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How are healthy, working populations affected by increasing temperatures in the tropics? Implications for climate change adaptation policies

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ABSTRACT

Climate change and land use change are increasing average and extreme temperatures. Hotter temperatures can detrimentally affect workers' health and their economic productivity and livelihoods, especially in rural areas in industrializing countries that may be more vulnerable and less resilient. A growing literature has examined these factors at large spatial scales, yet few studies have done so at finer scales. Micro-level data from developing regions is needed to understand the extent of heat exposure, as well as current and future adaptation strategies of working, healthy, and rural populations. We fill this gap using objective environmental measurements from 3M^{TM} Questemp^{TM} 46 Heat Stress Monitors, as well as survey data from working, healthy, and rural communities in East Kalimantan, Indonesia. Our data contain two groups: those who work in only open areas, and those who work in both forests and open areas. We document workers' livelihood strategies, work schedules, perceptions of how temperatures impact their work, and future adaptation strategies for even hotter days. Ambient temperatures are 2.6–8.3 °C cooler in forests compared to open areas, indicating the temperature effects of deforestation can be immediate and significant. Those working only in open areas face up to 6.5 h of exposure to temperatures above the accepted Threshold Limit Value for worker well-being. Workers adapt to hotter temperatures by altering the timing of their work shifts and breaks, indicating our sample is already adapting to increasing temperatures from climate and land use change. We also find differential adaptation strategies between those working only in open areas compared to those working in both forests and open areas, suggesting current acclimatization may be a factor in how people adapt. Our results suggest the need for adaptation and mitigation policies tailored to the unique constraints of rural workers that specifically incorporate extant adaptation strategies.

1. Introduction

A growing literature examines the potential effects of increasing temperatures on populations living in low- and mid-latitude countries. Since the 1960s, the annual global land area impacted by extreme hot summers has increased from approximately 0.1–10% (Hansen et al., 2013). Absent mitigation, the earth's average surface temperature is projected to increase between 2.6–4.8 °C before the end of this century (IPCC, 2014), with potential dire consequences of increasing temperatures for populations in low- and mid-latitude countries (Harrington et al., 2016; Mora et al., 2017b; Mueller et al., 2016). Significant increases in local temperature could lead to mass migration (Hsiang and Sobel, 2016; Mueller et al., 2014), decreased economic output (Carleton and Hsiang, 2016), increased morbidity and mortality (Gasparrini et al., 2017; Hajat and Kosatky, 2010), and lower human capital (Garg et al., 2018). While extreme heat events and their adverse impacts on people have gained increasing attention, an important but understudied topic is how chronic increases in local temperatures are already affecting healthy, working populations in rural communities (Mani et al., 2018).

Chronic temperature changes may be acutely experienced by those

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living in low- and mid-latitude settings, especially in frontier areas such as tropical forests. Communities in these areas are at the forefront of rapid environmental change, and these changes are detrimental for climate goals and the well-being of local communities (Houghton and Nassikas, 2017; Le Quéré et al., 2015). As tropical forests can provide the cooling power of approximately two average household central air-conditioning units per day (Ellison et al., 2017), deforestation significantly affects local temperatures by reducing these cooling services at local and regional scales (Bonan, 2008; Bright et al., 2017; Ellison et al., 2017; McAlpine et al., 2018; Scott et al., 2018; Wolff et al., 2018). Despite adverse impacts on local populations and for global climate goals, tropical deforestation continues at a rapid clip (Song et al., 2018). Any additional variation in local temperatures – whether from chronic temperature increases or extreme heat events – may be detrimental for communities in low-latitude regions, as current climatic conditions already approach human thermoregulatory thresholds (Mora et al., 2017a).

For these reasons, we study how deforestation events and chronic temperature increases are affecting rural communities in and around forests in Indonesia. Although temperature trends in Indonesia (and other tropical regions) are expected to closely track mean global projections (e.g., 3–4 °C by 2100 under RCP 8.5; Stocker et al., 2013), the human impacts of this change could be disproportionately high due to the inherently low temperature variability in the tropics (Harrington et al., 2016). In Indonesia, these global heat risks are exacerbated by the loss of forest cooling services (Ellison et al., 2017; McAlpine et al., 2018; Wolff et al., 2018) driven by some of the highest rates of deforestation observed anywhere in the world (Hansen et al., 2013; Margono et al., 2014). Tropical forests can reduce solar radiation on the ground and transpire hundreds of liters of water a day (Ellison et al., 2017). One of the few studies documenting this cooling effect at local scales found primary and secondary forests in Sumatra were > 4 °C cooler than nearby open areas (Ramdani et al., 2014). Conversion of forest to more open landscapes (which can occur over a single season) can increase temperatures equivalent to nearly a century of warming under high emissions scenarios (Rogelj et al., 2012).

In recognition of climate projections and rapid environmental change, countries have started developing national climate action plans explicitly recognizing the potential adverse health and economic impacts of climate change. Though referenced as an instigator of other climate risks, rising temperatures as a harmful phenomenon in itself is often overlooked. The Indonesian National Action Plan for Climate Change Adaptation specifically discusses risks of, and adaptations to, increased sea surface temperatures, changing rainfall patterns, and sea level rise, but does not mention heat or increasing temperatures as a direct threat to health and well-being (BAPPENAS, 2013).

