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LETTER

Association between work in deforested, compared to forested, areas and human heat strain: an experimental study in a rural tropical environment

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Abstract

Background. With climate change, adverse human health effects caused by heat exposure are of increasing public health concern. Forests provide beneficial ecosystem services for human health, including local cooling. Few studies have assessed the relationship between deforestation and heat-related health effects in tropical, rural populations. We sought to determine whether deforested compared to forested landscapes are associated with increased physiological heat strain in a rural, tropical environment. *Methods.* We analyzed data from 363 healthy adult participants from ten villages who participated in a two-by-two factorial, randomized study in East Kalimantan, Indonesia from 10/1/17 to 11/6/17. Using simple randomization, field staff allocated participants equally to different conditions to conduct a 90 min outdoor activity, representative of typical work. Core body temperature (CBT) was estimated at each minute during the activity using a validated algorithm from baseline oral temperatures and sequential heart rate data, measured using chest band monitors. We used linear regression models, clustered by village and with a sandwich variance estimator, to assess the association between deforested versus forested conditions and the number of minutes each participant spent above an estimated CBT threshold of 38.5 °C. *Results.* Compared to those in the forested condition ($n = 172$), participants in the deforested condition ($n = 159$) spent an average of 3.08 (95% confidence interval (CI) 0.57, 5.60) additional minutes with an estimated CBT exceeding 38.5 °C, after adjustment for age, sex, body mass index, and experiment start time, with a larger difference among those who began the experiment after 12 noon (5.17 [95% CI 2.20, 8.15]). *Conclusions.* In this experimental study in a tropical, rural setting, activity in a deforested versus a forested setting was associated with increased objectively measured heat strain. Longer durations of hyperthermia can increase the risk of serious health outcomes. Land use decisions should consider the implications of deforestation on local heat exposure and health as well as on forest services, including carbon storage functions that impact climate change mitigation.

Introduction

Adverse human health effects caused by heat exposure are of public health concern as mean temperatures, in addition to the frequency and severity of heat waves, are projected to increase with climate change (IPCC 2013). To date, studies investigating the relationship between heat exposure and health have focused largely on vulnerable populations in developed countries, including older adults, very young children, and those performing heavy physical exertion, such as outdoor workers, athletes, and military personnel (Kovats and Hajat 2008). In the general population, heat waves are associated with increased hospital admissions for outcomes that include heat-related illness and dehydration, renal disease, diabetes, and obstructive lung disease and with increased emergency medical services calls, and all-cause mortality (Kovats and Hajat 2008, Isaksen *et al* 2015, Calkins *et al* 2016). In occupational populations, heat stress, from ambient heat exposure and internal heat generated from heavy physical work, is associated with occupational heat-related illness and exertional heat stroke deaths (Bonauto *et al* 2007, Gubernot *et al* 2015), traumatic injuries (Morabito *et al* 2006, Xiang *et al* 2014, Adam-Poupart *et al* 2015, Spector *et al* 2016, McInnes *et al* 2017, Binazzi *et al* 2019), and acute kidney injury (Moyce *et al* 2017) and is hypothesized to contribute to an epidemic of chronic kidney disease of unknown etiology (CKDu) in multiple areas of the world (Weaver *et al* 2015). Risk factors for heat-related illness include modifiable workplace factors (Spector *et al* 2015) and personal risk factors such as lack of acclimatization to heat, non-breathable clothing, certain medications and chronic diseases, inadequate hydration, and certain beliefs about the treatment and prevention of heat-related illness (Jackson and Rosenberg 2010, Lam *et al* 2013, Stoecklin-Marois *et al* 2013).

While studies have assessed heat exposure and potential risk and resiliency factors in industrial agricultural settings in the United States, few studies have been conducted in tropical, rural populations, particularly in small-holder agricultural settings in industrializing countries. Yet, there are over 570 million households farming on small agricultural plots ($<$10 hectares), primarily for subsistence purposes, globally (Lowder *et al* 2016). A better understanding of heat exposure and risks is particularly important in low-latitude, poorer, tropical countries because these countries are already experiencing hot, humid climates and are projected to have the most extreme future temperatures (UNDP 2016, Mora *et al* 2017, Bathiany *et al* 2018). Tropical industrializing countries may also have limited adaptive capacity to address adverse health effects from increasing temperatures (Coffel *et al* 2018).

