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To cite this article: Yuta J Masuda *et al* 2020 *Environ. Res. Lett.* **15** 124015

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# Environmental Research Letters



## LETTER

### OPEN ACCESS

RECEIVED  
5 April 2020

REVISED  
10 August 2020

ACCEPTED FOR PUBLICATION  
17 September 2020

PUBLISHED  
16 December 2020

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## Heat exposure from tropical deforestation decreases cognitive performance of rural workers: an experimental study

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**Keywords:** deforestation, heat stress, heat exposure, heat strain, cognitive performance, Indonesia, tropical forests

Supplementary material for this article is available [online](#)

### Abstract

The effect of tropical deforestation on heat exposure and subsequent human health outcomes remains understudied, especially among an increasingly vulnerable population—healthy, adult subsistence workers in rural industrializing tropical countries. We report on a field experiment that estimated the short-term effects of heat exposure from deforestation on cognitive performance. We randomly assigned rural, adult subsistence workers in East Kalimantan, Indonesia to deforested or forested settings, and standard or high incentive piece rate payments. Participants worked in forested or deforested settings for up to 90 min, where ambient and black globe temperatures in deforested areas were, on average, 2.1 °C and 10 °C higher. After completing the experimental task, participants were asked to take a validated general cognitive assessment test (CAT) and episodic memory test (EMT). We found participants in deforested settings had statistically significant lower scores on both CAT and EMT. Effects were largely driven by heat effects on male participants and those working after noon. Our results highlight how heat exposure from tropical deforestation may lead to declines in cognitive performance even in favorable work settings. Policymakers should consider how land use planning that takes into account the cooling services of trees can play a significant role in increasing resilience to heat from climate and land use change in the tropics.

### 1. Introduction

The role of climate change on heat exposure and heat-related health effects for populations in low-latitude countries has gained increasing attention from researchers and policymakers [1–3]. Despite the significant growth in literature on climate change, increasing heat exposure, and heat-related health effects among workers in low-latitude countries, large research gaps remain for advancing policies that informs both research and practice. Research to date has primarily focused on health effects of heat exposure from extreme heat events in the general population in high income countries [4], and exertional heat illness in occupational, and

military populations. The role of land use change on heat exposure and subsequent human health outcomes remains largely understudied. Land use change, such as deforestation, can cause sudden, significant increases in heat exposure. Ramdani *et al* [5] and Masuda *et al* [6], for instance, found ambient temperature differences between forested and deforested areas in Indonesia could be as much as 4 °C and 8 °C, respectively. This is equivalent to nearly a century of warming under high emission scenarios [7]. Second, the effects of significant heat exposure on cognitive performance—not just physical health—have been understudied among rural workers in low-latitude industrializing countries [8]. The emphasis has instead been on the effects of heat

exposure on heat strain, heat exhaustion, heat stroke [1, 9–11], and more recently, kidney disease [12]. A recent meta-analysis [1] of 111 studies of workers in both industrialized and industrializing countries found workers exposed to wet bulb globe temperatures (WBGT) between 22 °C–24.8 °C were at greater risk of, or had adverse effects on, occupational heat strain, productivity, and overall worker physical health. There is little to no work on how heat exposure—especially from deforestation—can affect cognitive performance among rural working populations in low-latitude, industrializing countries [13]. This information is critical for identifying and quantifying vital ecosystem services that can increase resilience to climate change. We fill this gap by reporting on a field experimental that studied the effects of deforestation and varying financial incentives on the cognitive performance of healthy, working adults engaged in subsistence agriculture in East Kalimantan, Indonesia.

Theoretically, temperature increases are thought to initially improve cognitive performance before having deteriorative effects beyond some temperature threshold [14–18]. Empirically, there is general agreement that excessive heat exposure can negatively affect cognitive performance. Simple tasks (e.g. short-term memory, simple arithmetic) are less susceptible to being affected by heat stress compared to complex tasks (e.g. complex motor coordination) [19–22]. Short bouts of low or moderate activity can improve performance on simple or complex cognitive tasks [14, 23, 24], while longer and more intense bouts of activity can decrease it [25]. Dehydration can exacerbate this effect on, for instance, short-term memory [26]. Studies have also found that the negative effects of heat exposure on cognitive performance are more sensitive to changes in thermal comfort rather than increases in core body temperature [20, 21, 27], perhaps due to thermal discomfort affecting an individual's cognitive load by diverting attention away from cognitive tasks [20]. Still, elevated core body temperatures can detrimentally affect cognitive performance [21]. There is also significant variation in factors such as gender [20]. Importantly, reduced cognitive performance has implications for worker health and occupational safety. Heat stress is associated with greater risks of workplace injury [28], as impaired cognitive performance can decrease dexterity for complex motor tasks [21, 29].