Omitting the direct risks from rising temperatures suggests some countries may be underprepared to tackle some of the gradual yet insidious effects of increasing temperatures. This can have wide ranging consequences. For instance, increasing temperatures may decrease labor productivity and supply (Burke et al., 2015; Lee et al., 2016), which may stall or setback the significant progress made in international development agendas in the past decade (Bank, 2017). Dunne et al. (2013) found increased heat in the workplace is already reducing productivity to 90%, while the Lancet Countdown Report (Watts et al., 2017) stated labor capacity has decreased by 5.3% since 2000. Recent estimates using Representative Concentration Pathway 8.5 found economic productivity could be at least 10% lower in developing countries in Asia by 2100 due to rising temperatures compared to the business as usual case (Lee et al., 2016), assuming future adaptations are similar to past strategies. While some research suggests projections may underestimate people's adaptive capacity (Hondula et al., 2015), these projections are nonetheless noteworthy because significant productivity losses can have cascading effects on human well-being and progress.

There are primarily two plausible ways gradual increasing temperatures can affect economic productivity and livelihoods in rural communities (Kjellstrom et al., 2016; Watts et al., 2017). First, temperature increases will directly reduce crop yields (Schlenker and Lobell, 2010; Schlenker and Roberts, 2009) while increasing water demand (Iglesias et al., 2011). After 2050, crop production is expected to be significantly lower in low-latitude countries for scenarios where temperature increases are 2 °C or higher (Porter et al., 2014). Second, economic losses may come directly from declines in productivity through two person-specific pathways. The first pathway is through behavioral responses during heat events, whereby people may choose to work less (Malik et al., 2010). The second pathway is through adverse physiological effects from working in the heat, including dehydration, heat strain, heat exhaustion, and heat stroke (Mora et al., 2017a). These physiological effects undermine people's ability to carry out physical work both indoors and outdoors (Kakota et al., 2011; Semenza et al., 1999), although temperature thresholds may vary across regions due to acclimatization. While this literature is still developing and commonly extrapolates from studies done in economically developed country settings, it provides important insights into the plausible impacts of increasing temperatures on economic productivity and livelihoods of rural communities in low-latitude countries.

Notably, all economic impacts from the second pathway are driven by heat's detrimental effects on health (Mora et al., 2017a). Beyond elevated risks of heat stroke and heat exhaustion (Spector and Sheffield, 2014), studies indicate excessive heat exposure increases risk of injuries or accidents (Crowe et al., 2015; Fogleman et al., 2005; Morabito et al., 2006; Spector et al., 2016; Tawatsupa et al., 2013) and can have negative effects on mental health (Berry et al., 2010; Kjellstrom, 2009a). Recent work even suggests heat stress may contribute to kidney disease (Moyce et al., 2017; Raines et al., 2014; Tawatsupa et al., 2012). In the most extreme cases, prolonged heat exposure while engaging in rigorous activities can be fatal (Barreca et al., 2013).

Impacts from increasing temperatures on rural, healthy populations are already substantial. In El Salvador, male sugarcane plantation workers have experienced increasing cases of heat death due to kidney failure (Peraza et al., 2012). Researchers in Costa Rica found sugarcane workers experienced increasing adverse health effects from working without adapting to extreme heat (Crowe et al., 2015). In Ghana, workers overwhelmingly expressed concern for their health in the heat, and almost half reported a 50% income reduction from farming due to heat (Kwasi et al., 2014). Despite these advances, we still know very little about, for instance, the level of exposure rural, healthy populations have to hotter temperatures, their work habits, and how they are being affected by increasing temperatures. A significant barrier to advancing this area of research is the lack of micro-level data in data poor regions. Understanding the current adaptation strategies, particularly behavioral insights, in specific micro-level contexts could help inform adaptation strategies in other settings.

Bridging this evidence gap is important for several reasons. A significant portion of rural populations in low-latitude countries work in conditions vulnerable to heat, such as agricultural or manual labor (McKinnon et al., 2016). These communities often have limited capacity to adapt to rising temperatures (Coffel et al., 2018; Whitmee et al., 2015), and face distinct challenges, such as fewer livelihood options and lack of access to infrastructure. In addition, carefully characterizing the unstructured nature of work in these communities provides critical insights for public health and economic policies. The nature of work is likely different in these communities compared to developed countries. Individuals commonly have more than one job, hours are flexible, and agricultural work is often unpredictable and seasonal. Attitudes, expectations, and commitments around work for livelihoods – not just incomes – may require adapting or reprioritizing existing recommendations for worker health and public health interventions (Peckham et al., 2017). Further, it is important to document whether these populations are already experiencing the negative effects of increasing temperatures because it can provide policy-relevant information on current individual- and household-level adaptation strategies, constraints, and vulnerabilities. Research indicates differential autonomous adaptation approaches to climate change adaptation policies (Mersha and van Laerhoven, 2018), highlighting the importance of understanding heterogeneity within communities. National climate action plans may miss critical information needed to understand the human health and economic impacts of increasing chronic temperatures and how to take those into account in local climate adaptation strategies. For example, local adaptation may first be driven by changes in individual and household behaviors, such as working less, changing when to work, or adopting new livelihood strategies. These micro-level behaviors may be overlooked by macro-scale research.

We advance this literature by reporting on a study examining a rural, healthy population's exposure to heat, their livelihood strategies, work schedules, perceptions of how current and hotter temperatures impact their work, and their stated adaptation strategies to further increasing temperatures. We use data from surveys and objective measurements from 10 rural communities in and around forests in the Berau Regency of Indonesia. We examine forest communities because they are at the forefront of areas facing significant land use pressures (Griscom et al., 2016), and recent research indicates they are acutely aware of hotter temperatures driven by these changes (Wolff et al., 2018). Further, our study region is particularly vulnerable to climate change impacts (Mora et al., 2017a; Struebig et al., 2015; Verbesselt et al., 2016), and almost exclusively reliant on agricultural and natural resource extraction to sustain their livelihoods which limits adaptation opportunities.