In tropical and other environments, forests provide multiple services relevant to human health, including absorption of greenhouse gases and capture of pollutants, infectious disease modulation, and local cooling (Coutts and Hahn 2015). Exceptionally high carbon sequestration within tropical forests means that conserving these habitats is critical for achieving global emissions goals (Griscom *et al* 2016). Locally, tropical forests act as natural air conditioners, through transpiration and evaporation (Ellison *et al* 2017), and play an integral role in environmental temperature regulation (McAlpine *et al* 2018). Economic pressures to expand agricultural sectors have contributed to deforestation (Hansen *et al* 2013), which threatens ecosystem services provided by forests, including cooling (McAlpine *et al* 2018, Wolff *et al* 2018). For example, Berau Regency in East Kalimantan, Indonesia, has lost approximately 1400 km^2 of forest between 2001 and 2010, about 6.6% of the land area (Griscom *et al* 2016).

The effect of deforestation on heat-related health in rural tropical populations is poorly understood. Unlike the gradual effects from climate change, temperature effects from deforestation are potentially immediate and substantial. For example, over a 37 day period in October–November 2017 in Berau Regency, the maximum difference in ground-level mean and maximum temperatures in deforested and forested landscapes was 2.6 °C and 8.3 °C, respectively (Masuda *et al* 2019). Yet, little research has investigated the potential adverse human health effects of heat from deforestation on working populations in these communities or characterized the potential adaptive capacity of affected populations. Characterizing the link between deforestation and heat-related health is needed to understand the effects of deforestation on local heat exposure and to guide development of strategies at national, regional, community, workplace, and individual levels to prevent adverse heat health effects and protect well-being.

The objective of our study was to examine how forest conditions relate to health effects of heat exposure among healthy, working populations in rural, tropical environments. We hypothesized that participants working in deforested conditions would have a higher risk of exceeding a safe core body temperature (CBT) threshold and would be more likely to report heat strain symptoms compared to those working in forested areas. This is the first study that examines these questions in a field experimental setting.

Methods

Study design and setting

This study was part of a larger two-by-two factorial, randomized study that aimed to investigate the links between forest cover, local temperature regulation, human health, and productivity in tropical forest landscapes in Berau Regency, East Kalimantan, Indonesia (Anggraeni *et al* 2018). We compared outcomes of participants who completed a 90 min generalizable work activity in deforested versus forested conditions. Experiments occurred between 1 October, 2017 and 6 November, 2017, which falls during the tail end of the dry season in Berau Regency. Additional characteristics of Berau Regency are described in the supplemental material, available online at stacks.iop.org/ERL/14/084012/mmedia.

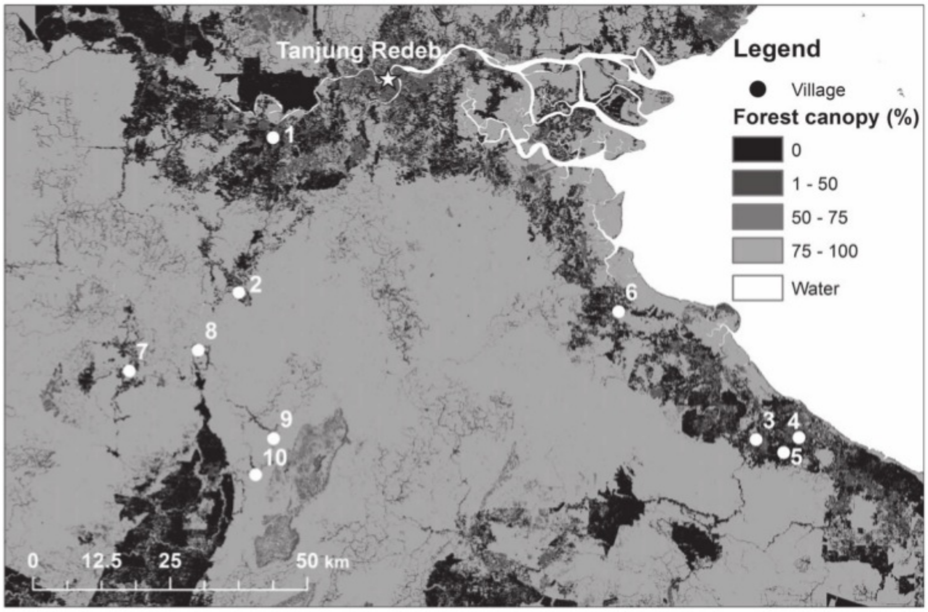

Figure 1. Sampled villages in Berau Regency, East Kalimantan, Indonesia.