We are aware of little research that examines the effect of heat on cognitive performance of working adults. However, given existing research on heat and resilience, factors affecting a person's resilience to heat is likely to vary significantly across occupation and workplace, acclimatization to hot and humid environments, overall health, gender [30], and other factors, raising questions about the external validity of past efforts for these populations. This oversight is significant because populations in these

settings commonly work in occupations with significant heat exposure [31]—such as subsistence agriculture or manual labor—and can be less resilient and thus more vulnerable to increasing temperatures [32]. Examining cognitive impacts from heat exposure is important for understanding overall worker safety and well-being in low-latitude countries. In order to fully account for the health impacts of heat on working populations, quantifying and uncovering the effects of heat on both physical health and cognitive performance is necessary to develop appropriate interventions that account for the economic and health costs associated with increasing temperatures.

We focus on how deforestation in the tropics may affect cognitive performance of healthy, working adults engaged in subsistence agriculture for several reasons. Deforestation in the tropics continues at a rapid pace [33]. Deforestation can induce local warming via the loss of cooling services provided via shade and evapotranspiration [34], and recent work has found larger deforested areas can lead to more extreme warming [35] that can extend up to 50 km beyond the deforested site [36]. While detrimental to global climate goals, this suggests adverse effects from increased heat exposure on working populations is an existing and growing local challenge. But what is unique about heat exposure from deforestation is that increases in heat exposure can be significant and occur in a single season, and deforestation events themselves are relatively predictable and can be influenced by local policies. For example, deforestation events are manageable through zoning regulations, titling reform, agricultural programs, and other policies affecting land use and management [37–39]. This contrasts to the longer time horizons associated with chronic temperature increases from climate change, or the relative unpredictability of extreme heat events. Further, temperatures in tropical forests in low-latitude countries, where high heat and humidity are present, are already approaching thresholds for human safety [40]. Recent modeling results suggests reduced 'workability' (i.e. monthly mean WBGT exceeding 34 °C) will affect nearly 1 billion people by 2100 if temperatures increase 2.5 °C [2]. Populations in these countries bear a disproportionate amount of exposure to climate change and are the most vulnerable to its effects [32], while contributing the least to emissions [41]. Finally, understanding whether heat exposure from deforestation may affect the cognitive performance of healthy, adult workers engaged in informal work is critical for developing practical public health and climate mitigation and adaptation policies, as well as improving our understanding of the local costs of deforestation. Informal workers, such as those engaged in farming or day labor, have unique constraints and behavioral strategies. Subsistence farmers may have flexible work hours that can limit exposure to hot environments, but they may also lack access to water and shade. New

interventions to promote worker health and safety may be necessary [42], and trees and their associated cooling services may be an overlooked strategy.

We overcome several past limitations and provide evidence on the effects of heat exposure from deforestation on cognitive performance in several ways. First, we provide, to the best of our knowledge, the first evidence of the effect of heat exposure on cognitive performance on a vastly understudied but increasingly vulnerable population—healthy, adult subsistence workers in rural industrializing tropical countries. Second, our research design is aimed at estimating the causal effect of heat exposure from deforestation on cognitive performance using a field experiment. Past studies have relied mostly on experimentally manipulating heat exposure in a laboratory setting (usually through passive heat exposure—i.e. sitting in a hot room), or relied on observational study designs. Finally, the experimental activity had participants engage in a generalizable task commonly done in day-to-day work (i.e. harvesting, carrying, and unloading). This ensures that heat in our experiment is driven by two factors found in real world settings: internal heat generation through active movement from an everyday task, and heat generation from the environmental setting (i.e. being in a deforested setting). The experimental activity is thus designed to maximize generalizability to real world settings while maintaining control of experimental factors. We hypothesize that those working in deforested areas will perform significantly lower on cognitive performance tests, that those receiving higher incentive payments will have lower cognitive performance scores because they will be incentivized to exert more effort, and that those in deforested settings receiving higher incentive payments will have the lowest cognitive test scores.

## 2. Methods

The study recruited healthy, working adults from ten rural villages in the Berau Regency of East Kalimantan, Indonesia from October 1–6 November 2017, the tail end of the dry season (figure S1 (available online at <https://stacks.iop.org/ERL/15/124015/mmedia>) presents a map). We employed a multiphase random sampling approach to select individuals into our study. Enumerators allocated participants via simple randomization to one of four conditions in a  $2 \times 2$  factorial design, where participants selected their experimental assignment out of a container. Our primary analysis examines the main effects of each factor on cognitive performance. All study protocols were approved by the University of Washington Institutional Review Board. Study protocols and outcomes were registered at the American Economic Association's Randomized Control Trial Registry.