We investigate three questions. First, what type of work do people engage in, where do they work, and what is the extent of their exposure to hot temperatures as a result of their work? Second, what are the current effects of increasing temperatures on work, livelihood, and adaptation strategies? Finally, what are the stated adaptation strategies to future scenarios where a greater proportion of the day is subject to hotter temperatures? Importantly, we fill an important gap in the literature by focusing on the chronic temperature effects of climate change and deforestation in the rural tropics.

2. Data and study site

We use primary data from a study on how healthy individuals in rural forest communities cope and will adapt to increasing temperatures (Anggraeni et al., 2018). We primarily use two data sources: 1) individual-level survey data and 2) objective temperature measurements collected via 3M^{TM} Questemp^{TM} 46 Heat Stress Monitors. We also utilize focus group interviews conducted during the scoping phase of the study as a complement to our two primary data sources. Data collection was from October 1, 2017-November 6, 2017 in Berau Regency, East Kalimantan, Indonesia. The Berau Regency makes an ideal site for studying effects of temperatures on heathy, working age populations. Daylight hours and sunrise and sunset times vary at most 30 min throughout the year because of the Berau Regency's proximity to the equator (Figure B1). The Berau Regency has a rainy and dry season, and our study period falls during the tail end of the dry season. Further, while there is a rainy season, rainfall occurs sporadically throughout the year, and focus group interviews indicate communities are engaged in agricultural activities throughout the entire year.

The Berau Regency has experienced high land use pressures in the past decade, and represents a landscape undergoing significant change. A recent land use change evaluation of the Berau Regency (Griscom et al., 2016) found the mean annual rate of forest loss from 2000 to 2010 (0.71%) was 60% higher than the pantropical mean (0.45%) reported in Hansen et al (2013). Approximately 28% of this forest loss was driven by clearing for oil palm, followed by logging (17%), fiber plantations (9%) and mining (3%). The majority (43%) of converted forest was for unspecified agricultural purposes. Nearly half (47%) of the remaining forests are currently zoned for conversion. Despite these recent forest losses, 85% of the Berau Regency's original forest is still standing, and only 11% of the land area has no forest cover (Griscom et al., 2016). Agriculture, logging, and oil palm are major economic activities in the Berau Regency (Berau, 2017).

Our sampling frame focuses on healthy, working populations living in rural communities in and around forests. We employed a three-stage random sampling approach to select individuals into our study, where we randomly selected eligible villages, and then randomly selected households and eligible individuals within households. Inclusion criteria were applied at the village- and individual-level in order to capture our population of interest: healthy, working populations living in and around forests that engage in manual labor outdoors. This population is likely to be acutely aware of environmental changes. In order to capture this population, we deliberately exclude villages that are, for instance, island or coastal communities or are close to the regency capitol and thus may be engaged in more industrial industries. We included villages that are:

1 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 more than 20 km straight-line distance from the regency capitol; and
5 are accessible by road.

At the time of the study, the Berau Regency consists of 113 villages. 37 villages (33%) meet these criteria. We randomly selected five villages above and below the median of intact forest (31% of landcover in the 5 km buffer is intact forest) from the 37 villages to have even representation of communities more deeply imbedded in the forest (Fig. 1).

Within each village, we interviewed approximately two randomly selected healthy adults from each of the 20 randomly selected household. We used village-level household rosters to randomly select households, and then gathered household rosters from each randomly selected household to randomly select individuals. To be eligible for our study, individuals were required to be above 21 years old, able to lift more than 10 kg, and have no recent or chronic reported respiratory or cardiac issues.

In total, we recruited 405 individuals to participate in the study, and 90% participated. Of the 10% (n = 42) that did not participate, two declined to participate, while the remaining could not participate due to work obligations, travel, childcare (i.e., taking care of sick children), or to illness. As a result, our analytic sample includes 363 individuals from 201 households across ten villages. Here, we focus on a subset of respondents that either worked only in open areas (n = 266; herein referred to as O group) or worked in both forest and open areas (n = 95; herein referred to as FO group). We exclude two respondents who reported working only in forests. These groups were not selected *a priori* to the study, and were identified once data were collected.

We provide a descriptive understanding of the nature of the work carried out in forest communities, heat exposure, current stated adaptations to increasing temperatures, and future intended adaptations to increasing temperatures. As such, our analytic strategy involves identifying trends and patterns emerging from our diverse datasets, and where appropriate, making comparisons between groups to explore heterogeneity per Mersha and Laerhoven (2018). Where appropriate, we present regression results in Appendix C for robustness checks between subpopulations of interest because our sampling strategy did not randomly select on groups.