Recruitment, enrollment, and participants

The study recruited participants using a multi-phase approach, in which villages, households within villages, and individuals within households were randomly sampled and recruited, as described in the supplemental materials. Included villages and the study flow are illustrated in figures 1 and 2, respectively. Individuals were eligible to participate if they were 21 years of age or older, spoke English or Indonesian as their primary language, were able to lift more than ten kilograms, and did not report acute or chronic respiratory or cardiovascular illnesses at the time of recruitment. In total, field staff (enumerators) enrolled 363 individuals to participate in the study. Participants were excluded from the analysis if they were missing heart rate data altogether ($n = 16$) or had less than 20 min of heart rate data ($n = 15$) or, in one case, was missing 20 min of heart rate data in the middle of the experiment (figure 2). 331 (91.2%) of enrolled individuals were included in the analysis. Study procedures were reviewed and approved by the University of Washington Institutional Review Board, and participants provided informed consent prior to participation.

Allocation, field experiment, and measurements

Enumerators used simple randomization to equally allocate participants to different conditions in which to perform a field experiment, as described in the supplemental materials. Enumerators and participants were not blinded to the group allocation, and enumerators scheduled each participant's experiment time after group assignment. Participants who performed the experiment in deforested versus forested settings were compared in this analysis. Forested settings were areas with near complete tree canopy cover in a patch of forest that was at least one square kilometer, and deforested settings were those with no tree canopy cover or shade from surrounding trees.

Participants performed a 90 min outdoor work activity and completed a survey, as previously described (Anggraeni *et al* 2018, Masuda *et al* 2019). The field activity involved packing 14 bags of dried corn kernels, each weighing 500 g, into a backpack, carrying the backpack 25 m, unpacking the bag and creating a neat pile, and repeating for the duration of the experiment. Participants were informed that they could stop and rest *ad libitum*, and drinks, snacks, and a shaded area were provided.

During the activity, heart rate was measured every second with Polar® (Polar Inc., Lake Success, NY) and Wahoo Tickr X (Wahoo Fitness, Atlanta, GA) chest band monitors, which log heart rate and transmit heart rate signals to a mobile phone application using Bluetooth. Prior to starting the activity, enumerators recorded two oral temperatures with an oral thermometer (53-287 Digital Oral Thermometer; 3M Company, Maplewood, MN) and calculated the mean oral temperature. Enumerators also measured height and weight to calculate body mass index (BMI (kg m^{-2})) (CDC 2017). Although the primary exposure in our analysis was deforested, compared to forested, conditions, we also described ambient conditions in forested and deforested experimental settings to provide