We first randomly selected eligible villages, followed by households, and finally eligible individuals

within randomly selected households. We applied strict inclusion criteria and limited recruitment to healthy, adult populations living in rural villages. To be eligible, villages (1) had to be on the main land; (2) have less than 15% of water cover within a 5 km buffer around the village; (3) have less than 5% mangrove cover within a 5 km buffer around the village; (4) be more than 20 km straight-line distance from the regency capitol; and (5) be accessible by road. We applied a 5 km buffer based on Wolff *et al*'s [43] results indicating people perceived heat effects from deforestation in Kalimantan within these buffers. Out of 113 villages in the Berau Regency, 37 villages met these criteria. Five villages above and below the median of intact forest cover (31% of land cover being intact forest in a 5 km buffer) were randomly selected from the 37 eligible villages. Household rosters were collected from randomly selected villages, and approximately 20 households per village were randomly selected to participate. Up to two randomly selected adult household members meeting inclusion criteria were then selected to participate. Individuals were eligible if they were (1) above 21 years old, (2) able to lift more than 10 kg, and (3) had no recent or chronic reported respiratory or cardiac issues. The study provided informed consent prior to participation. Participants were offered 20 000 Rupiah for participating in the experimental activity, and, in addition, had the opportunity to earn more based on their performance on the experimental activity.

### 2.1. Experimental protocol

The experiment involved having participants conduct a generalizable work activity for up to 90 min. For the activity, participants packed 14, 500 gram bags of dried corn kernels into a backpack, then carried the filled backpack 25 m and unpacked the bags and created a neat pile, which they repeated for the duration of the experiment. The activity was designed to mimic harvesting activities typical in the study region. Participants were provided water, snacks, and a shaded area to rest *ad libitum*, and were encouraged to take breaks or quit whenever they wanted. Our study protocol involved extensive village buy-in and validation and testing to ensure incentives were high enough so participants would take the experimental task and survey seriously.

The experiment involved two factors: work setting and the amount of the financial incentive. The first factor, work setting, had participants being randomly assigned to either forest or deforested settings (i.e. an open field). Forested and deforested sites were selected in consultation with village leaders, relying on local knowledge to identify suitable sites. Forested settings were patches of forest at of at least 1 km<sup>2</sup> that had near complete tree canopy cover. Deforested settings were those with no tree canopy cover or shade from surrounding trees. The second factor, the financial incentive, had participants randomly assigned

to one of two piece rate payment schemes: a standard and high piece rate incentive for each pile the participant created. The standard piece rate scheme paid 500 IDR for each pile, while the high piece rate scheme paid 1000 IDR for each pile. The average total was set so that participants in the standard piece rate scheme could earn, on average, the daily wage for a day laborer in local villages in 90 min (65 000 IDR), and those in the high piece rate scheme could earn approximately double the average daily wage for a day laborer in local villages in 90 min (110 000 IDR). The activity was done only during daylight hours, which vary little during the year. Participants worked with the enumerator to schedule the day and time of the experimental activity to maximize participation, and within day randomization indicates this should not be a source of non-random bias in our estimates.

Once participants completed the experimental activity they rested in a shaded area where they were given water and snacks and allowed to rest before answering survey questions and cognitive assessment tests (CATs). In addition, we report on data from 53-287 Digital Oral Thermometers (3M Company, Maplewood, MN), scales to weigh participants, Polar® (Polar Inc. Lake Success, NY) and Wahoo Tickr X (Wahoo Fitness, Atlanta, GA) to measure heart rate during the activity, Axivity AX3 3-axis accelerometer (Axivity Ltd, New Castle upon Tyne, UK) for measuring participant movement, and 3M QUESTemp WBGT monitors (3M Company, Maplewood, MN) which measured ambient temperature, wet bulb temperature, black globe temperature, relative humidity, and WBGT at experimental sites. One WBGT monitor was placed in the center of human activity at each experimental site approximately 1.1 m off the ground. These monitors measured the thermal environment every 5 min from the time the enumerator team entered the village until the minute the team left the villages. Participants had their oral temperature taken twice before the activity, which was then averaged and used with the heart rate monitor data to calculate core body temperature during the activity using Buller *et al*'s [44] validated algorithm. The Buller *et al* [44] algorithm was converted to R [45] from Matlab, and tested to confirm code conversion was successful. Participants wore accelerometers on their dominant hand, which collected data every second. Accelerometer data were used to estimate Moderate-to-Vigorous Physical Activity as is standard protocol [46–49]. Detailed experimental protocol steps are included in the supplementary materials.

Power calculations for a  $2 \times 2$  factorial experiment with one observation per participant, and indicate 400 individual participants were needed to estimate the interaction effect. Here, our interest is estimating the main effects, and thus we have sufficient statistical power given the efficiency gains from employing a factorial design.

