study days varied based on how many receivers were available (Table 2).

Recovery Survey, Hydration, and Anthropometric Measures

Workers were weighed in work clothing only (pants and long-sleeved shirt) with boots, shin guards, and other equipment removed. The morning weight was measured with a digital scale that was calibrated before each data collection session (Seca 874 DR, Seca Corporation, Chino, CA) and was used to calculate body mass index (BMI) with height, which had been collected at baseline in November (beginning of the harvest) of each study year. Hydration was assessed by urine specific gravity (USG) immediately in the field using a digital refractometer (5) (ATAGO PAL-10S, Tokyo, Japan). Urine samples were collected at the end of the workday to evaluate workday hydration and the next morning preshift to estimate off-work hydration. A recovery survey was administered verbally in Spanish at the end of the 24-h monitoring period to ask workers about their recovery practices after work, that is, the evening and overnight prior. The survey included questions related to hydration, sleep and rest quantity and quality (38-40), and nutrition, behaviors including off-work medication, tobacco, and alcohol use, how and when they arrived home the previous evening, activities they did after arriving home, the time they went to bed, and the time they woke up that morning.

Statistical Analysis

Data cleaning. Our goal was to collect and analyze continuous environmental and core body temperature over a 24-h period. Since workers ingested the first pill for the workday and the second pill for the off-work period, the T_c data were initially comprised of two separate datasets; potential “overlap” between the two pills was not a concern since each pill was linked to a separate receiver. To address the missing data in the T_c measurements, which occurred at random, we removed individuals from analysis with more than 30% missing data or through visual inspection to determine whether there were sufficient data across the monitoring period. A total of 55 participants had both T_{pa} and workday T_c and were included in the final dataset for analysis, with 64 participants (54%) having been removed for missing either T_c or T_{pa} data. Of the final 55, 17 workers had off-work T_c available for analysis. Other than the calculation of heat index as described above and T_c data cleaning described below, all analyses were conducted using SAS version 9.4 (Cary, NC).

Several measures were taken to clean and smooth the T_c data based on methods applied in similar work (37, 41). First, to allow time for the pill to reach the lower gastrointestinal tract and for the readings to stabilize, we excluded observations within the first 60 min from the time the pill was ingested at the beginning of the monitoring period to begin analysis. Next, there were abrupt decreases in T_c that were outside of physiological plausibility given the

body cooling measures that are available in the fields to the sugarcane cutters. These abrupt changes (termed the “bouncing ball” effect) were likely due to beverage consumption (36, 37). To clean the T_c data, a script in R statistical software (v. 4.4.1; R Core Team 2021) developed by Petropoulos et al. (41) was used, which flagged physiologically implausible drops in the T_c data resulting from the “bouncing ball” effect—but otherwise deemed usable—and removed T_c data outliers based on 1) the magnitude of the slope between neighboring points 1, 2, and 3 points away, or 2) the data point was deemed physiologically implausible based on the change in T_c . These methods are described in detail by Petropoulos et al. (41). All T_c data were then smoothed using local regression (LOESS).

Data analysis. Descriptive statistics were generated to characterize heat exposure (T_{pa} and heat index) and T_c on and off work. Descriptive statistics are reported as means $\pm$ standard deviation (SD) and maximum unless otherwise stated. The average and maximum for T_c and ambient temperature for each individual during the workday and off-work period were used separately and also produced descriptive statistics for each *study day* (1-10) and each hour of the monitoring periods. For figures of heat exposure and T_c data, a smoothed line was fit with a 95% confidence interval (CI) using LOESS regression estimation procedures and splines in SAS (9, 42). Heat strain is presented as T_c exceeding 38.0°C, 38.3°C, or 38.5°C for at least two consecutive measures, in accordance with the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for safe repeated exposure to heat stress and to be consistent with other occupational studies using the telemetric pill. (41, 43-45). Briefly, the ACGIH TLV incorporates both internal metabolic and environmental heat factors and states that for acclimatized, euhydrated, and unmedicated workers to be exposed to heat stress conditions safely, T_c should not exceed 38.0°C (100.4°F) “for extended periods,” the level that indicates heat strain, although it is not clear what the limit of time should be, and agricultural workers often labor long hours daily under heat stress conditions (18, 46). The 2017 TLV (47) further states that while most individuals should maintain T_c below 38.3°C, in some cases, that is, acclimatized individuals who are under close medical supervision and physiological monitoring, T_c may safely exceed 38.3 but should go no higher than 38.5°C (101.3°F) (18), the level that indicates excessive heat strain. The TLV references personal risk factors that should also be considered, such as chronic health conditions as well as repeated heat exhaustion, since there is evidence of a “carry-over effect” from heat exposure on the previous day (47). At rest, the human body T_c is generally maintained close to $37 \pm 0.5^\circ\text{C}$, with the lowest T_c level occurring around 0400 and the highest typically around 1800 (48, 49).

RESULTS

Table 1 displays cohort demographics and anthropometric data. The median age of the cohort was 29 yr [interquartile range (IQR): 24, 36]. The average weight was 57 ± 6 kg, and the average body mass index was 21 ± 2 kg/m². Most workers (96%) were “normal weight” based on BMI. The average hours worked per day during the study period was 9.5 ± 0.5 h.

Workday Data

Table 2 shows the average workday heat index and T_{pa} across the 10 study days, with the frequency (%) of heat strain (exceeding T_c of 38.0°C, 38.3°C, and 38.5°C) on each day. Based on the T_{pa} data, *study days 7* and *10* had the highest mean temperatures. The highest average HI was on *day 9* (39.4°C). *Study days 8* and *10* saw the highest frequency of individuals exceeding a T_c of 38.0°C (80%), followed by *day 4* and then *day 3*. *Day 4* was the coolest day based on HI, and yet 75% of workers exceeded a T_c of 38.0°C, whereas three workers also exceeded 38.3°C, and two workers exceeded 38.5°C. At least 50% of study participants exceeded a T_c of 38.0°C on four of the 10 days.

Overall, 44% of workers experienced workday heat strain (exceeded 38.0°C), 16% exceeded 38.3°C, and 6% exceeded 38.5°C (Table 2). Figure 1 shows a time series with a LOESS estimate of the central tendency of T_c of the workers across the workday period, and on average, T_c increased across the workday. A total of five individuals (9%) were dehydrated (USG > 1.020) postshift. Two of the five workers (one on *study day 4* and the other on *study day 8*) also exceeded T_c 38.0°C on the day they were dehydrated.

During the workday, T_{pa} increased until ~1300 then decreased slightly until the end of the workday (Fig. 2). As shown in Table 2, the average T_c across all workers during the workday was $37.3^\circ\text{C} \pm 0.5^\circ\text{C}$ and reached an average maximum of $37.9 \pm 0.4^\circ\text{C}$ in the early afternoon. The average and maximum T_c tended to increase across the day (Fig. 1). Workers who exceeded T_c of 38.0°C did so starting from 1000 until the end of the workday.

Off-Work Data

The T_{pa} temperatures were lower during the early evening hours and started to increase around 2100–2200 (Fig. 2) until ~0300, when they started to decrease again, on average. T_c measures were highest from 1900 to 2200. The hourly off-work T_{pa} and T_c data can be viewed in APPENDIX.

Figure 3 displays the off-work trajectory of T_c following the workday. The average off-work max was 37.6°C and was recorded early in the off-work period, between 1800 and 2000 before starting to decrease after 2000. As described earlier, after 2000 when T_c started to decrease, T_c gradually increased sometime after 0400, which is also when many workers are beginning to wake up and get ready for the commute to work the next day, as described further below. On average, T_c decreased by one degree during the off-work/overnight period. Seven workers (41%) exceeded 37.5°C while off work. No one exceeded a T_c of 38.0°C during the off-work period. Five individuals (29%) experienced a higher or equal off-work max T_c compared with their max workday T_c . These data are shown in the Appendix Table A2 and Appendix Fig. A1, which contains T_c and T_{pa} data for each of the workers individually across both the workday and off-work period, as well as the workers' reported time returning home from work and time they reported going to bed, as a preliminary assessment of off-work practices. Notably, in the same survey, which is detailed further below, most workers, including those individuals with higher (>37.5°C) off-work T_c , reported not doing any physical activity like playing sports after work, and most arrived home after dark (Appendix Table A3).

Among at least four individuals (24%), their T_c off-work increased again after having already reported going to bed before they woke up the next morning. Indeed, in Fig. 3, the average T_c increased just before 0200 and decreased again just before 0400. As shown in the Appendix Table A1 and Fig. 2, the average T_{pa} was also elevated at this time, during 0100–0159.