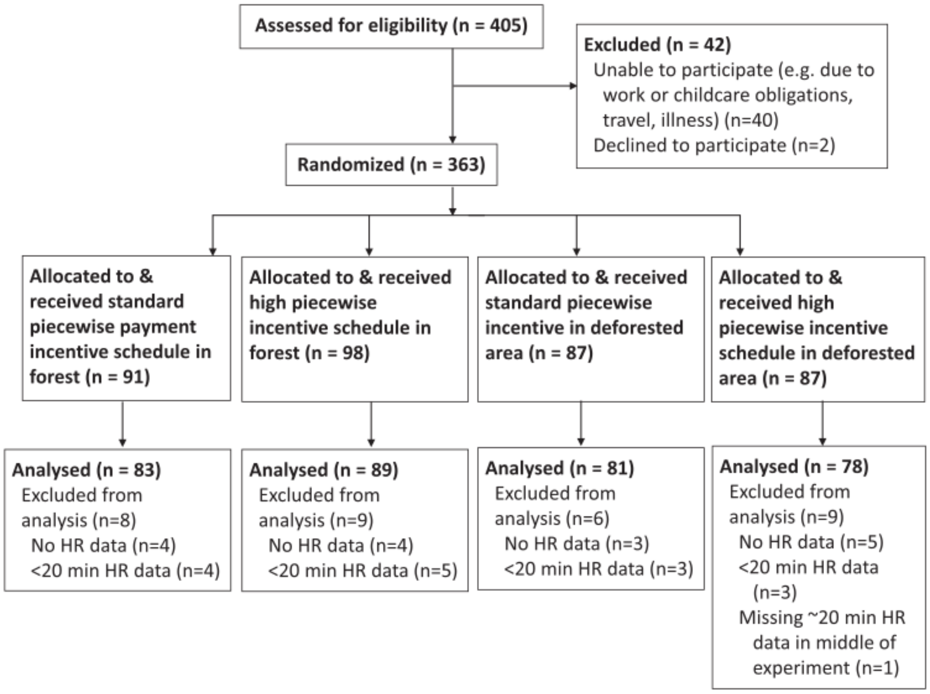

Figure 2. Study flow (HR = heart rate).

additional context. 3M QUESTemp wet bulb globe temperature (WBGT) monitors (3M Company, Maplewood, MN) recorded, every 5 min, environmental dry air temperature, black globe temperature, and wet bulb temperature, which we used to calculate WBGT, a standard measure of heat stress (Budd 2008). Directly after the activity, participants answered survey questions about working and adapting to hot environments, including a question about heat strain symptoms experienced during the experiment.

Outcomes

The primary outcome was number of minutes during which CBT exceeded 38.5 °C. Per American Conference of Governmental Industrial Hygienists (ACGIH) guidelines (ACGIH 2015), a CBT above 38.5 °C indicates physiological heat strain in acclimatized workers. We processed sequential one second heart rate data to estimate CBT at each minute of the activity using a validated algorithm (Buller *et al* 2013). First, we excluded non-physiological heart rate values (<40 or >200 beats per minute) from the raw dataset. We then computed 1 min average heart rates using all available data within each minute. We calculated estimated baseline CBT by adding 0.5 °C to mean baseline oral temperatures (Mazerolle *et al* 2011). Finally, we inputted estimated baseline CBT and 1 min average heart rate values into the Buller algorithm to obtain estimated CBT for each minute of the experiment (Buller *et al* 2013). The secondary outcome was reporting having experienced two or more heat-related symptoms (skin rash or skin bumps, painful muscle cramps or spasms, dizziness or light-headedness, fainting, headache, heavy sweating, extreme weakness or fatigue, nausea or vomiting, confusion, or other symptom) while engaged in the field activity.

Statistical analysis

In the primary analysis, we assessed the relationship between deforested, compared to forested, conditions and the number of minutes each participant spent above an estimated CBT threshold of 38.5 °C using linear regression. We accounted for clustering by village, which was highly correlated with day of experiment, and used a sandwich variance estimator. In a minimally adjusted model, we adjusted for mean-centered age (years), mean-centered age squared (years^2), mean-centered BMI (kg m^{-2}), and sex. In a moderately adjusted 'main' model, we additionally adjusted for time of experiment, and in a fully adjusted model, we further adjusted for previous healthcare worker-diagnosed heat-related illness. We dichotomized time of experiment as starting at 12 pm or earlier versus after 12 pm, as experiment start times largely occurred in the morning or afternoon, and CBTs are known to have diurnal trends, with higher

Table 1. Participant and experiment characteristics, stratified by forest condition (mean ± standard deviation or n[%]).