## 2.2. Outcomes

The two primary outcomes we used to assess the impact of heat exposure on cognitive performance come from the Indonesian Family Life Survey East (IFLS East) (Supplemental Materials) [50], and are validated tests for our study population and geography. For all tests, higher scores indicate a better performance. The first test was an episodic memory test (EMT) via free recall (range: 1–10). This test involved reading participants a series of ten words, which the participant would then have to recall in any order at two points in the survey. This test examines remembered items rather than trivia (i.e. recalling known facts) [51], and is thought to be tied to working memory necessary for problem solving and decision-making [52]. In the first recall exercise, enumerators informed participants that they would be read a series of ten words, that they should memorize as many as possible, and that the enumerator could not repeat the word list. Enumerators then randomly selected one of four word lists. Enumerators were instructed to slowly read each word from the randomly selected word list, taking approximately 2 s between each word. The second recall occurred after the cognitive performance test (described below), at which point enumerators prompted participants to recall the list of words that was read to them a few minutes ago. As is standard for free recall tests, we use the second recall to assess episodic memory [51].

The second test was a general CAT, which included a series of 18 mathematical and pattern recognition questions (Supplemental Materials) (range: 1–18), which in the IFLS East was given to respondents ages 7–24 ensuring it was feasible for our study population. Here, respondents are tested on basic arithmetic problems, as well as visual puzzles where participants are asked to complete a pattern given a patterned image. These types of tests are commonly used to evaluate cognitive performance [27], and both tests captured cognitive factors that recent reviews have found to be especially susceptible to heat stress in industrialized countries [19–22, 27].

## 2.3. Randomization

The study recruited 405 eligible individuals in randomly selected villages and households. Forty-two were unavailable or declined to participate in the study, leaving 363 individuals (90%) that underwent randomization (figure 1). Baseline characteristics are presented in table 1. The randomization largely balanced groups along key covariates; however, there were statistically significant differences for gender and experience working in forests. There were also statistically significant differences between groups for the timing of the session, which was not a randomly manipulated factor but rather scheduled to maximize participation.

**Table 1.** Baseline sample characteristics by experimental condition<sup>a</sup>.

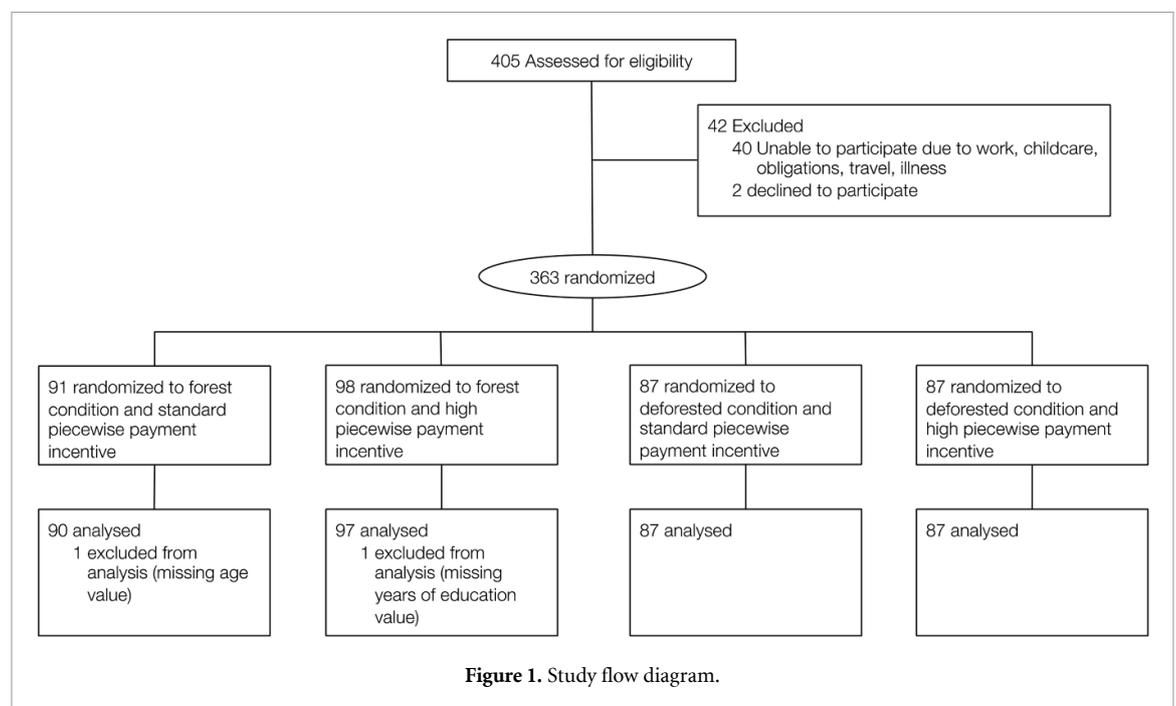
	Forest-standard	Forest-high	Deforested-standard	Deforested-high
<b>Participant characteristics</b>				
Age	41 (12)	42 (10)	40 (11)	44 (11)
Female	31 (34%)	62 (63%)	34 (39%)	46 (53%)
Years of education	6.2 (3.8)	6.1 (3.2)	7.0 (3.5)	5.8 (3.6)
Firewood collector	57 (63%)	67 (69%)	54 (62%)	56 (64%)
Works in forest	64 (71%)	80 (82%)	56 (64%)	67 (77%)
Farmer	72 (80%)	85 (88%)	68 (78%)	75 (86%)
Individual health assessment <sup>b</sup>	3.1 (0.75)	3.1 (0.86)	3.1 (0.81)	3.1 (0.84)
Body mass index	23 (3.8)	25 (4.3)	23 (3.8)	24 (3.8)
Resting oral temperature (°C)	36.8 (0.29)	36.8 (0.41)	36.7 (0.40)	36.7 (0.38)
Hours of sleep the previous night	7.4 (1.7)	7.2 (1.4)	7.3 (1.5)	7.3 (1.4)
<b>Household characteristics</b>				
Household size	4.6 (1.5)	4.4 (1.5)	4.5 (1.5)	4.5 (1.4)
Log household income (IDR) <sup>c</sup>	16 (2.2)	16 (1.9)	16 (2.8)	16 (2.7)
Log household assets (IDR) <sup>c</sup>	17 (0.98)	17 (1.2)	17 (1.1)	17 (1.0)
<b>Experiment characteristics</b>				
Session after 12pm	39 (43%)	36 (37%)	59 (68%)	63 (72%)
Session interrupted by rain	8.0 (8.9%)	8.0 (8.3%)	9 (10%)	5 (5.8%)
Wet-bulb globe temperature (°C) <sup>d</sup>	27 (1.3)	27 (1.3)	30 (2.4)	30 (1.9)
Ambient temperature (°C)	28 (2.3)	29 (2.4)	31 (2.6)	31 (2.2)
Black globe temperature (°C)	30 (2.4)	30 (2.6)	40 (7.0)	41 (5.9)
Relative humidity (%)	84 (12)	83 (13)	75 (13)	72 (11)
<i>n</i>	90	97	87	87