We use survey data on demographic and health characteristics, as well as responses to questions asking individuals about their time use during the previous day, work habits in and outside the forest, the current effects of hot temperatures on work, and prospective questions about whether and how they would adapt to future increases in temperatures (main survey modules in Appendix A). We collected a

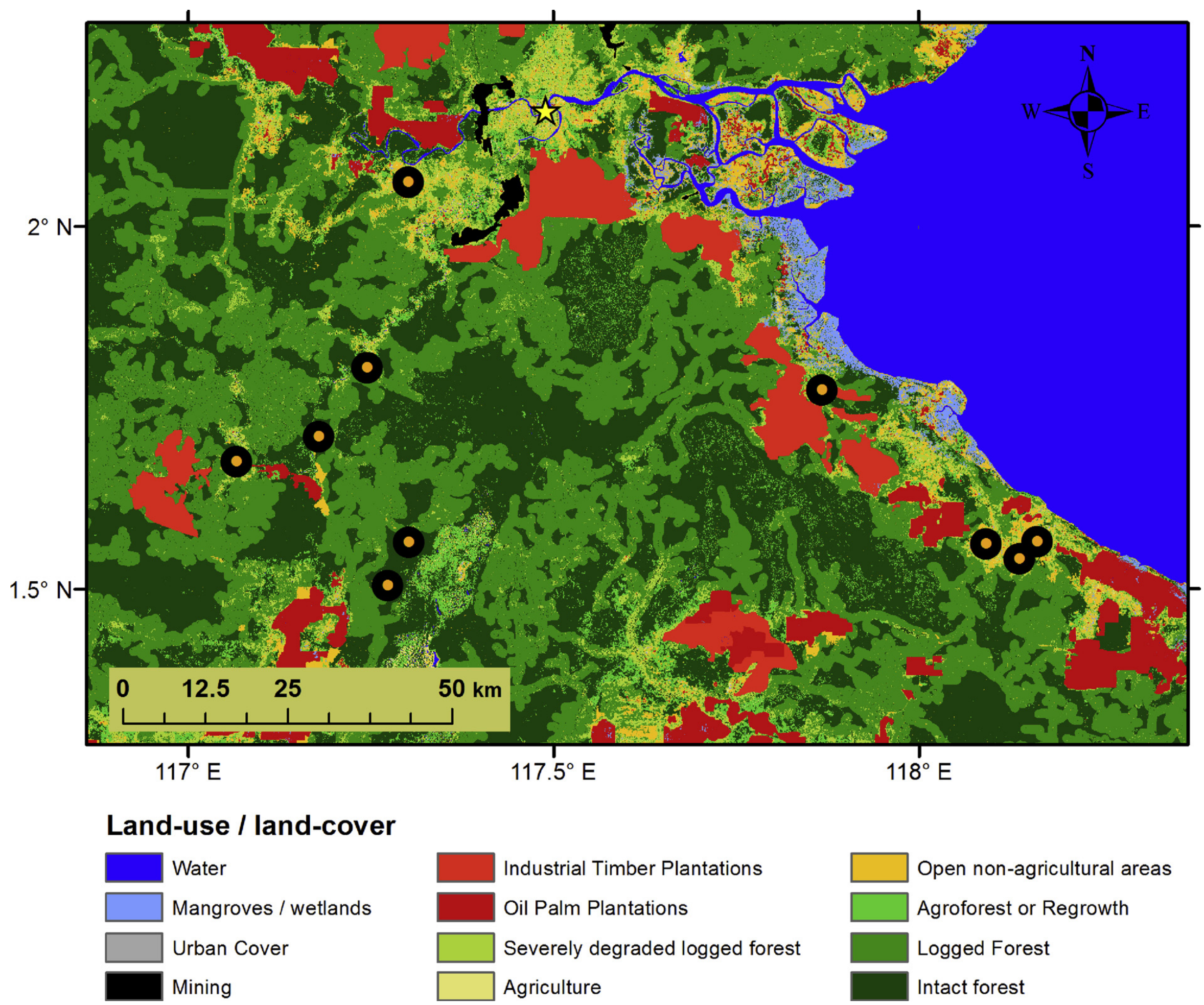

Fig. 1. Map of study area and villages.[a]
[a]The star represents the district capitol, Tanjung Redeb, while black circles with orange centers are study villages.

respondent's weight and height, as well as their overall self-assessed health status, consumption of alcohol and tobacco products, and diagnoses by a doctor or health provider of 12 health conditions. Previous day time use data provide information on what and where an individual did an activity every 15 min from the time they woke up to the time they went to bed the day before the respondent responded to the survey. However, time use data provide a cross section of information for how the study population allocates time, and may miss seasonal variation that is common with agricultural communities. Questions on work habits collected data on whether an individual works in open areas, forests, or both, and their regular morning and afternoon work shifts when working in forests and open areas. Questions about the current effects of increasing temperatures asked respondents about whether and how they adjust to hotter days, and whether the frequency of these days changed in the past year.

Finally, we collected data on the perceived hottest time of day, asking respondents when they thought the hottest time of day started and ended. Adaptations at this scale for this population can be driven by perceptions of increasing temperatures (Marx et al., 2007; Orlove et al., 2010; Spence et al., 2011; Weber, 2006). For that reason, we explore data on subjective perceptions about the hottest time of day to examine whether respondents can approximate objective measures. Comparing perceptions to objective measurements provides an indication of how sensitive individuals are to temperatures, and it can also provide insights into how people are adapting. Building on these questions, we then asked a series of questions about two future scenarios. The first scenario asked respondents about their stated adaptation strategy if the hottest time of day increased by one hour at the beginning and end of the current hottest time of day. The second scenario was similar, except it asked respondents about adaptation strategies imagining a scenario where the hottest time of day increases by two hours at the beginning and end of the current hottest time of day.