Participant characteristics	Forested ($n = 172$)	Deforested ($n = 159$)	All ($n = 331$)
Male	86 (50.0)	85 (53.5)	171 (51.7)
Age (years)	42.1 ± 11.1[a]	42.5 ± 11.0	42.3 ± 11.0[a]
Farmer is primary occupation	146 (84.9)	132 (83.0)	278 (83.9)
Years of education completed	6.2 ± 3.5[b]	6.4 ± 3.7	6.3 ± 3.6[b]
Diagnosed heat illness	6 (3.5)	4 (2.5)	10 (3.0)
Diagnosed diabetes	2 (1.2)	2 (1.3)	4 (1.2)
Diagnosed cardiovascular disease	1 (0.6)	0 (0.0)	1 (0.3)
BMI (kg m^{-2})	24.2 ± 4.1	23.4 ± 3.7	23.8 ± 3.9
Experiment characteristics			
Length of participation (minutes)	87.4 ± 8.6	85.9 ± 11.3	86.7 ± 10.0
Sleep duration prior to experiment (hours)	7.3 ± 1.4	7.1 ± 1.6	7.2 ± 1.5
Time of day of start of experiment			
12 pm or earlier	70 (40.7)	110 (69.2)	180 (54.4)
After 12 pm	102 (59.3)	49 (30.8)	151 (45.6)
10 am to 2 pm	22 (13.8)	77 (44.8)	99 (29.9)
Before 10 am and after 2 pm	137 (86.2)	95 (55.2)	232 (70.1)
Wet-bulb globe temperature (°C) during experiment	26.4 ± 1.8	28.6 ± 3.0	27.4 ± 2.7
Black globe temperature (°C) during experiment	28.3 ± 3.2	36.3 ± 8.9	31.8 ± 7.7

[a] One observation missing.

[b] One participant unsure; assigned as missing.

values expected in the afternoon (Gisolfi and Wenger 1984). Interaction models assessed whether experiment start time modified the association between experimental condition and the outcome.

In secondary analyses, we examined the relationship between deforested versus forested conditions and the odds of reporting two or more heat strain symptoms during the activity using logistic regression models that accounted for clustering by village. We also assessed the relationship between the number of minutes each participant spent above the estimated CBT threshold and the odds of reporting at least two symptoms of heat strain, using logistic regression models that accounted for clustering by village. We adjusted all secondary analyses for 'main' model covariates. We conducted several sensitivity analyses, as described in the supplemental materials. Analyses were conducted using Stata version 14.1 (StataCorp, College Station, TX) and R 3.4.1 (R Foundation, Vienna, Austria) (R Core Team 2014).

Results

Characteristics of the 331 participants are shown in table 1, and the distribution of heat strain symptoms by forest cover group is shown in table 2. Participants spent an average (standard deviation) of 86.7 (10.0) minutes engaged in the experimental activity, with similar participation times in the deforested and forested groups. Overall, forested and deforested groups were well balanced in these characteristics.

The time of the start of the experiment varied by forested and deforested conditions. Approximately 41% of participants in the forested condition started at 12 pm or earlier, while 69% of those in the deforested condition started in that timeframe. Mean (standard deviation) WBGT in the deforested condition was 28.6 (3.0) °C compared to 26.4 (1.8) °C in the forested condition.

Summaries of estimated CBT values are shown in table 2. In general, participants' estimated CBT rose relatively smoothly or stayed relatively constant during the activity. Approximately 10% of participants had a CBT above 38.5 °C for at least one minute. The mean percent of time with an estimated core temperature above 38.5 °C was relatively small in the whole sample (2.8%) but was larger in the deforested condition (4.7%) compared to the forested condition (1.1%). The mean percent of time in the whole sample with an estimated core temperature above 38.0 °C, the threshold for unacclimatized individuals (ACGIH 2015), was 16.2%. The mean number of heat strain symptoms was 1.3 and was similar in both groups. 26.2% of participants reported two or more heat strain symptoms in the forested group, compared to 34.0% of participants in the deforested group.

Results of linear regression models estimating the difference between the experimental conditions in the number of minutes above a core temperature of 38.5 °C are shown in table 3. When comparing the deforested to the forested condition, the mean difference in the number of minutes of exceedance of the core temperature threshold of 38.5 °C was 3.08 (95% confidence interval (CI) 0.57, 5.60), after adjustment for age, sex, BMI, and time of experiment. We observed effect modification by experiment start time of after noon versus noon or earlier (p-value for interaction = 0.006). Comparing deforested to forested conditions, the difference in the number of minutes

Table 2. Outcome characteristics, stratified by forest condition (mean ± standard deviation or n[%])[a].