<sup>a</sup> Data are *n* (%) or mean (SD).

<sup>b</sup> For the individual health assessment, respondents were asked to assess their overall health status on a five point scale which asked, 'Would you say that, in general, your health is excellent, very good, good, fair, or poor?'

<sup>c</sup> Household income includes both farm and non-farm income. Household assets include productive (e.g. plows, machetes) and non-productive household assets (e.g. televisions, radios). Temperature conditions were available for 308 participants.

<sup>d</sup> Data are presented for measurements taken during daylight hours on days of the experiment. See figure S2 in the supplementary materials for average across 24 h periods in forested and deforested study sites.

**Figure 1.** Study flow diagram.

## 2.4. Statistical analysis

Our empirical strategy to estimate the main effects of the two experimental factors (forested vs. deforested setting and payment scheme) used ordinary least

squares regressions with indicator variables for the two experimental factors, and clustered robust standard errors at the individual-level [53] and village fixed effects to account for unobserved heterogeneity

across villages. We show results for the fully adjusted model, which includes covariates for age, an indicator variable for female, years of education, an indicator variable if the respondent indicated their primary occupation was farming, an indicator for regularly collecting firewood for the household which reflects familiarity with the experimental activity, an indicator for regularly working in forest, self-assessed health status, body mass index, an indicator variable if the activity was conducted past noon to account for diurnal trends, and an indicator variable if it rained during the activity. Including these covariates increased precision of estimates in case baseline covariates are correlated with the outcome, as well as to correct for any imbalance in baseline covariates between the experimental groups [54, 55]. Doing so can increase statistical power and efficiency by subtracting explained variation for linear models [54, 55].

We also estimated gender-specific models given the literature suggests the possibility of differential effects of heat exposure on cognitive performance between males and females, where women are expected to perform worse after prolonged heat exposure [20]. Further, we conducted several sensitivity analyses to assess whether the time of day and duration of activity (i.e. heat exposure) differentially affects outcomes between experimental conditions. Core body temperatures are known to have diurnal trends [56], with higher core body temperatures commonly found in the afternoon which can differ by as much as 0.7 °C [56]. We thus expect effects of heat exposure to have a greater effect on cognitive performance for those conducting the experiment in the afternoon, as core body temperatures are already elevated and any additional heat exposure would likely increase the effects of heat on cognitive performance. To capture likely diurnal variation, we dichotomized the time of experiment as starting at noon or earlier versus after noon, as experiment start times largely occurred in the morning or afternoon. Finally, heat exposure will vary by the duration of the activity, and prevailing theories on the relationship between heat exposure and cognitive performance suggest that longer exposure times, assuming comparable work rates, have a greater likelihood of having adverse effects on cognitive performance [14–16]. As a result, we expect participants engaging in the full 90 min experimental activity to have larger effects from heat exposure on cognitive performance. To examine this, we separately estimated models for the subset of participants that completed the entire experimental session. Full model outputs are available in the Supplementary Materials.