Recovery Practices

Workers' reported practices from the recovery survey and off-work hydration are displayed in Table 3. The survey was administered just before workers began their next workday, at the end of the 24-h monitoring period; the average amount of time elapsed since waking up and the morning survey time was 2.8 h (range: 1.5–4.4 h). Few workers were dehydrated in the morning (5.5%), although approximately three-quarters reported drinking fewer than five cups of water after leaving work the previous day, before bed, and 35% had only had one cup of water since waking up that morning. Workers consumed a range of other beverages during the off-work period, shown in Appendix Table A3, including atol, which is a warm, traditional corn-based beverage, coffee, juice or soda, and electrolyte solution.

In terms of sleep and rest, 15% slept fewer than 7 h overnight; approximately the same proportion reported this to be their usual amount of sleep (18%). The average amount of time spent at home between shifts was 10 h (range: 8–13 h). Several questions were asked related to sleep issues, shown in Table 3. Six workers (11%) reported feeling exhausted when they woke up that morning. One of the six workers who felt exhausted was among those who reported sleeping fewer than 7 h overnight. As shown in Appendix Table A3, five workers (9%) reported feeling neither alert nor sleepy at the time of the survey, and one worker felt sleepy. Most workers were sharing a bed with at least one other person (partner or child), with 15% sharing with two other people and 4% with three others. Just two workers reported doing any physical activity after work—either playing sports or doing work around their home/land.

No one reported drinking alcohol during off-work hours, and one individual reported taking an unnamed medication to help with sleeping. Four workers (7%) reported feeling a little to moderately hungry before going to bed. Of those four, one of them was among the six who reported feeling exhausted. Four percent (two workers) reported that their family did not have enough food to eat during the previous month. The most common foods that workers reported eating for dinner were beans (44%), chicken or meat (33%), rice or pasta (27%), and eggs (18%). Other examples of foods consumed by a minority of workers (<10%) included soup, cheese, and potatoes. Corn tortillas are commonly consumed at most meals by the workers in this population, based on anecdotal evidence and our prior experience with and knowledge of workers' diets (50); however, workers did not specifically report tortillas in this survey.

DISCUSSION

In this study, we characterized the trajectories of ambient and core body temperature, across both the workday and off-work hours, among male Guatemalan sugarcane workers at daily risk for HRI. We found that a high proportion (44%) of workers experienced heat strain,

a known risk factor for developing HRI ($T_{\text{c}} > 38.0^{\circ}\text{C}$) during the workday, including 16% who exceeded 38.3°C and 6% who exceeded $T_{\text{c}} 38.5^{\circ}\text{C}$, despite workplace hydration and rest break programs. In this study, T_{c} increased on average across the workday and continued to rise after ambient temperature began to fall in the late afternoon. Over 40% of workers sustained a $T_{\text{c}} > 37.5^{\circ}\text{C}$ while off work, thus exceeding what is considered the human body's normal range of resting T_{c} (49). We found preliminary evidence that some workers' T_{c} may not sufficiently decrease and may even increase after going to bed. We do not yet know whether the off-work findings are primarily driven by the inability to cool down following heat strain during the workday, the conditions of the home environment, normal diurnal variation, or perhaps multiple factors. Workers' T_{c} decreased by 1.0°C on average during off-work/overnight hours. As has been noted by other researchers, it is not yet understood what "normal" T_{c} recovery looks like in this or other agricultural worker populations, both during rest breaks and after the completion of the work shift (51). Approximately 29% of workers experienced a higher off-work max T_{c} compared with their workday max T_{c} , which tended to occur several hours after having already left work for the day. Future research is needed to further assess how much heat strain is extending into the off-work period and whether conditions of the home environment are conducive to nighttime cooling and recovery. Finally, our evaluation of the off-work recovery practices of workers provides preliminary information on workers' available time and resources for recovery in their off-work period, which will guide future intervention research to improve health in this population.

A strength of the study was that it was conducted during the second half of the sugarcane harvest season, at a time when workers were already acclimatized to the heat. Acclimatization, which improves thermoregulation, has been shown to be one of the most important prevention measures against heat-related illness (HRI), both in workers and in athletes (18). Yet, we saw that acclimatized workers still experience heat strain. Our results are similar to findings from a 3-day study in Florida among fernery workers, which also used the ingestible pill to measure T_{c} , finding that T_{c} exceeded 38.0°C at some point on 61% of the workdays and that 83% of workers had $T_{\text{c}} \geq 38.0^{\circ}\text{C}$ on at least one of the days (37). In that study, among those who had three full days of data ($n = 37$), 32% had 1 day, 16% had 2 days, and 41% had all 3 days on which $T_{\text{c}} \geq 38.0^{\circ}\text{C}$ (37), indicating that workers are experiencing heat strain on consecutive days. Another study among agricultural workers in the Central Valley of California found that 8.5% of workers had a $T_{\text{c}} \geq 38.5^{\circ}\text{C}$ during a work shift (51). A study by Petropoulos et al. (41) conducted among sugarcane workers in El Salvador and Nicaragua found between 41% and 81% of workers exceeded 38.0°C for at least 5 min. Finally, a recent study among sugarcane workers in Brazil observed that all nine participants exceeded 38.0°C , and roughly half met or exceeded 38.5°C . Other studies of heat stress in agricultural workers have often depended on the reporting of symptoms of HRI by workers using questionnaires. Our previous studies have shown that reliance on self-reported symptoms may underestimate the true burden of HRI in this population. For example, in a study at the same sugar mill, only three (3%) participants reported common signs and symptoms of HRI (5). This discrepancy in reported and measured HRI highlights the importance of additional studies with objective field measurements of heat strain to better understand the current extent of HRI among agricultural workers, as well as the future

burden due to rising temperatures from climate change (52). These data are also valuable for developing practical heat exposure thresholds in workplace settings and for measuring the impact of interventions to prevent HRI and other negative health outcomes, such as kidney injury (5).

Workers in this study were provided with purified water, electrolytes, and mandatory rest breaks by their employer (5). Few (9% overall) were dehydrated at the end of the work shift based on USG. Nonetheless, we found that many workers' T_c reached 38.0°C before 1200, similar to what was observed among sugarcane workers in Brazil (45), and was often sustained or continued to rise across the work shift, despite ambient temperature decreasing in the afternoon. These findings combined with those of other researchers (37, 51), suggest that current work-to-rest schedules, such as those recommended by NIOSH (18) and a new occupational heat rule proposed by the Occupational Safety and Health Administration (OSHA) (<https://www.federalregister.gov/documents/2024/08/30/2024-14824/heat-injury-and-illness-prevention-in-outdoor-and-indoor-work-settings>), should be further evaluated for safe strenuous work under these environmental conditions, especially at the level of work intensity of sugarcane harvesting, which is likely to be even higher than that of some other types of farm work, pointing to the need for more context-specific guidance (51, 53). In the new proposed OSHA rule, which would be the first federal heat safety standard for workers in the United States, the threshold for providing drinking water and break areas begins at a heat index of 26.7°C. Employers must monitor for signs of HRI and provide mandatory 15-min rest breaks every 2 h beginning at 32.2°C. In the present study, the average heat index across the study period was $36.8 \pm 4.7^\circ\text{C}$. Finally, regarding T_c , most agricultural workers are not under close medical supervision or physiological monitoring, which the ACGIH states should be the case for workers exceeding T_c thresholds of 38°C or 38.3°C (47). Since these workers are exposed to heat stress conditions daily, it is important to also consider the potential health impact of such “carry-over” heat exposure that accumulates from 1 day to the next across the harvest season (47).

We found that T_c continued to rise even after the work shift ended, and a significant proportion (41%) exceeded the normal range of T_c while at rest after work ($>37.5^\circ\text{C}$). Almost one-third experienced a higher or equal off-work max T_c compared with their max workday T_c . The pattern of off-work T_c varied among the workers in this subcohort. Survey data indicated the workers rarely participated in physical activity during their off-work time (only 2 workers reported any additional activity). Based on the limited amount of time (10 ± 1 h) at home, we believe that most would only have had enough time to eat and rest before the next workday. Additional research is needed to understand the variability of T_c recovery both during and after work in this population.

Based on the T_{pa} data, environmental temperature increased after workers reported going to bed. We speculate that workers may spend the first part of their evening outside, where it is cooler, returning inside to sleep. Therefore, it will be helpful to better understand the drivers of off-work heat exposure, since it is known that a hot sleep environment can inhibit normal declines in T_c during the night and also may increase risk for HRI and other health effects (54). The average off-work environmental temperatures collected with the iButtons were comparable with those observed in a recent study in Nicaragua (24). Through the pilot

home visits, we observed that most homes consisted of one or two rooms, with one or zero windows. No one had air conditioning available, and few had access to a fan. Nearly all homes used an open wood-burning stove for cooking, sometimes located inside the home, with little ventilation. The majority of homes had little to no shade cover available from trees or other vegetation, and roofs and siding were constructed of corrugated metal sheeting. Future work will further assess these home environment factors.