	Forested (n = 172)	Deforested (n = 159)	All (n = 331)
Experiment duration (minutes)	87.4 (8.6)	85.9 (11.3)	86.7 (10.0)
Number of minutes with estimated core temperature above 38.5 °C[b]	0.9 (5.8)	4.2 (11.9)	2.5 (9.4)
Number of minutes with estimated core temperature above 38.0 °C	12.6 (22.1)	15.7 (24.0)	14.1 (23.0)
Percent of time with estimated core temperature above 38.5 °C[b]	1.1 (6.6)	4.7 (13.1)	2.8 (10.4)
Percent of time with estimated core temperature above 38.0 °C	14.5 (25.7)	17.9 (27.3)	16.2 (26.5)
Heat strain symptoms			
Skin rash/bumps	3 (1.7)	5 (3.1)	8 (2.4)
Muscle cramps/spasms	19 (11.0)	25 (15.7)	44 (13.3)
Dizziness/light-headedness	14 (8.1)	16 (10.1)	30 (9.1)
Fainting	0 (0)	0 (0)	0 (0)
Headache	0 (0)	0 (0)	0 (0)
Heavy sweating	146 (84.9)	139 (87.4)	285 (86.1)
Extreme weakness/fatigue	3 (1.7)	2 (1.3)	5 (1.5)
Nausea/vomiting	0 (0)	2 (1.3)	2 (0.6)
Confusion	6 (3.5)	4 (2.5)	10 (3.0)
Other	16 (9.3)[c]	13 (8.2)[d]	29 (8.8)[e]
Number of heat strain symptoms	1.2 ± 0.7	1.3 ± 0.7	1.3 ± 0.7
Two or more heat strain symptoms[f]	45 (26.2)	54 (34.0)	99 (29.9)

[a] Summaries in table are summaries of individual-level data.

[b] *A priori* primary outcome.

[c] 15 thirsty, 1 earache.

[d] 12 thirsty, 1 increased heart rate.

[e] 27 thirsty, 1 earache, 1 increased heart rate.

[f] *A priori* secondary outcome; possible symptoms include skin rash/bumps, muscle cramps/spasms, dizziness/light-headedness, fainting, headache, heavy sweating, extreme weakness/fatigue, nausea/vomiting, confusion, or other.

Table 3. Estimated increase in number of minutes above an estimated core body temperature of 38.5 °C (95% confidence intervals) from linear regression models comparing deforested to forested conditions.

	Coefficients (95% confidence interval)
Unadjusted	
Deforested (ref: Forested)	3.28 (0.88, 5.69)
Minimally adjusted[a]	
Deforested (ref: Forested)	3.54 (1.13, 5.96)
Moderately adjusted[b]	
Deforested (ref: Forested)	3.08 (0.57, 5.60)
Fully adjusted[c]	
Deforested (ref: Forested)	3.14 (0.55, 5.74)

[a] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI.

[b] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI, time of experiment.

[c] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI, time of experiment, previous heat illness.

Table 4. Odds ratios (95% confidence intervals) from logistic regression models of whether two or more symptoms of heat strain were reported to be experienced during the experiment, comparing deforested to forested conditions.

	Odds ratio (95% confidence interval)
Unadjusted	
Deforested (ref: Forested)	1.45 (0.92, 2.29)
Minimally adjusted[a]	
Deforested (ref: Forested)	1.47 (0.93, 2.31)
Moderately adjusted[b]	
Deforested (ref: Forested)	1.37 (0.84, 2.24)
Fully adjusted[c]	
Deforested (ref: Forested)	1.36 (0.82, 2.26)

[a] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI.

[b] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI, time of experiment.

[c] Adjusted for mean-centered age, mean-centered age^2, sex, mean-centered BMI, time of experiment, previous heat illness.

exceeding the core temperature threshold of 38.5 °C was larger for start times after 12 noon (5.17 [95% CI 2.20, 8.15]) than at noon or earlier (0.51 [95% CI −2.42, 3.43]).

Deforested conditions were associated with 1.37 times the odds of reporting two or more heat strain symptoms during the experiment compared to forested conditions, after adjustment for age, sex, BMI, and time of experiment (table 4). However, this effect was not statistically significant (95% CI 0.84, 2.24). We observed no relationship between the number of minutes above an estimated core temperature of 38.5 °C and participant report of two or more symptoms of heat strain during the experiment (OR 1.00 [95% CI 0.97, 1.03]). Results of sensitivity and post-hoc analyses are described in the supplemental materials.