### 3. Results

Images of example experimental sites are shown in figure 2. Importantly, experimental work sites provided expected differences in heat exposure for

participants (table 1), and analyses of core body temperatures and work effort supports that any differences in cognitive performance between participants in forested compared to deforested areas is due to differences external work environments. Forested sites had significantly lower WBGT ( $-2.7$  °C,  $p < 0.0001$ ), ambient temperature ( $-2.1$ ,  $-2.1$  to  $-2.08$ ,  $p < 0.0001$ ), and black globe temperature ( $-10$ ,  $-10.8$  to  $-10.6$ ,  $p < 0.0001$ ), and had higher relative humidity (8.9, 8.5 to 9.2,  $p < 0.0001$ ), indicating that the thermal environment in forested settings was significantly cooler. Participants in deforested settings had higher incidence of hyperthermia ( $>38.5$  °C;  $p < 0.001$ , table S1), and sensor data suggest that this was driven by the thermal environment rather than internal heat generation. We found no statistically significant difference in work effort (a source of internal heat generation) as proxied by accelerometer data that measured participant movement every second (table S1).

#### 3.1. The main effects of deforestation and higher incentives on cognitive performance

We focus on main effects as there was no statistically significant interaction effect of the two experimental factors (table 2). Participants working in deforested settings had significantly lower CAT and EMT scores compared to those working in forest settings, with differences between the two groups being approximately one less question and one free recall word on the CAT ( $-0.94$ ,  $-1.86$  to  $0.01$ ,  $p < 0.05$ ) and the EMT ( $-0.88$ ,  $-1.57$  to  $0.20$ ,  $p < 0.05$ ), respectively. Higher incentive payments also led to higher scores on the CAT, with those receiving a higher incentive payment answering, on average, one additional question (1.03, 0.077 to 1.97,  $p < 0.05$ ).

#### 3.2. Heat effects on male participants drive estimates of cognitive performance decline

We also found the effect heat exposure on cognitive performance differed by gender, although the direction of the effects of heat exposure ran counter to expectations. The effect of heat on the CAT and EMT appear to be driven by the negative effect of heat on male participants, as there was no statistically significant effect of working in a deforested setting for female participants (table 2), although there were relatively fewer female participants in deforested settings. The magnitude of difference between experimental setting for male participants was larger compared to those in the primary regression results. Males working in open areas scored, on average,  $-1.20$  points lower ( $-2.48$  to  $0.73$ ,  $p < 0.10$ ) and  $-1.42$  points lower on the CAT and EMT ( $-2.38$  to  $-0.47$ ,  $p < 0.01$ ), respectively, compared to male participants in forested settings. Finally, a higher incentive payment was associated with a higher CAT score for female participants only (1.38,  $-0.20$  to  $2.96$ ,  $p < 0.01$ ).

Panel A: Forested setting



Panel B: Deforested setting



Figure 2. Examples of experimental setting sites.

### 3.3. Sensitivity analyses

We conducted sensitivity analyses to test whether (1) participants engaging in the full 90 min and (2) those engaging in the experimental activity past noon had larger adverse effects from heat on cognitive performance tests (table 2). We found support for both, although the effect of heat varied by cognitive performance test. Participants that engaged in the full 90 min experimental session had a  $-1.16$  lower score ( $-2.15$  to  $-0.17$ ,  $p < 0.05$ ) on the CAT and a  $-1.06$

( $-1.81$  to  $-0.30$ ,  $p < 0.01$ ) lower score on the EMT compared to those working in forested settings. These effects were larger than primary regression results. Participants engaging in the experimental activity past noon had larger and statistically significant heat effects on EMT scores compared to those in deforested settings. Their scores were, on average,  $-1.41$  points lower ( $-2.43$  to  $-0.39$ ,  $p < 0.01$ ). We also found the positive effect of higher incentives to be robust for CAT scores in both sensitivity analyses,

Table 2. Main effects for work setting and incentive payment<sup>a</sup>.