We augment survey data using data from 3M™ Questemp™ 46 Heat Stress Monitors that collected data on ambient temperatures, wet bulb globe temperature (WBGT), solar radiation, and relative humidity every five minutes. WBGT is a type of apparent temperature developed in the 1950s by the US military as part of a campaign to control heat-related illness in field training camps. WBGT and human thermal equilibrium have been integrated into occupational exposure limits and health and safety guidelines, which take into account additional factors that contribute to heat stress, including clothing and work-rest cycles (Hygienists, 2015; Parsons, 2013). WBGT is derived using the equation $WBGT = 0.7T_w + 0.2T_g + 0.1T_d$. Here, T_w is the natural wet bulb temperature (which is influenced by humidity), T_g is the globe temperature (measured with a black globe thermometer, which is a measure of radiant heat), and T_d is the dry bulb temperature (i.e., ambient air temperature). Dry bulb temperature is a more practical, though less comprehensive, heat exposure metric and has been commonly used in large epidemiologic studies that have reported associations between heat events, defined based on dry air temperature, and various adverse health outcomes and increased mortality in certain populations. Environmental sensors collected data for, on average, 3.5 days per village for a total of 34 days. For our current analysis, we report on four data loggers that were deployed to open areas (e.g., agricultural fields) and forests (e.g., primary or secondary forests) per village. Sites were identified with the help of village leaders, and we prioritized primary forests that were adjacent to open fields. Within a village, each sensor was placed in a distinct landscape area. For this study, we take the mean temperature for any given five minute time interval across all 34 days.

3. Results

3.1. Descriptive statistics

Study villages are, on average, 70 km from the regency capitol. All villages have varied land use classifications within a five kilometer buffer. Ninety percent have areas zoned for oil palm, 60% have areas zoned for logging, and 70% have areas zoned for mining. Within a five kilometer buffer, on average, 23% of the buffer is intact forest, 31% is used for logging, 14% of forests are severely degraded, and 11% is used for oil palm or other plantation industries. Access to public utilities is limited: just 0.5% and 36% of households used electricity from the grid for cooking and lighting, respectively, and 11% of households had piped household access.

The average ambient temperature, globe temperature, and WBGT during daylight hours (approximately 6:00am – 6:03pm, see Figure B1 for details) was 28 °C, 35 °C, and 28 °C, respectively (Fig. 2). The average relative humidity was 84% during daylight hours. These temperatures varied significantly by setting. The maximum daily temperature recorded in an open area was 37.8 °C and 33.9 °C for forest areas (Figure B2 presents images of an open area and forest area in a study location). During the study period, 3.25 h of the day (27% of daylight hours) in open areas was 30 °C or higher, which is the point at which labor supply and productivity can decrease dramatically (Zivin and Neidell, 2014). In comparison, the maximum average hourly recorded ambient temperature in forested areas was 28 °C. Overall, our ambient temperature data are consistent with long-run averages. Eighty-nine percent of daily temperature readings from Tanjung Redeb (The Regency capitol) Airport (2.155 °N, 117.432 °E) from 1995 to 2016 had daily maximum temperatures greater than 30 °C (Global Historical Climatology Network, Station ID: IDM00096529 (Menne et al., 2012)).

Our sampling frame is deliberately rural, working-age, and healthy. Respondents are, on average, 41 years old. Approximately half are female (Table 1). Respondents in our study are in overall good health. Eighty-three percent of respondents assessed their own health status as good or better, and 87% are normal or overweight. There are significant sex differences in recent alcohol and tobacco consumption, with 7% vs. 0% and 70% vs. 6% for recent consumption of alcohol and tobacco for men vs. women, respectively. The most common chronic health condition was high blood pressure (13%).

Despite the varied land cover in and around villages, nearly all of our sample (83%) reported their primary occupation as farming. Given the seasonal nature of agricultural work, however, respondents commonly reported having more than one job. Sixty-nine percent of farmers stated they had more than one occupation in the past 12 months. Seven percent reported having more than three jobs. Among farmers, the most common secondary occupations include wage labor (e.g., daily laborer for other farms) (20%), construction (11%), agricultural trade (8.6%), and wildlife harvesting (8.3%). Less than 3% of farmers reported working in jobs where activities are done indoors (e.g., public servant).