It is important to understand off-work recovery practices that may be beneficial in helping workers recover and prepare themselves for work the following day, as are frequently recommended for athletes competing in hot environments. The preliminary information presented here from the surveys provides insights into workers' available time and resources, especially those related to hydration, rest, and nutrition, that are necessary for their physical and cognitive recovery. Future studies should include an examination of the relationship of T_c with measures of physical exertion (9, 55). In this study, workers' T_c continued to rise during the workday even after ambient temperature began to fall in the late afternoon; it may be that workers exerted additional effort during this period to increase their production. Overexertion may also explain why levels of heat strain were so high on *day 4*, which was the coolest day of the study based on the heat index. We acknowledge that there are other ways to explore changes in T_c , and thus examine recovery, such as by comparing workers' T_c during different periods of the workday and off-work and comparing it with their baseline for that period or for that day, as well as looking at whether they return to their baseline and when (56).

Finally, with this study, we demonstrated that off-work, community-based data collection of heat exposure and core body temperature is both feasible and acceptable to agricultural workers in this setting. Additional research is needed to confirm these findings and to help inform interventions to address the current and future risk for HRI in agricultural worker populations.

Limitations and Future Directions

This study carries several limitations. We were limited by a small sample size during the off-work period, restricting our ability to draw comparisons. Nonetheless, this was the first study to examine off-work T_c and one of the very few to date to have measured T_c in the field during the workday in a relatively large agricultural worker population. We did not analyze the potential lag between environmental heat exposure and T_c . This may be an important consideration in understanding the relationship between T_c and the ambient environment that may have implications for proposed mitigation strategies. In this analysis, we did not account for the potential variability in workload during the workday, which will influence workday T_c . We speculate from the recovery survey data that off-work activity levels are more similar across the cohort, though this will require further study. In addition, we conducted this study across 6 days in February 2022 and 4 days in April 2023, and therefore, the results may not be indicative of other times in the harvest season or generalizable to agricultural workers in other regions. Nonetheless, we observed variability in the HI and T_{pa} data even across those 10 days. Ultimately, future studies will be needed to

understand the generalizability of our findings to other conditions of work and to other home environments of agricultural workers.

Perspectives and Significance

The data presented in this study lay the groundwork for further investigation into the physiological recovery process of workers exposed to daily heat and physical exertion. In this study, male agricultural workers in Guatemala experienced high rates of heat strain during their workday, as measured internally through T_{c} . T_{c} continued to increase across the workday, including into the off-work hours after completing the work shift. Questions remain around how to define “recovery” of T_{c} in this population, including following workday rest breaks, right after work, and during overnight sleep. Longitudinal studies are needed to understand whether workers are experiencing heat strain daily and whether such cumulative stress, without adequate recovery, leads to adverse health outcomes over the longer term. Future research in this cohort will further explore the relationship between T_{c} and ambient temperature and humidity, as well as other factors that can impact heat-related illness, including physical exertion. Our results point to the need to better understand the conditions and practices relevant to the home environment and off-work hours that may influence recovery and the subsequent response to heat and exertion at work. By also capturing round-the-clock environmental heat exposure, this work will help inform future intervention research to identify strategies that better protect workers from heat-related illness and related effects.

ACKNOWLEDGMENTS

Resources were also provided by Pantaleon under a memorandum of understanding with the University of Colorado.

GRANTS

This work was supported by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Grant No. 1U19OH011227; and the National Institutes of Health, National Institute for Environmental Health Sciences, Grant No. R01 ES31585-01A1.

DATA AVAILABILITY

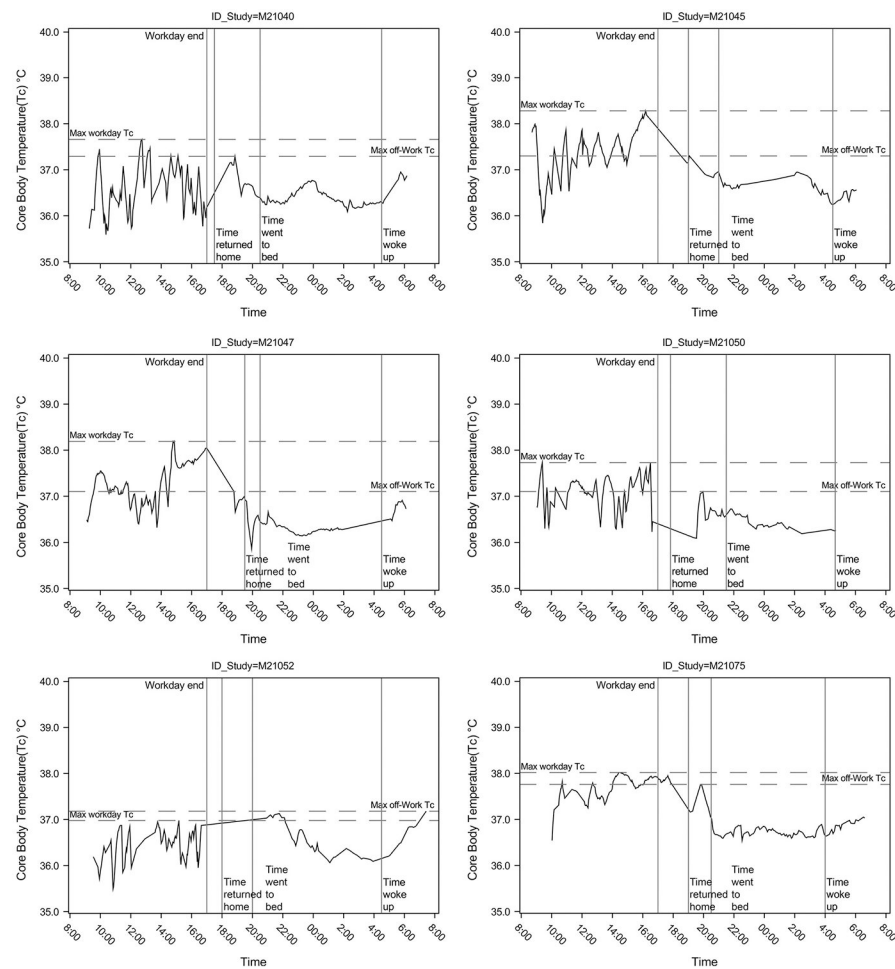
Data will be made available upon reasonable request.