Discussion

Results from our study of relatively healthy participants from rural villages in East Kalimantan, Indonesia indicate that participants performing the experimental activity in a deforested environment spent an average of approximately three additional minutes with a CBT exceeding 38.5 °C, compared to those performing the activity in a forested environment. Rising core temperatures can ultimately result in a transition from thermal equilibrium to uncompensable heat stress (Sawka *et al* 2011). A longer duration with a CBT estimated using the Buller algorithm above 38.5 °C reflects convergence toward a temperature that could become uncompensable with continued effort (Showers *et al* 2016). Longer durations of hyperthermia can increase the risk of serious health outcomes and end-organ damage (Yang *et al* 2017). Overall, our findings suggest that work in deforested conditions may result in further increases in the length of time above a safe CBT, implying subsequent increases in the risk of serious heat-related illness in the absence of other mitigating factors.

Our findings, however, are likely an underestimate of the true effect of deforestation on heat strain. In our study, a greater percentage of participants in the deforested, compared to the forested, condition started the experiment in the morning, while the reverse was true in the afternoon. Although we adjusted our statistical analyses for dichotomized time of day to correct for this imbalance, some residual confounding may remain which would be expected to bias our effect estimates downwards. Further, the experiment was limited to 90 min, and participants were provided with water, snacks, and access to shade during *ad libitum* breaks. However, agricultural workers rarely work just 90 min, and in many rural villages in industrializing countries it is rare for subsistence workers to have easy access to water, snacks, and shade. Survey data from our study population show that over two thirds of respondents reported typically working solely in open areas for an average of over six hours per day, and only about half of these workers reported having access to water while working outdoors (Masuda *et al* 2019). Typical day-to-day conditions for this population, therefore, may present a higher risk for heat strain than was captured in the experimental conditions.

Both internal heat generation from heavy physical work and ambient heat exposure influence the degree of heat strain and adverse health outcomes. Skeletal muscle contraction is only about 20% efficient, with about 80% of expended energy released as heat (Sawka *et al* 2011). Early in a bout of exercise, internal heat can drive elevations in CBT in a manner that is largely independent of ambient heat exposures and subsequently trigger heat-dissipating reflexes (Sawka *et al* 2011). When exposed to heat stress, the human body's natural behavioral response to cool down is to reduce exercise performance, for example by reducing work pace (Sawka *et al* 2011). In certain industrial agricultural settings, workers reported that they do not feel that they are allowed by their supervisors to take extra breaks, rest, or drink water and prefer to take less time for rest and hydration in order to maximize earnings (Lam *et al* 2013). Interestingly, the prevalence of estimated CBTs above 38.5 °C for at least one minute was approximately 10% in our subsistence agricultural population, which is a lower prevalence of heat strain than was reported in studies in commercial agricultural settings in more temperate climates (Spector *et al* 2018). Though subsistence agricultural workers in tropical settings may experience different pressures than industrial agricultural workers, such as pressure to sow fields before annual rains, more flexibility in daily work organization may contribute to resilience to heat exposure. Further work is needed to determine how best to balance a more flexible approach to work organization with agricultural production demands while optimizing adaptive capacity to heat.

Deforested conditions exhibited higher WBGTs during the experiment than forested conditions, indicating greater environmental heat exposure. This was the case even though a smaller percentage of participants underwent the experiment in the afternoon in the forested versus the deforested conditions. After the initial stages of a bout of exercise, a steady thermal state is achieved, unless ambient heat exposure exceeds the 'upper limit of prescriptive zone,' in which CBTs further rise (Sawka *et al* 2011). A recent meta-analysis reported that individuals working a single shift under heat stress (WBGT 22.0 °C–24.8 °C) were four times more likely to experience heat strain than individuals working in thermoneutral conditions (Flouris *et al* 2018). In our study, forest cover appeared to mitigate the risk of reaching CBTs in excess of 38.5 °C, presumably through cooling services provided by forests (Ellison *et al* 2017). Forests may be particularly important in contexts where there is limited infrastructure and adaptive capacity to address adverse health effects from increasing temperatures.