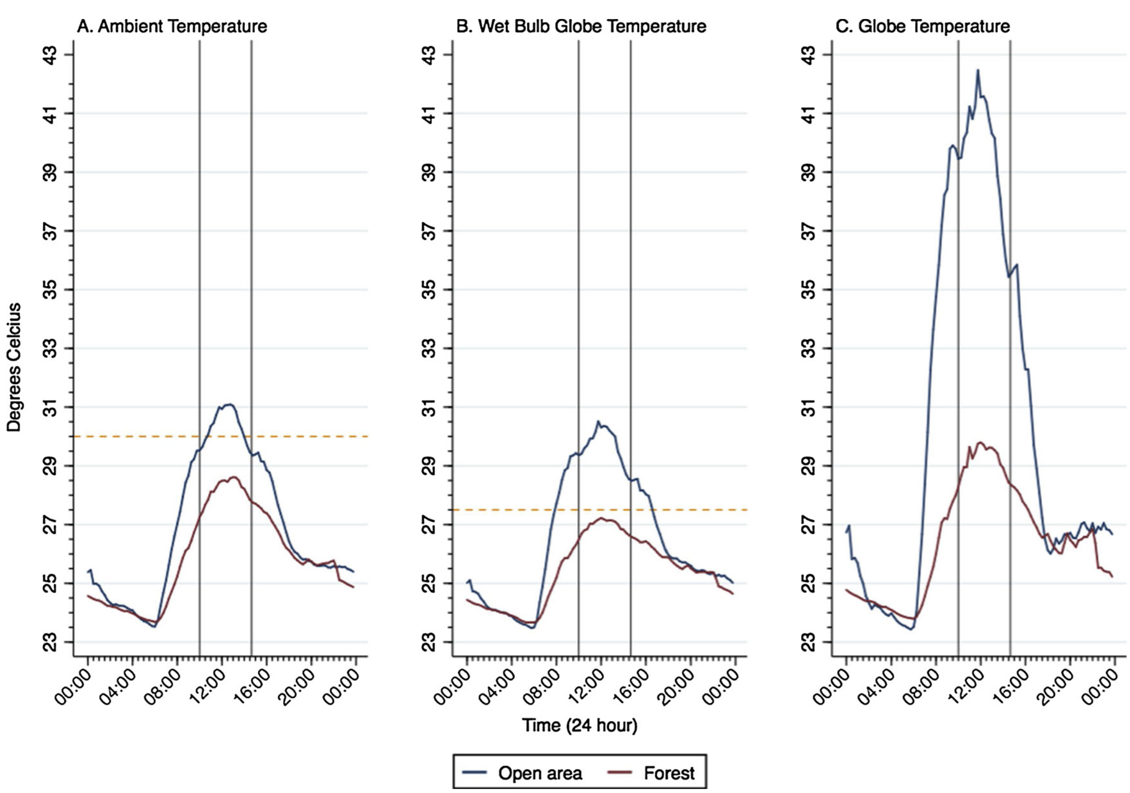

Fig. 2. Average ambient, wet bulb globe, and globe temperature through a 24 h period in study villages.[a]

[a]Solid black lines represent the average hottest time of day as reported by respondents. Dashed orange lines represent thresholds at which temperatures can affect human health and productivity. For Panel A, the line represents 30 °Celsius, which is the temperature at which labor productivity and labor supply was found to be adversely affected (Zivin and Neidell, 2014). For Panel B, the line represents 27.5 °C, which is the recommended Threshold Limit Value (TLV) by the American Conference of Governmental Industrial Hygienists (2015) for heavy workload (415 W) at a 50–75 percent work and recovery cycle.

Table 1
Summary statistics by work setting.[a]

Individual characteristics	FO group		O group		Diff[b]
	Mean	SD	Mean	SD	
Age	40	12	43	11	−2.7**
Female (%)	25	44	56	50	−31***
Years of schooling	6.3	3.3	6.3	3.6	−0.025
Farmer (%)	86	35	82	38	3.9
Logger (%)	1.0	10	0.0	0.0	1.1*
Day laborer (%)	5.0	22	4.0	20	1.1
Government employee (%)	0.0	0.0	1.0	9.0	−0.75
Full-time student (%)	0.0	0.0	2.0	12	−1.5
Other occupation (%)	4.0	20	2.0	14	2.3
Earnings in past year (Millions IDR)	14	18	12	20	2.8
Health conditions[c]					
Diabetes (%)	0.0	0.0	2.3	15	−2.2
High blood pressure (%)	11	31	15	36	−4.5
Heart disease (%)	0.0	0.0	0.0	6.0	0.0
Lung disease, including asthma (%)	0.0	0.0	3.0	16	−2.6
Heat-related illness[d] (%)	0.0	0.0	4.0	20	−4.1**
Kidney disease (%)	0.0	0.0	1.0	9.0	−0.7
Liver disease (%)	2.0	14	0.0	0.0	2.1**
High cholesterol (%)	2.0	14	7.0	26	−5.0*
Conditions affecting balance[e] (%)	1.0	10	1.0	11	0.0
Sleep problems[f] (%)	0.0	0.0	1.0	11	−1.1
Cancer (%)	1.0	10	0.0	0.0	1.1†
Physical fitness					
BMI: Underweight (%)	3.2	18	4.5	21	−1.4
BMI: Normal weight (%)	78	42	54	49	23***
BMI: Overweight (%)	15	36	31	46	−16***
BMI: Obese (%)	4.2	20	9.8	30	−5.5*
Household characteristics					
Household size	4.4	1.5	4.5	1.4	−0.071
Household assets (Millions IDR)	46	76	41	57	5.4
Productive assets (Millions IDR)	3.6	4.6	4.2	8.2	−0.64
Income from farming (Millions IDR)	1.4	2.7	2.8	6.4	−1.4**
Nonfarm income (Millions IDR)	22	24	23	36	−1.1
n	95		266		

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.
[a] Table D1 presents the full range of values for the sample population.
[b] Differences between groups tested via a two-tailed *t*-test for continuous variables and a test on the equality of proportions for dichotomous variables.
[c] Responses come from a question asking, “Has a doctor or health provider ever told you that you have any of the following conditions?”.
[d] This includes conditions such as dizziness, headache, skin rash, cramps, nausea, and confusion.
[e] This includes conditions such as stroke and problems with the inner ear.
[f] This includes conditions such as obstructive sleep apnea.

On average, 83% of household income was from non-farm activities, such as trading, construction, and selling non-timber forest products, suggesting farming is primarily for household consumption rather than income generation.