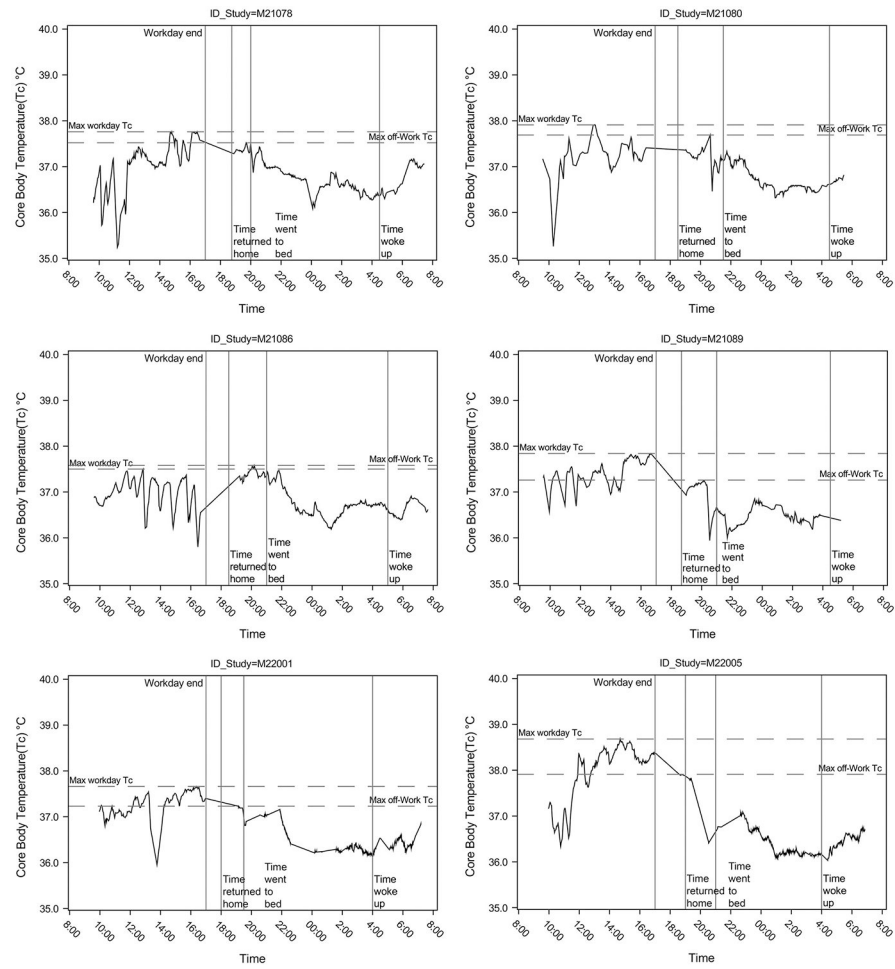
APPENDIX

Appendix Fig. A1 displays the core body temperature (T_{c}) data for each worker individually ($n = 17$), across both the workday and off-work period, linked together (Appendix Table A1). Those workers who did not have workday T_{c} data due to missingness are not included in the figure ($n = 7$). Horizontal reference lines indicate workers' T_{c} max off-work and T_{c} max during the workday, and vertical lines show the approximate time that the workday ended, the time when the worker reported returning home, the time he went to bed, and the time he woke up. Of all the 24 workers observed off-work, most experienced their off-work T_{c} max between the start of the evening and ~2000. One worker (M22083) reached their maximum early the following morning, just before beginning their next work shift. Several

workers' T_c continued to rise even after the workday ended and they had returned home, and some experienced a higher off-work max T_c compared with their workday max T_c , shown in Appendix Table A2. Among at least four workers (M21040, M21089, M22020, and M22083), their T_c increased again after having already reported going to bed, before they woke up the next morning.

Appendix Table A2 shows the same individual timeline data as in Appendix Fig. A1, with the individual personal ambient temperature (T_{pa}) data alongside, for all those with off-work T_c data ($n = 24$). As had been shown in Fig. 2, the overnight T_{pa} data show variability among these 24 individuals. M2205 was exposed to the highest off-work environment temperature, with an average of 30.9°C (2.5°C), while also having exceeded T_c of 38.5°C during the workday; during off-work hours, he reached a maximum T_c of 37.9°C at 1844. Of the 17 workers with both workday and off-work T_c data available, five (29%) experienced a greater or equal max T_c during their off-work hours as they did during the workday. Eleven workers in total (46%) reached or exceeded 37.5°C during off-work (Appendix Table A2). Appendix Table A3 displays additional variables that were collected as part of the morning recovery survey, related to hydration, rest and nutrition.





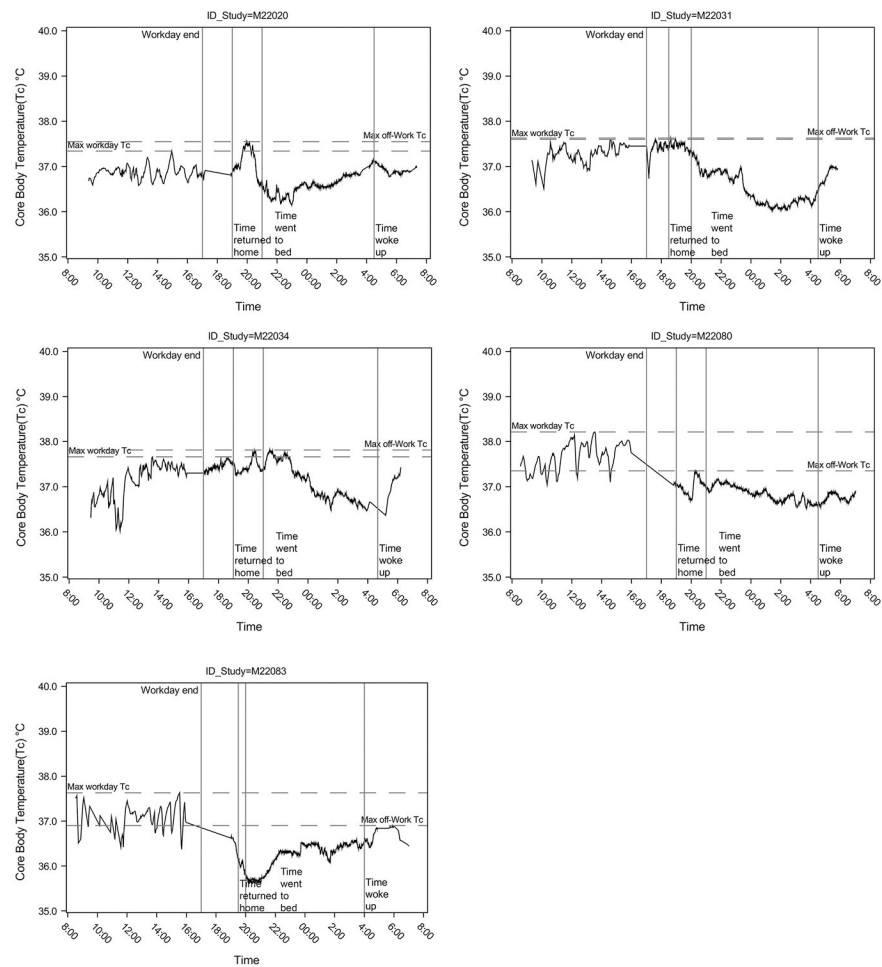


Figure A1. Timeline of workday and off-work core body temperature (T_c) by individual study ID, among those workers with both T_c workday and overnight data available ($n = 17$). Dashed horizontal reference lines indicate max workday T_c and max off-work T_c . Solid vertical reference lines indicate the time of workday end, the time worker returned home, the time he went to bed, and the time he woke up. T_c , core body temperature.

Table A1. Summary of heat exposure data by hour during off-work hours, among those workers with off-work T_c data available ($n = 17$)

Time	Hourly Off-Work $T_{c, \text{ } ^\circ\text{C}}$	Hourly Off-Work $T_{pa \text{ Temp, } ^\circ\text{C}}$
	Means (SD) max	Means (SD) max
1800–1859	37.4 (0.2) 37.9	29 (2) 32.6
1900–1959	37.1 (0.4) 37.8	28.4 (1.7) 33.2
2000–2059	36.9 (0.6) 37.8	28.5 (2.3) 36.6
2100–2159	36.8 (0.6) 37.8	29.7 (2.7) 35.6
2200–2259	36.8 (0.4) 37.7	31 (2.1) 35.5

Time	Hourly Off-Work T_{c} , °C	Hourly Off-Work T_{pa} Temp, °C
	Means (SD) max	Means (SD) max
2300–2359	36.7 (0.3) 37.4	30.9 (1.9) 35.6
0000–0059	36.6 (0.3) 37.3	31 (2.5) 36.1
0100–0159	36.4 (0.3) 36.9	31.2 (2.5) 36.1
0200–0259	36.5 (0.3) 37	31 (2.7) 35.6
0300–0359	36.5 (0.2) 36.9	30.3 (3.1) 35.2
0400–0459	36.6 (0.3) 37.1	29.1 (3.8) 35.7
0500–0559	36.7 (0.2) 37.2	26.7 (3.2) 36.1
0600–0659	36.7 (0.2) 37.4	24.3 (3.7) 32.6

Boldface indicates the overall column maximums (mean and max) for each variable. °C, Celsius; T_c , core body temperature; T_{pa} , personal ambient temperature.

Table A2.

Timeline of workday and off-work T_c and T_{pa} data by individual study ID (n = 24)