We observed effect modification by experiment start time of after noon versus noon or earlier. Among participants starting the experiment in the morning, we observed a small and not statistically significant effect. It is plausible that during cooler morning hours, workers have similarly less exposure to heat stress in both forested and deforested settings and therefore their overall risk of heat strain is diminished. For participants starting the experiment in the afternoon, the effect was larger, with participants performing the activity in a deforested environment spending an average of approximately five additional minutes with a CBT exceeding 38.5 °C, compared to those performing the activity in a forested environment. CBTs are known to have diurnal fluctuations, and higher values are expected in the afternoon (Gisolfi and Wenger 1984). These diurnal trends may have resulted in greater susceptibility to heat strain in deforested, compared to forested conditions, in the afternoon than in the morning.

In our study, there did not appear to be a relationship between exceedances in objectively-measured CBT thresholds and self-reported heat strain symptoms. Heat strain and heat-related illness symptoms can be non-specific (e.g. headache) and can reflect milder (e.g. light-headedness) or more severe (e.g.

confusion) heat-related illness. Heat stress can affect cognition (Mazlomi *et al* 2016), which could influence symptom recognition and reporting. There is currently no consensus in the published literature about how best to conceptualize the range of symptoms of heat strain and heat-related illness, though several different approaches have been proposed (Spector *et al* 2015, Mutic *et al* 2018).

In our study setting, where there is minimal temperature variation during the year, participants may be more accustomed to heat-related symptoms and less likely to be aware of or report them. The prevalence of heavy sweating (86%) in our study was higher than in a recent study of US agricultural workers (66%), but the prevalence of other symptoms was lower (e.g. headache [0%], dizziness [9%], and muscle cramps [13%] in our study population, compared to headache [58%], dizziness [32%], and muscle cramps [30%] Mutic *et al* 2018). Early recognition of symptoms can contribute to the prevention of life-threatening heat stroke (Mutic *et al* 2018). Future studies should further investigate awareness of early adverse heat health effects, as enhancing awareness may be a low-cost first step that complements other approaches in the prevention of adverse heat health effects (Mutic *et al* 2018).

Our study has implications for land use decisions, especially in frontier areas with high land use pressures such as the tropical forests. Current land use decisions in these settings rarely consider how changes to ecosystem services may affect local heat exposure and health. Greater attention is given to carbon storage functions of forests that contribute to climate change mitigation (Ellison *et al* 2017). While the latter is important, failing to incorporate more immediate values of ecosystem services for local human health underestimates the importance of forests. A common land use after forests are cleared is cultivating oil palms. Evidence suggests that the cooling services provided by oil palms are less than those provided by natural forests (Ramdani *et al* 2014, Hardwick *et al* 2015, Sabajo *et al* 2017). In addition, oil palm is a rotational crop with approximately 25 year cycles, so for portions of the rotation, there is open canopy and increased solar radiation and heat exposure (Dislich *et al* 2017). Future work should investigate the costs and benefits of different land use patterns on the health and well-being of local populations.

Strengths of this study include an experimental design with participants randomly sampled to be representative of the general adult working population in the area studied, randomized assignment to the experimental conditions, detailed surveys of subjects' characteristics and medical history including prior heat-related illness, ambient environmental sampling during the experiment, individual estimates of CBT computed every minute, and experimental activities representative of local work activities.

This study also has several limitations. First, gold standard estimates of CBT, such as gastrointestinal temperature measured using wireless ingestible CBT sensors, were not available or feasible. These more invasive sensors were not considered acceptable by local government officials and representatives of local communities. Although the Buller algorithm was validated against gold standard core temperature measurements (Buller *et al* 2013), it was not validated in an Indonesian population. However, physiological relationships between heart rate and CBT are not expected to be different in different populations. Second, the start time of the experiment was not balanced between the experimental groups. Although we adjusted for morning versus afternoon start times in the analysis, future studies should better address time of day in the design. Third, our experimental design dictated that we focus on two landscape types: forested and deforested landscapes. However, it is common to have mosaic landscapes, such as those incorporating agroforestry practices. The specific spatial distribution of forests should be considered in future studies. Finally, results from this study in Indonesia may not be generalizable to all other populations and settings.

Conclusion

This is the first study that addresses the paucity of knowledge on the relationship between forest cover and heat health effects in tropical, rural environments among subsistence farmers using a field experimental design. The findings from this study add to the literature on the potential human heat health effects of deforestation. These results may inform assumptions made in projections of the health risks of increasing temperatures with climate change and national adaptation plans, particularly in tropical, rural countries.

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