Primary analyses	Cognitive assessment test			Episodic memory test		
	Coefficient	95% CI	<i>p</i> value	Coefficient	95% CI	<i>p</i> value
<b>Full sample (<i>n</i> = 361)</b>						
Deforested setting	−0.94	−1.86 to −0.01	0.04	−0.88	−1.57 to −0.20	0.01
High incentive payment	1.03	0.07 to 1.97	0.03	0.024	−0.66 to 0.71	0.94
<b>Gender disaggregated analyses</b>						
<b>Males only (<i>n</i> = 188)</b>						
Deforested setting	−1.20	2.48 to 0.07	0.06	−1.42	−2.38 to −0.47	0.004
High incentive payment	0.95	−0.34 to 2.26	0.14	0.18	−0.78 to 1.16	0.70
<b>Females only (<i>n</i> = 173)</b>						
Deforested setting	−0.56	−2.08 to 0.95	0.46	−0.21	1.25 to 0.82	0.68
High incentive payment	1.38	−0.20 to 2.96	0.087	−0.20	−1.28 to 0.87	0.70
<b>Sensitivity analyses</b>						
<b>Full sessions (<i>n</i> = 331)</b>						
Deforested setting	−1.16	−2.15 to −0.17	0.02	−1.06	−1.81 to −0.30	0.006
High incentive payment	1.13	0.12 to 2.14	0.02	0.08	−0.65 to 0.82	0.81
<b>Past noon (<i>n</i> = 197)</b>						
Deforested setting	−1.06	−2.42 to 0.29	0.12	−1.41	−2.43 to −0.39	0.007
High incentive payment	1.07	−0.15 to 2.29	0.08	0.0048	−0.08 to 0.88	0.99

<sup>a</sup> Coefficients come from regressions that includes covariates for age, indicator variable for female, years of education, an indicator for firewood collector, an indicator for regularly working in forest, self-assessed health status, body mass index, an indicator variable if the session was past noon, an indicator variable if it rained during the in-field experiment, and village fixed effects. An interaction term for the two experimental factors was also included. Regressions employed clustered robust standard errors at the individual-level. Tables S3–S5 display regressions with main and interaction effects.

with scores being, on average, 1.13 (0.12 to 2.14,  $p < 0.05$ ) and 1.07 (−0.15 to 2.29,  $p < 0.01$ ) points higher for those engaged in the full 90 min activity and past noon, respectively.

Finally, we found gender-specific effects were consistent with the primary gender disaggregated analysis in our sensitivity analyses, with heat exposure adversely affecting only male participants (tables S6 and S7). Male participants engaged in the full 90 min experimental activity scored, on average, −1.22 (−2.61 to 0.17,  $p < 0.01$ ) and −1.59 (−2.66 to −0.53,  $p < 0.01$ ) points lower on the CAT and EMT, respectively. For male participants engaging in the experimental activity past noon, we found the effect of heat exposure EMT scores was nearly twice as large as the coefficient from the primary gender disaggregated model (−2.31, −3.71 to −0.92,  $p < 0.001$ ).

#### 4. Discussion

We found heat exposure in deforested areas can lead to adverse effects on cognitive performance. We also found effects varied by gender, time of day, and length of heat exposure. Adverse effects from heat exposure were robust across sensitivity analyses for the EMT. Counter to expectations, we found adverse heat effects from deforestation are largely driven by its effects on male participants, with scores being as much as 20% lower for men working in deforested compared to forested areas.

The existing literature provides some insights on why cognitive declines were driven by men rather

than women. For instance, physiological factors could be a reason for differential cognitive performance to hot environments and heat stress [57], as research has found gender differences in perceptions of thermal comfort in hot environments [58–60]. Given these considerations, it is possible that the gender differences in cognitive performance is driven by women adapting more rapidly to hotter thermal environments to reduce thermal loading via alliesthesial effects (i.e. feelings of displeasure).

Overall declines in cognitive performance as measured by CAT and EMT are likely driven by differences in the thermal environment rather than internal heat generation. Our analysis looking at the subsample of participants in the afternoon session indicate that adverse effects on cognitive performance from heat is more pronounced when core body temperatures and the thermal environment are elevated following diurnal cycles [56]. The overall thermal environment as measured by WBGT was approximately 2.7 °C hotter in deforested compared to forested areas. Radiative heating from a lack of shade may especially be detrimental to cognitive performance, as recent research [61] suggests that radiative heating from direct solar radiation rather than hyperthermia is an earlier predictor of adverse effects on cognitive performance. Given our research design is a field experiment, however, we are unable to disentangle whether the effect of solar radiation rather than the overall thermal environment played a greater role in cognitive performance declines. Contrary to expectations, higher financial incentives did not have

an adverse effect on cognitive performance, suggesting the piece rate financial incentive did not induce greater exertion and heat stress.

While declines in cognitive function from heat is in and of itself noteworthy, it is also correlated with elevated risk of injury [62, 63]. Subsistence farming and day labor in our study setting often requires vigorous activity using sharp equipment (e.g. machetes, plows), and decreases in dexterity and any resulting injury could have significant consequences. The cost of accessing healthcare can be higher for many rural populations in low-latitude industrializing countries because it is often distant. As a result, the economic impacts of injury-related disabilities are amplified [64] and may perpetuate poverty traps absent social insurance [65]. Declines in cognitive performance is itself important to quantify in poorer settings, especially in light of a growing body of work showing that poverty itself impedes cognitive function [66]. Other factors that can increase risk of injury from heat include impaired balance [67, 68], changes in safety behavior [69], and dehydration [63, 68]. Many of these factors may also simultaneously adversely affect cognitive performance, suggesting elevated risk of injury from heat exposure's effects on cognitive performance may be multimodal. Cognitive function may also relate to decision-making processes that influence the risk of heat illness through changes in executive function [70]. Heat can affect executive functions necessary to make decisions [70], such as decisions to engage in heat-protective behaviors.