Study ID	Max Workday T_c , °C	Time of T_c	Time Home	T_c Off-Work, °C	Time of T_c	Time Went to Bed	Time Woke Up	T_{pa} Off-Work, °C
		Max-Work		Mean (SD) max	Max-Off-Work			Mean (SD) max
M21040	37.7	12:44:09	17:30:00	36.5 (0.2) 37.3	18:51:19	20:30:00	4:30:00	29.5 (3.6) 34.6
M21045	38.3	16:11:17	19:00:00	36.6 (0.2) 37.3	19:04:38	21:00:00	4:30:00	29.1 (3.9) 35.7
M21047	38.2	14:51:33	19:30:00	36.4 (0.3) 37.1	18:47:06	20:30:00	4:30:00	27.2 (3) 33.6
M21050	37.7	14:47:33	17:50:00	36.5 (0.2) 37.1	19:58:51	21:30:00	4:40:00	27.9 (3.3) 35.6
M21052	37.0	9:24:33	18:00:00	36.6 (0.3) 37.2	19:26:22	20:00:00	4:30:00	29.2 (3.2) 34.1
M21071	No data	15:10:20	19:30:00	36.3 (0.3) 37.1	19:37:18	21:00:00	4:30:00	29 (3.2) 35.1
M21075	38.0	14:25:57	19:00:00	36.8 (0.2) 37.8	19:52:47	20:30:00	4:00:00	29 (3.3) 35.5
M21078	37.8	14:43:51	18:45:00	36.8 (0.3) 37.5	19:42:55	20:00:00	4:30:00	30.6 (2.6) 36.6
M21080	37.9	12:55:52	18:30:00	36.8 (0.3) 37.7	20:38:12	21:30:00	4:30:00	30.8 (3.4) 36.1
M21086	37.5	12:51:03	18:30:00	36.8 (0.4) 37.6	20:11:33	21:00:00	5:00:00	28.8 (3.6) 35.6
M21089	37.8	16:39:54	18:40:00	36.6 (0.3) 37.3	20:08:58	21:00:00	4:30:00	28.6 (3.2) 34.6
M22001	37.7	16:22:23	18:00:00	36.4 (0.3) 37.2	19:08:30	19:30:00	4:00:00	29.2 (1.8) 33.1
M22005	38.7	14:42:32	19:00:00	36.4 (0.3) 37.9	18:44:26	21:00:00	4:00:00	30.9 (2.5) 35.6
M22007	No data		20:00:00	36.6 (0.2) 37.2	19:01:04	22:00:00	4:30:00	28.1 (2.8) 35.1
M22016	No data		19:00:00	36.4 (0.2) 36.9	19:05:32	21:00:00	4:25:00	29.2 (2.7) 34.6

Study ID	Max Workday T _c , °C	Time of T _c Max- Work	Time Home	T _c Off- Work, °C Mean (SD) max	Time of T _c Max-Off- Work	Time Went to Bed	Time Woke Up	T _{pa} Off- Work, °C Mean (SD) max
M22017	No data		16:40:00	36.6 (0.3) 37.5	19:34:22	20:30:00	4:40:00	24.8 (2.7) 30.6
M22020	37.3	14:57:25	19:00:00	36.7 (0.3) 37.6	19:58:36	21:00:00	4:30:00	28.6 (3.7) 35.1
M22022	No data		19:00:00	36.9 (0.3) 37.7	19:38:13	20:30:00	5:00:00	29.2 (2.4) 35.6
M22025	No data		18:35:00	36.9 (0.2) 37.4	19:09:41	21:30:00	4:30:00	29.6 (3.2) 35.5
M22031	37.6	14:34:48	18:30:00	36.7 (0.5) 37.6	18:38:53	20:00:00	4:30:00	30.1 (2.9) 35.5
M22032	No data		19:30:00	37.1 (0.4) 38.1	18:14:10	21:00:00	4:30:00	30.2 (2.9) 36.7
M22034	37.7	13:35:17	19:00:00	37.2 (0.4) 37.8	21:27:08	21:00:00	4:40:00	29.8 (2.8) 34.7
M22080	38.2	13:31:32	19:00:00	36.8 (0.2) 37.4	20:15:20	21:00:00	4:30:00	29.1 (3.1) 36.1
M22083	37.6	15:33:24	19:30:00	36.3 (0.3) 36.9	5:55:50	20:00:00	4:00:00	28.8 (3.2) 35.6
Overall				36.7 (0.4) 38.1				29.1 (3.3) 36.7

Boldface indicates having experienced a higher off-work T_c max compared with workday T_c max. °C, Celsius; T_c, core body temperature; T_{pa}, personal ambient temperature.

Table A3.

Additional recovery survey variables

Hydration	
What other types of beverages did you drink between ending work yesterday until going to bed? Select all that apply	<i>n</i> (%)
Atol	21 (40)
Alcohol	0
Coffee	7 (13)
Energy drink	0
Juice	11 (20)
Soda	2 (4)
Electrolyte solution	15 (28)
Other	3 (6)
What did you drink since waking up this morning?	
Water	37 (67)
Atol	23 (43)
Coffee	9 (17)
Energy drink	0
Juice	0
Soda	3 (6)
Electrolyte solution	16 (30)

Other	3 (6)
Cups of water since waking up (8 oz)	
1 cup	13 (35)
2–4 cups	18 (49)
>4 cups	6 (16)
Cups of electrolyte solution since waking up (8 oz)	
½–1 cup	4 (25)
2–4 cups	6 (37.5)
>4 cups	6 (37.5)
Sleep and rest	
(Sleep complaints) Did not feel refreshed on waking up	2 (4)
How would you rate your sleepiness now? (past 5 min)	
Extremely alert	25 (46)
Alert	24 (44)
Neither alert nor sleepy	5 (9)
Sleepy	1 (2)
Apart from your sleep, did you get enough rest yesterday after work?	
Yes, definitely enough	47 (86)
Yes, almost enough	7 (13)
No, slightly too little	1 (2)
Behaviors and nutrition	
During the last month, do you feel that your family had enough food to eat?	
Yes	53 (96)
No	2 (4)

REFERENCES

1. García-Trabanino R, Jarquín E, Wesseling C, Johnson RJ, González-Quiroz M, Weiss I, Glaser J, José Vindell J, Stockfelt L, Roncal C, Harra T, Barregard L. Heat stress, dehydration, and kidney function in sugarcane cutters in El Salvador—a cross-shift study of workers at risk of Mesoamerican nephropathy. *Environ Res* 142: 746–755, 2015. doi:10.1016/j.envres.2015.07.007. [PubMed: 26209462]
2. Paula Santos U, Zanetta DM, Terra-Filho M, Burdmann EA. Burnt sugarcane harvesting is associated with acute renal dysfunction. *Kidney Int* 87: 792–799, 2015. doi:10.1038/ki.2014.306. [PubMed: 25229334]
3. Crowe J, Nilsson M, Kjellstrom T, Wesseling C. Heat-related symptoms in sugarcane harvesters. *Am J Ind Med* 58: 541–548, 2015. doi:10.1002/ajim.22450. [PubMed: 25851165]
4. Roncal-Jimenez C, García-Trabanino R, Barregard L, Lanaspa MA, Wesseling C, Harra T, Aragón A, Grases F, Jarquin ER, González MA, Weiss I, Glaser J, Sánchez-Lozada LG, Johnson RJ. Heat stress nephropathy from exercise-induced uric acid crystalluria: a perspective on Mesoamerican nephropathy. *Am J Kidney Dis* 67: 20–30, 2016. doi:10.1053/j.ajkd.2015.08.021. [PubMed: 26455995]
5. Butler-Dawson J, Krisher L, Yoder H, Dally M, Sorensen C, Johnson RJ, Asensio C, Cruz A, Johnson EC, Carlton EJ, Tenney L, Asturias EJ, Newman LS. Evaluation of heat stress and cumulative incidence of acute kidney injury in sugarcane workers in Guatemala. *Int Arch Occup Environ Health* 92: 977–990, 2019. doi:10.1007/s00420-019-01426-3. [PubMed: 30997573]
6. Wesseling C, Aragón A, González M, Weiss I, Glaser J, Rivard CJ, Roncal-Jiménez C, Correa-Rotter R, Johnson RJ. Heat stress, hydration and uric acid: a cross-sectional study in workers of

three occupations in a hotspot of Mesoamerican nephropathy in Nicaragua. *BMJ Open* 6: e011034, 2016. doi:10.1136/bmjopen-2016-011034.