3.2. Work location, timing, and exposure

Understanding where and when people work is important for understanding the population’s risks of heat illness, as well as the current impacts of increasing temperatures on work. Using data from a survey module on work habits asking respondents about work shifts when working in forests and open areas, our population was classified into two groups based on where they work: those in the O group, and those in the FO group. Seventy-four percent of individuals reported working solely in open areas, and approximately a quarter of respondents work in both forests and open areas. A significantly greater proportion of those in the FO group are male and younger, although they are largely similar along other key characteristics (Table 1).

These two groups differ along key characteristics important to understanding their risk to heat illness. Body mass index – here, seen as a proxy for physical fitness – was lower for respondents in the FO group. A greater proportion of those in the FO group are normal weight, and fewer are overweight or obese. Further, individuals in the FO group were generally in better health. Responses to a series of questions about health conditions diagnosed by a health provider or doctor indicate this group had significantly fewer respondents who have experienced heat-related illness (4%) or have high cholesterol (5%). Although not statistically significant, this group also had fewer respondents with diabetes, high blood pressure, lung disease, kidney disease, and sleep problems.

We now turn to examining when people work and rest, as it is important for assessing exposure to high temperatures and heat illness risk in different environments (Fig. 3). Open areas are subject to direct solar radiation, and forests can be cooler due to shade, evaporation, and transpiration (Bright et al., 2017; Ellison et al., 2017; Scott et al., 2018). During our study period, the largest difference in average ambient temperatures between open areas and forests was 2.6 °C, but the difference in maximum ambient temperatures was 8.3 °C. Ambient temperature alone may underestimate the effects people feel from heat: humidity, solar radiation, and wind are also important factors affecting people’s experiences of heat (Parsons, 2003). In open areas, the maximum average hourly globe temperature – a measure of radiant heat – was 42 °C compared to just 29 °C in forested areas. For WBGT, the difference in average WBGT differed as much as 3.2 °C, and the maximum WBGT differed as much as 3.8 °C.

We use self-reported work shifts for a typical work day in forests or in open areas to evaluate exposure in open areas and forests (Fig. 4). Work shifts in forest and open areas differed significantly (Table 2). When working in forests, respondents worked, on average, 1.3 h more in the afternoon, took 54 min shorter mid-day breaks, and a smaller proportion worked all day compared to those working only in open areas.

Time use data on the previous day’s activities provide complementary information on the nature of work. First, time use data indicate a smaller proportion of those working in forests take a mid-day break compared to those working in open areas (Fig. 3). Longer work days in forests may be driven by the type of work activities typically done. For instance, in focus group interviews conducted during the scoping phase of the study, villagers reported hunting in forests late into the night. Other common activities include collecting firewood and medicinal plants, and logging. The most common forest activities reported in the time use data by men was non-farm labor (e.g., logging, hunting), and for women it was farming (e.g., agroforestry). Among those working in forests, men spent, on average, significantly more time in forests compared to women (7 h vs. 3.8 h). Farming was by far the most common activity in open areas. Finally, time use data suggest working in both forests and open areas in the same day was rare (only 4.4%). Those working in both settings in the same day worked, on average, 4.7 h in the forest and 4.3 h in open areas.

Among those working a full day, the average workday started at 7:54am and 7:41am and ended at 7:43pm and 4:36pm for forests and open areas, respectively. Individuals working in open areas took longer mid-day breaks (approximately an hour longer), as respondents working in forests started their breaks, on average, 22 min later and ended their breaks 34 min earlier. Eighteen percent of respondents working in forests reported working past sunset (5:57pm), compared to about 1% of those working in open areas. The American Conference of Governmental Industrial Hygienists (2015) Threshold Limit Value (TLV) for individuals engaging in heavy work activity (metabolic rate of 415 W) at a 50–75% work and recovery cycle is 27.5 °C for WBGT. Based on this assumption and the work shift data and objective temperature measurements (Fig. 2), individuals working a full day in open areas were subject to WBGT above the TLV for up to 6.5 h a day given an individual takes the average 2.5 h mid-day break. Despite significant exposure faced by individuals working in open areas, survey data indicated respondents took precautions for their occupational health (Table 3). Survey questions asking about breaks on subjectively