Importantly, the experimental setting provided favorable work conditions unlikely to be seen in real world settings. Thus, our results are likely a lower bound estimate of the effects of heat from deforestation on cognitive performance. Our results also indicate that working as little as 90 min in similar settings can adversely affect cognitive performance for acclimatized populations. Our study population reported working, on average, 6.5 h in deforested areas, taking an average of 2.1 breaks during the day [6]. As the relationship between heat exposure and cognitive performance is non-linear [14], it is possible that there are greater cognitive declines in real world settings. Heat protective behaviors may mitigate these effects. In our study population 94% and 90% of those working in deforested areas reported wearing protective clothing and having access to shade, respectively, although 40% reported not having access to water when working [6]. An additional strategy may be shifting when or how long to work to avoid high temperatures. But adaptive behavior may be difficult without adversely affecting material well-being, as 94% reported they were already adjusting when they work on hot days, usually by working less (60%), and nearly a quarter of respondents reported they were unable to work as much as they want because of

the heat [6]. Further work is needed to disentangle the relationship between cognitive performance declines and injuries and heat illness risk in these settings.

Our results have implications for the health and well-being of the approximately 800 million rural villagers living in the world's developing tropical forest nations [71]. Pantropical deforestation trends have remained consistently and alarmingly high over the past two decades [72], and an increasing proportion of tropical forests are losing their cooling services [73]. There is a growing likelihood the next 3–4 decades will lead to 1 °C of warming above present day (2 °C above pre-industrial) global temperatures [74]. Together, these threats of warming add urgency to protect remaining forests and the cooling services they provide. Although the economic forces driving deforestation are powerful, illuminating the connections between forest health and human health may bolster support for forest restoration and protection with local policymakers.

Natural climate solutions [75], such as expanding agroforestry, may be one such strategy for rural farming communities in low-latitude tropical countries. These practices can address global and national climate goals (e.g. nationally determined contributions for the Paris Agreement), and also provide cooling services for rural farmers that may lack access to water, shade, and other critical infrastructure that can increase resilience to working in hot environments. Our study indicates one additional pathway by which nature conservation affects human well-being [76].

Our study has several limitations that should be addressed in future research. Although we recruited nearly 400 participants, we still had some differences between groups, such as gender. The study population's daily constraints can make recruiting participants for the study challenging. It is also difficult to control the timing of the experiment. Applying strict scheduling requirements is possible, but this may come at a cost of higher attrition rates or lower participation rates. Our results are also limited to healthy, working adults in our study setting—a study population suited to our research design. Children and elderly do engage in work in our study setting, and they are also likely affected by increased heat exposure from deforestation. We also lacked information on clothing and other variables that may be of interest to researchers (e.g. metabolic rate). Finally, our study was unable to capture non-linear heat effects from deforestation on cognitive performance given the binary experimental factor. Conducting field experiments reliant on environmental conditions can mean losing precision in manipulating specific environmental factors. However, for our study we used sensors to document that there was, in fact, significant differences in temperatures (e.g. WBGT) between forested and deforested sites. Despite these limitations, we believe our results have external validity

to healthy, acclimatized adult subsistence workers in rural industrializing tropical countries.

## 5. Conclusion

Little is known about how heat effects cognitive performance of healthy, adult, subsistence workers in low-latitude, industrializing countries. These populations face significant threats from heat effects from deforestation and climate change, and are some of the most vulnerable to its effects. Results from our study indicate that deforestation can significantly increase local temperatures and heat exposure compared to forested areas, and that even 90 min of exposure to these thermal environments that have higher WBGT and direct solar radiation can lead to adverse effects that are statistically significant. Policymakers should carefully consider how to mitigate both short- and long-term effects of land use change on local populations. Our study provides causal evidence of heat effects from deforestation on a population that is rarely examined but increasingly vulnerable to environmental and health shocks. The study region is experiencing significant threats to forests from the expansion of agricultural, oil palm, and mining [77], and is thus may provide insights into the threats other populations living in and around forests may face due to rapid deforestation. Trees and their cooling services may be an important component in the strategies to mitigate adverse heat exposure, and are also instrumental for achieving global climate change goals [75].

## Acknowledgments

We declare no competing interests. The funder of the study had no role in the study design, data collection, analysis, and interpretation. This work was supported by Margaret A. Cargill Philanthropies and by in-kind support from 3M. We thank the two anonymous reviewers for their feedback.

## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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