7. El Khayat M, Halwani DA, Hneiny L, Alameddine I, Haidar MA, Habib RR. Impacts of climate change and heat stress on farmworkers' health: a scoping review. *Front Public Health* 10: 782811, 2022. doi:10.3389/fpubh.2022.782811. [PubMed: 35211437]
8. Mac VV, Tovar-Aguilar JA, Flocks J, Economos E, Hertzberg VS, McCauley LA. Heat exposure in central Florida fernery workers: results of a feasibility study. *J Agromedicine* 22: 89–99, 2017. doi:10.1080/1059924X.2017.1282906. [PubMed: 28118110]
9. Moyce S, Mitchell D, Armitage T, Tancredi D, Joseph J, Schenker M. Heat strain, volume depletion and kidney function in California agricultural workers. *Occup Environ Med* 74: 402–409, 2017. doi:10.1136/oemed-2016-103848. [PubMed: 28093502]
10. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014 - Impacts, Adaptation, and Vulnerability: Regional Aspects*. Cambridge University Press, 2014.
11. Arcury TA, Summers P, Talton JW, Chen H, Sandberg JC, Spears Johnson CR, Quandt SA. Heat illness among north carolina latino farmworkers. *J Occup Environ Med* 57: 1299–1304, 2015. doi:10.1097/JOM.0000000000000552. [PubMed: 26641825]
12. Tigchelaar M, Battisti DS, Spector JT. Work adaptations insufficient to address growing heat risk for U.S. agricultural workers. *Environ Res Lett* 15: 094035, 2020. doi:10.1088/1748-9326/ab86f4. [PubMed: 33133229]
13. Dutta P, Rajiva A, Andhare D, Azhar GS, Tiwari A, Sheffield P; Ahmedabad Heat and Climate Study Group. Perceived heat stress and health effects on construction workers. *Indian J Occup Environ Med* 19: 151–158, 2015. doi:10.4103/0019-5278.174002. [PubMed: 26957814]
14. Arbury S, Lindsley M, Hodgson M. A critical review of OSHA heat enforcement cases: lessons learned. *J Occup Environ Med* 58: 359–363, 2016. doi:10.1097/JOM.0000000000000640. [PubMed: 27058475]
15. Nunfam VF, Adusei-Asante K, Van Etten EJ, Oosthuizen J, Frimpong K. Social impacts of occupational heat stress and adaptation strategies of workers: a narrative synthesis of the literature. *Sci Total Environ* 643: 1542–1552, 2018. doi:10.1016/j.scitotenv.2018.06.255. [PubMed: 30189570]
16. Fleischer NL, Tiesman HM, Sumitani J, Mize T, Amarnath KK, Bayakly AR, Murphy MW. Public health impact of heat-related illness among migrant farmworkers. *Am J Prev Med* 44: 199–206, 2013. doi:10.1016/j.amepre.2012.10.020. [PubMed: 23415115]
17. Mix J, Elon L, Vi Thien Mac V, Flocks J, Economos E, Tovar-Aguilar AJ, Stover Hertzberg V, McCauley LA. Hydration status, kidney function, and kidney injury in Florida agricultural workers. *J Occup Environ Med* 60: e253–e260, 2018. doi:10.1097/JOM.0000000000001261. [PubMed: 29271837]
18. Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H Turner, N NIOSH. NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2016–106, 2016.
19. Tyler CJ, Reeve T, Hodges GJ, Cheung SS. The effects of heat adaptation on physiology, perception and exercise performance in the heat: a meta-analysis. *Sports Med* 46: 1699–1724, 2016. doi:10.1007/s40279-016-0538-5. [PubMed: 27106556]
20. Cramer MN, Jay O. Biophysical aspects of human thermoregulation during heat stress. *Auton Neurosci* 196: 3–13, 2016. doi:10.1016/j.autneu.2016.03.001. [PubMed: 26971392]
21. Horn GP, Blevins S, Fernhall B, Smith DL. Core temperature and heart rate response to repeated bouts of firefighting activities. *Ergonomics* 56: 1465–1473, 2013. doi:10.1080/00140139.2013.818719. [PubMed: 23869685]
22. Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, Hayes K, Reid CE, Saha S, Spector J, Berry P. Extreme weather and climate change: population health and health system implications. *Annu Rev Public Health* 42: 293–315, 2021. doi:10.1146/annurev-publhealth-012420-105026. [PubMed: 33406378]

23. Quandt SA, Brooke C, Fagan K, Howe A, Thornburg TK, McCurdy SA. Farmworker housing in the united states and its impact on health. *New Solut* 25: 263–286, 2015. doi:10.1177/1048291115601053. [PubMed: 26320122]
24. Lucas RAI, Hansson E, Skinner BD, Arias-Monge E, Wesseling C, Ekström U, Weiss I, Castellón ZE, Poveda S, Cerda-Granados FI, Martinez-Cuadra WJ, Glaser J, Wegman DH, Jakobsson K. The work-recovery cycle of kidney strain and inflammation in sugarcane workers following repeat heat exposure at work and at home. *Eur J Appl Physiol* 125: 639–652, 2025. doi:10.1007/s00421-024-05610-3. [PubMed: 39369140]
25. Okamoto-Mizuno K, Mizuno K. Effects of thermal environment on sleep and circadian rhythm. *J Physiol Anthropol* 31: 14, 2012. doi:10.1186/1880-6805-31-14. [PubMed: 22738673]
26. Flouris AD, Dinas PC, Ioannou LG, Nybo L, Havenith G, Kenny GP, Kjellstrom T. Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health* 2: e521–e531, 2018. doi:10.1016/S2542-5196(18)30237-7. [PubMed: 30526938]
27. Centers for Disease Control and Prevention (CDC). Heat-related deaths among crop workers—United States, 1992–2006. *MMWR Morb Mortal Wkly Rep.* 57: 649–653, 2008. [PubMed: 18566563]
28. Stoecklin-Marois M, Hennessy-Burt T, Mitchell D, Schenker M. Heat-related illness knowledge and practices among California hired farm workers in The MICASA Study. *Ind Health* 51: 47–55, 2013. doi:10.2486/indhealth.2012-0128. [PubMed: 23411756]
29. Kearney GD, Hu H, Xu X, Hall MB, Balanay JAG. Estimating the prevalence of heat-related symptoms and sun safety-related behavior among Latino farmworkers in Eastern North Carolina. *J Agromedicine* 21: 15–23, 2016. doi:10.1080/1059924X.2015.1106377. [PubMed: 26479455]
30. Spector JT, Krenz J, Blank KN. Risk factors for heat-related illness in Washington crop workers. *J Agromedicine* 20: 349–359, 2015. doi:10.1080/1059924X.2015.1047107. [PubMed: 26237726]
31. Butler-Dawson J, Krisher L, Asensio C, Cruz A, Tenney L, Weitzkamp D, Dally M, Asturias EJ, Newman LS. Risk factors for declines in kidney function in sugarcane workers in guatemala. *J Occup Environ Med* 60: 548–558, 2018. doi:10.1097/JOM.0000000000001284. [PubMed: 29370016]
32. Anderson GB, Bell ML, Peng RD. Methods to calculate the heat index as an exposure metric in environmental health research. *Environ Health Perspect* 121: 1111–1119, 2013. doi:10.1289/ehp.1206273. [PubMed: 23934704]
33. National Weather Service. The Heat Index Equation (Online). National Weather Service. Weather Prediction Center. 2014. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml.
34. Bongers CCWG, Daanen HAM, Bogerd CP, Hopman MTE, Eijsvogels TMH. Validity, reliability, and inertia of four different temperature capsule systems. *Med Sci Sports Exerc* 50: 169–175, 2018. doi:10.1249/MSS.0000000000001403. [PubMed: 28816921]
35. Byrne C, Lim CL. The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *Br J Sports Med* 41: 126–133, 2007. doi:10.1136/bjsm.2006.026344. [PubMed: 17178778]
36. Travers GJS, Nichols DS, Farooq A, Racinais S, Périard JD. Validation of an ingestible temperature data logging and telemetry system during exercise in the heat. *Temperature (Austin)* 3: 208–219, 2016. doi:10.1080/23328940.2016.1171281. [PubMed: 27857951]
37. Hertzberg V, Mac V, Elon L, Mutic N, Mutic A, Peterman K, Tovar-Aguilar JA, Economos E, Flocks J, McCauley L. Novel analytic methods needed for real-time continuous core body temperature data. *West J Nurs Res* 39: 95–111, 2017. doi:10.1177/0193945916673058. [PubMed: 27756853]
38. Shahid A, Wilkinson K, Marcu S, Shapiro CM. Karolinska sleepiness scale (KSS). In: *STOP, THAT and One Hundred Other Sleep Scales*, edited by Shahid A, Wilkinson K, Marcu S, Shapiro CM, Springer, 2012, p. 209–210.
39. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res* 28: 193–213, 1989. doi:10.1016/0165-1781(89)90047-4. [PubMed: 2748771]

40. Casa DJ. Sleep. In: Sport and Physical Activity in the Heat, edited by Giersch GEW, Adams WM, Duffield RS. Springer International Publishing, 2018, p. 113–124.
41. Petropoulos ZE, Keogh SA, Jarquín E, López-Pilarte D, Amador Velázquez JJ, García-Trabanino R, Amador Sánchez MR, Guevara R, Gruener A, Allen DR, Leibler JH, Delgado IS, McClean MD, Friedman DJ, Brooks DR, Scammell MK. Heat stress and heat strain among outdoor workers in El Salvador and Nicaragua. *J Expo Sci Environ Epidemiol* 33: 622–630, 2023. doi:10.1038/s41370-023-00537-x. [PubMed: 37041408]
42. Cleveland WS, Devlin SJ. Locally weighted regression: an approach to regression analysis by local fitting. *J Am Stat Assoc* 83: 596–610, 1988. doi:10.2307/2289282.
43. Mac VVT, Tovar-Aguilar JA, Elon L, Hertzberg V, Economos E, McCauley LA. Elevated core temperature in Florida fernery workers: results of a pilot study. *Workplace Health Saf* 67: 470–480, 2019. doi:10.1177/2165079919849466. [PubMed: 31315538]
44. Mac V, Elon L, Mix J, Tovar-Aguilar A, Flocks J, Economos E, Hertzberg V, McCauley L. Risk factors for reaching core body temperature thresholds in Florida agricultural workers. *J Occup Environ Med* 63: 395–402, 2021. doi:10.1097/JOM.0000000000002150. [PubMed: 33560064]
45. McKenna ZJ, Nava RC, Magalhães C, Magalhães de Castro F, Machado Moreira C, Shibuya E, da Cunha I, Maia PA, Cauduro Roscani R, Rocha-Vieira E, Santiago Moraes Barros TM, Bitencourt D, Amorim FT. A comprehensive evaluation of heat stress and heat strain in a sample of sugarcane cutters in Brazil. *J Appl Physiol* (1985) 135: 1431–1439, 2023. doi:10.1152/jappphysiol.00555.2023. [PubMed: 37916268]
46. ACGIH. TLVs® and BEIs®: threshold limit values for chemical substances and physical agents and bio- logical exposure indices (Online). American Conference of Governmental Industrial Hygienists. <https://www.acgih.org/heat-stress-and-strain-2/>.
47. ACGIH. Heat Stress and Strain: TLV Physical Agents Documentation. American Conference of Governmental Industrial Hygienists, 2017.
48. Walker HK, Hall WD, Hurst JW, (Editors). *Clinical Methods: The History, Physical, and Laboratory Examinations* (3rd ed.). Butterworths, 1990.
49. Hymczak H, Gołąb A, Mendrala K, Plicner D, Darocha T, Podsiadło P, Hudziak D, Gocoł R, Kosiński S. Core temperature measurement-principles of correct measurement, problems, and complications. *Int J Environ Res Public Health* 18: 10606, 2021. doi:10.3390/ijerph182010606. [PubMed: 34682351]
50. Krisher L, Butler-Dawson J, Schlosser K, Asensio C, Sinibaldi E, Yoder H, Dexter L, Dally M, Pilloni D, Cruz A, Jaramillo D, Newman LS. Body composition, anemia, and kidney function among guatemalan sugarcane workers. *Nutrients* 13: 3928, 2021. doi:10.3390/nu13113928. [PubMed: 34836182]
51. Mitchell DC, Castro J, Armitage TL, Vega-Arroyo AJ, Moyce SC, Tancredi DJ, Bennett DH, Jones JH, Kjellstrom T, Schenker MB. Recruitment, methods, and descriptive results of a physiologic assessment of Latino farmworkers: the California heat illness prevention study. *J Occup Environ Med* 59: 649–658, 2017. doi:10.1097/JOM.0000000000000988. [PubMed: 28414703]
52. Hartinger SM, Palmeiro-Silva YK, Llerena-Cayo C, Blanco-Villafuerte L, Escobar LE, Diaz A, Sarmiento JH, Lescano AG, Melo O, Rojas-Rueda D, Takahashi B, Callaghan M, Chesini F, Dasgupta S, Posse CG, Gouveia N, Martins de Carvalho A, Miranda-Chacón Z, Mohajeri N, Pantoja C, Robinson EJZ, Salas MF, Santiago R, Sauma E, Santos-Vega M, Scamman D, Sergeeva M, Souza de Camargo T, Sorensen C, Umaña JD, Yglesias-González M, Walawender M, Buss D, Romanello M. The 2023 Latin America report of the Lancet Countdown on health and climate change: the imperative for health-centred climate-resilient development. *Lancet Reg Health Am* 33: 100746, 2024. doi:10.1016/j.lana.2024.100746. [PubMed: 38800647]
53. Alahmad B, Flouris AD, Schlader ZJ, Berry J, Amorim F, Venugopal V, Lucas RAI, Prince HJ, Wegman DH, Glaser J. Roadmap to effective and attainable workplace heat standards in the USA and beyond. *Occup Environ Med* 81: 543–544, 2024. doi:10.1136/oemed-2024-109735. [PubMed: 39406485]
54. Kark JA, Burr PQ, Wenger CB, Gastaldo E, Gardner JW. Exertional heat illness in Marine Corps recruit training. *Aviat Space Environ Med* 67: 354–360, 1996. [PubMed: 8900989]

55. Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. *Am J Physiol Regul Integr Comp Physiol* 275: R129–R134, 1998. doi:10.1152/ajpregu.1998.275.1.R129.
56. Henderson MJ, Christmas BCR, Stevens CJ, Coutts AJ, Taylor L. Changes in core temperature during an elite female rugby sevens tournament. *Int J Sports Physiol Perform* 15: 571–580, 2020. [PubMed: 32023538]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

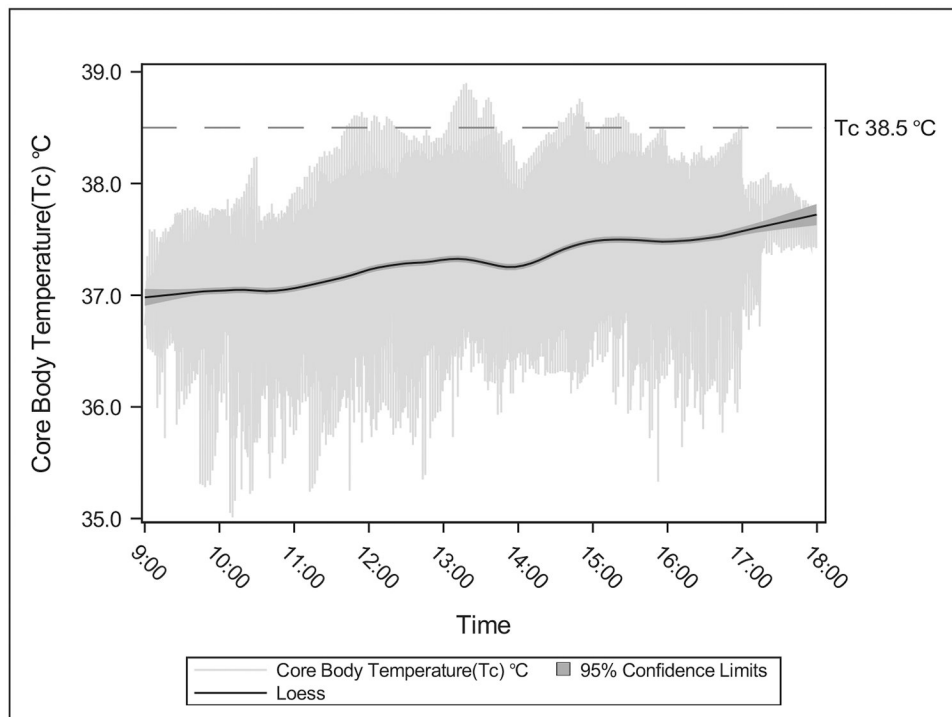


Figure 1.

Time series of core body temperature (T_c) across the workday for 55 workers. The horizontal line is at 38.5°C. The central trend line was estimated using a local regression (LOESS) smoother with 95% confidence limits indicated in dark gray. Vertical light gray lines represent the range of observations.

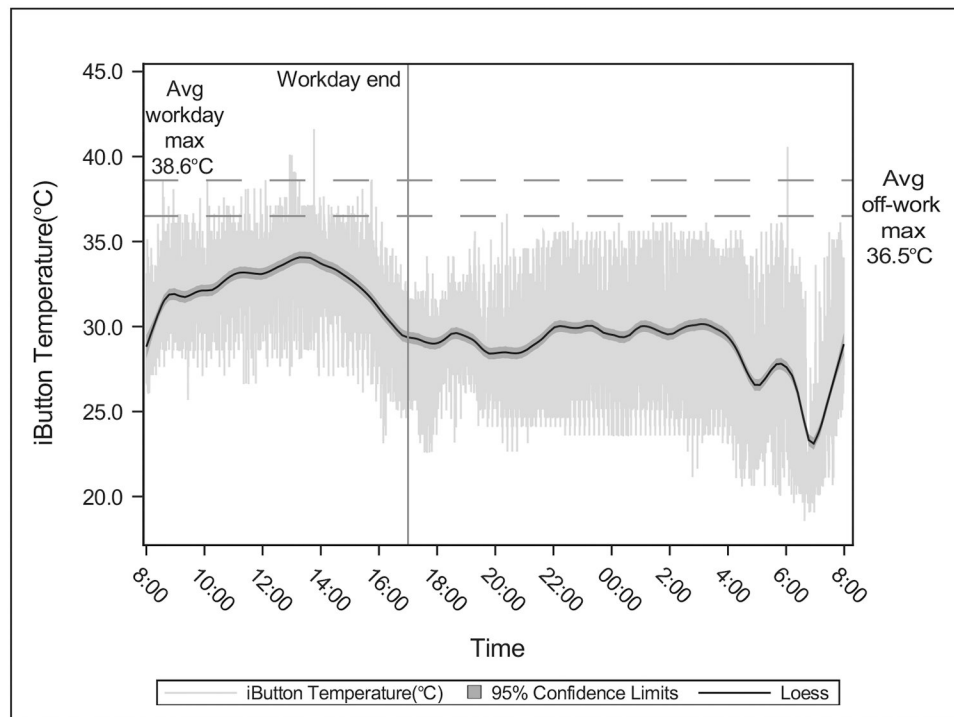


Figure 2. Workday + off-work personal ambient temperature from iButtons (T_{pa}) (°C) ($n = 55$ workers) with local regression (LOESS) estimated curve of central tendency, and 95% confidence limits, in dark gray. Vertical light gray lines represent the range of observations.

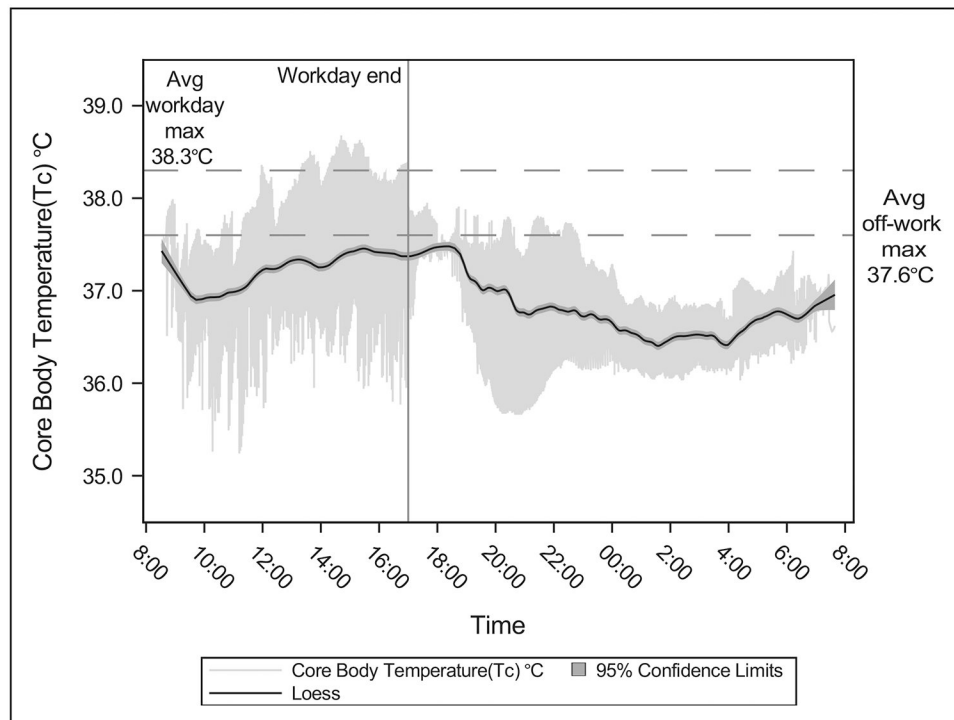


Figure 3.

Time series of workday + off-work T_c ($n = 17$) with LOESS estimated curve of central tendency and 95% confidence limits. Vertical lines show the range of observations. LOESS, local regression; T_c , core body temperature.

Table 1.
Demographics and anthropometric data of sugarcane workers in Guatemala (n = 55)

Characteristic	Mean (SD)	Reference Values
Age (median and IQR), yr	29 (24, 36)	
Weight preshift, kg	57 (6)	
Height, cm	163 (6)	
Body mass index (BMI), kg/m ²	21 (2)	
Underweight, <i>n</i> (%)	0	≤18.5 kg/m ²
Overweight, <i>n</i> (%)	2 (4%)	≥25 kg/m ²
Gender (male), <i>n</i> (%)	55 (100%)	

IQR, interquartile range.

Table 2.
Summary of workday exposure data and frequency of exceeding T_c 38.0, 38.3, and 38.5°C by study day

Variable	Study Day										Overall (n = 55)
	1 (n = 5)	2 (n = 6)	3 (n = 7)	4 (n = 8)	5 (n = 6)	6 (n = 9)	7 (n = 2)	8 (n = 5)	9 (n = 2)	10 (n = 5)	
Heat index (HI)	36.7 ± 3.0	37.1 ± 3.2	34.6 ± 7.8	30.1 ± 6.9	35.1 ± 5.2	38.8 ± 5.4	38.9 ± 3.3	39.0 ± 2.0	39.4 ± 4.0	37.8 ± 2.7	36.8 ± 4.7
Average T_{pa} , °C	32.2 ± 2.1	31.6 ± 2.5	31.8 ± 2.7	32.3 ± 3.7	32.2 ± 2.7	31.8 ± 3.9	32.5 ± 2.3	31.7 ± 2.4	32.1 ± 3.1	32.5 ± 2.4	32.0 ± 3.0
Average T_c , °C	37.1 ± 0.4	37.1 ± 0.5	37.5 ± 0.5	37.5 ± 0.6	37.1 ± 0.4	37.1 ± 0.5	37.0 ± 0.3	37.7 ± 0.5	37.2 ± 0.3	37.4 ± 0.5	37.3 ± 0.5
Average T_c max, °C	37.9 ± 0.4	37.6 ± 0.4	38.1 ± 0.2	38.3 ± 0.4	37.7 ± 0.4	37.8 ± 0.3	37.5 ± 0.2	38.2 ± 0.4	37.6 ± 0.0	38.2 ± 0.3	37.9 ± 0.4
$T_c > 38.0^\circ\text{C}$	2 (40)	1 (17)	4 (57)	6 (75)	1 (17)	2 (22)	0 (0)	4 (80)	0 (0)	4 (80)	24 (44)
$T_c > 38.3^\circ\text{C}$	0 (0)	0 (0)	1 (14)	3 (38)	0 (0)	1 (11)	0 (0)	2 (40)	0 (0)	2 (40)	9 (16)
$T_c > 38.5^\circ\text{C}$	0 (0)	0 (0)	0 (0)	2 (25)	0 (0)	0 (0)	0 (0)	1 (20)	0 (0)	0 (0)	3 (6)
USG > 1.020 post shift	0 (0)	0 (0)	0 (0)	1 (12.5) [‡]	2 (33)	0 (0)	0 (0)	1 (20) [‡]	1 (50)	0 (0)	5 (9)

Data in the first four rows are reported as means ± SD, and data in the last four rows are reported as n (%). ACGIH TLV for heat strain = $T_c > 38.0^\circ\text{C}$, $T_c > 38.3^\circ\text{C}$, and $T_c > 38.5^\circ\text{C}$ (indicating excessive heat strain, exceeded on ≥2 consecutive measurements). ACGIH, American Conference of Governmental Industrial Hygienists; T_{pa} , personal ambient temperature; T_c , core body temperature; T_c max, maximal T_c achieved; TLV, Threshold Limit Value; USG, urine specific gravity. [‡]Dehydrated and exceeded $T_c > 38.0^\circ\text{C}$.

Table 3.

Descriptive statistics of off-work hydration and recovery factors among sugarcane workers in Guatemala (n = 55)

Hydration	
Off-work hydration (AM USG)	1.011 ± 0.006
Dehydrated (USG > 1.020)	3 (5.5%)
Post-shift cups (0.25 L) of water (between the end of shift and going to bed)	
<5 cups	39 (72%)
5–15 cups	11 (20%)
>15 cups	4 (7%)
Pre-shift cups of water since waking up (8 oz)	
1 cup	13 (35%)
2–4 cups	18 (49%)
>4 cups	6 (16%)
Sleep and rest	
Total time at home, h	10 ± 1
Sleep hours last night <7	8 (15%)
Usual sleep hours <7	10 (18%)
(Sleep complaints) Felt too hot	7 (13%)
(Sleep complaints) Partner or child kept me awake	3 (6%)
(Sleep complaints) Woke up feeling exhausted	6 (11%)
How many people, including children, do you share a bed with? (not counting yourself)	
None	22 (41%)
1 other person	22 (41%)
2 others	8 (15%)
3 or more	2 (4%)
Behaviors and nutrition	
Smoked at least one cigarette yesterday	3 (5%)
Felt hungry before going to bed	
Not hungry at all	51 (93%)
A little to moderately hungry	4 (7%)
Ate snack(s) in addition to dinner	
No	32 (58%)
Had eaten something since waking up this morning	
No	8 (15%)

Data are reported as means ± SD or as *n* (%). USG, urine specific gravity.