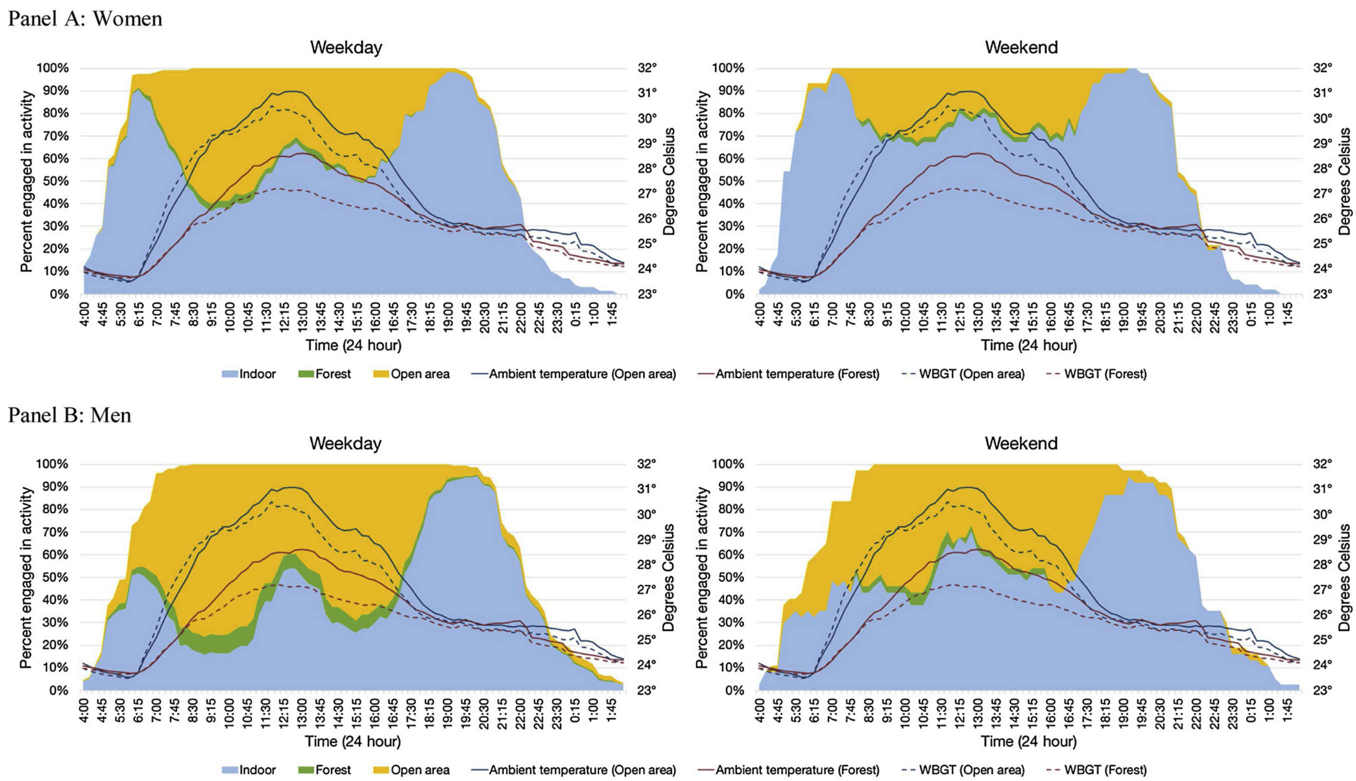

Fig. 3. Indoor and outdoor activity participation for weekday and weekend with open area and forest temperatures.[a]
Panel A: Women.
Panel B: Men.
[a]Data come from a time use module asking about the previous day's activities. Activities are coded as *indoor* and *outdoor* based on location data provided for every time use activity, which was recorded in 15 min increments. *Indoor* indicates activities were conducted inside a dwelling or other building (e.g., school). *Open area* indicates activities were done in an open field for agricultural or non-agricultural activities. Forest indicates activities were done in a primary forest, timber forest, acacia plantation, or oil palm plantation. Figure B3 presents detailed time use reports by weekday/end and sex.

assessed hot days indicated people take, on average, 3.5 breaks a day, compared to 2.1 breaks on less hot days. Further, when working in open areas 90% had easy access to a shaded area, and 94% reported wearing protective clothing, such as hats and loose long sleeve shirts and pants. Only 59%, however, reported having access to water when working in open areas.

3.3. Current effects and adaptation to increasing temperatures

What are the effects of increasing temperatures on current work? Using the 30 °C ambient temperature thresholds per Zivin and Neidell (2014) (Fig. 2) as an indicator of the hottest time of day, we found perceptions about the hottest time of day were overestimated by approximately one hour. In open areas, the average ambient temperature was 30 °C or higher from 10:00am to 1:30pm, while the average perceived hottest time was from 10:00am to 2:19pm. Responses did not significantly differ between those in the O group and the FO group.

Overall, 95% of respondents report they were adjusting when they work on hotter days (Table 4), mainly by working less. The second most common strategy was to work earlier. Sixty-six percent stated they were working less as a result of hot days in the past year, while 23% had not adjusted their work schedules. Twenty-seven percent have adopted new livelihood activities as a result of hotter temperatures. The most common livelihood activities were construction (6%), animal husbandry (11%), and trading agricultural products (9%). Most strikingly, 24% reported being unable to work as much as they wanted to because of hotter days. This indicated that, overall, our study population felt and was already adapting to increasing temperatures.

We found respondents in the FO group were significantly more affected by increasing temperatures compared to the O group: approximately 5% more respondents stated they adjusted when to work on hotter days, 11% more respondents stated they were working less in the past year due to hotter days, and 18% more respondents stated they were unable to work as much as they wanted because of the heat. Twenty-seven percent more respondents in the FO group reported taking on new activities as a result of hotter temperatures. Adaptation strategies also differed by group. Twelve percent of respondents the FO group reported working less on hot days, while 8% more of respondents in the O group worked later.

3.4. Stated adaptation to increasing temperatures in the future

Here, we turn to questions asking respondents how they would adapt, or not adapt, to two future scenarios. The two scenarios are situations where the hottest time of day (10:00am-2:19pm) would increase by two hours (9:00am-3:19pm) and four hours (8:00am-4:19pm), respectively.

Future stated adaptation strategies differed by scenario and by work setting (Table 4). With respect to adapting to a two hour increase in the hottest time of day (on average, from 9:00am to 3:19pm), nearly twice the number of people in the O group reported they would not adapt (i.e., continue business as usual), and 16% fewer respondents also stated they would work earlier or later. Although differences were not statistically significant, respondents in the O group also had a larger proportion reporting they would work less or stop working.

For adaptation to a four hour increase in the hottest time of day (on average, 8:00am to 4:19pm), we found similar patterns to a two hour increase in the hottest time of day except responses reflected greater adaptation. A greater proportion of all respondents stated they would work less, stop working, or engage in another job or activity that avoids

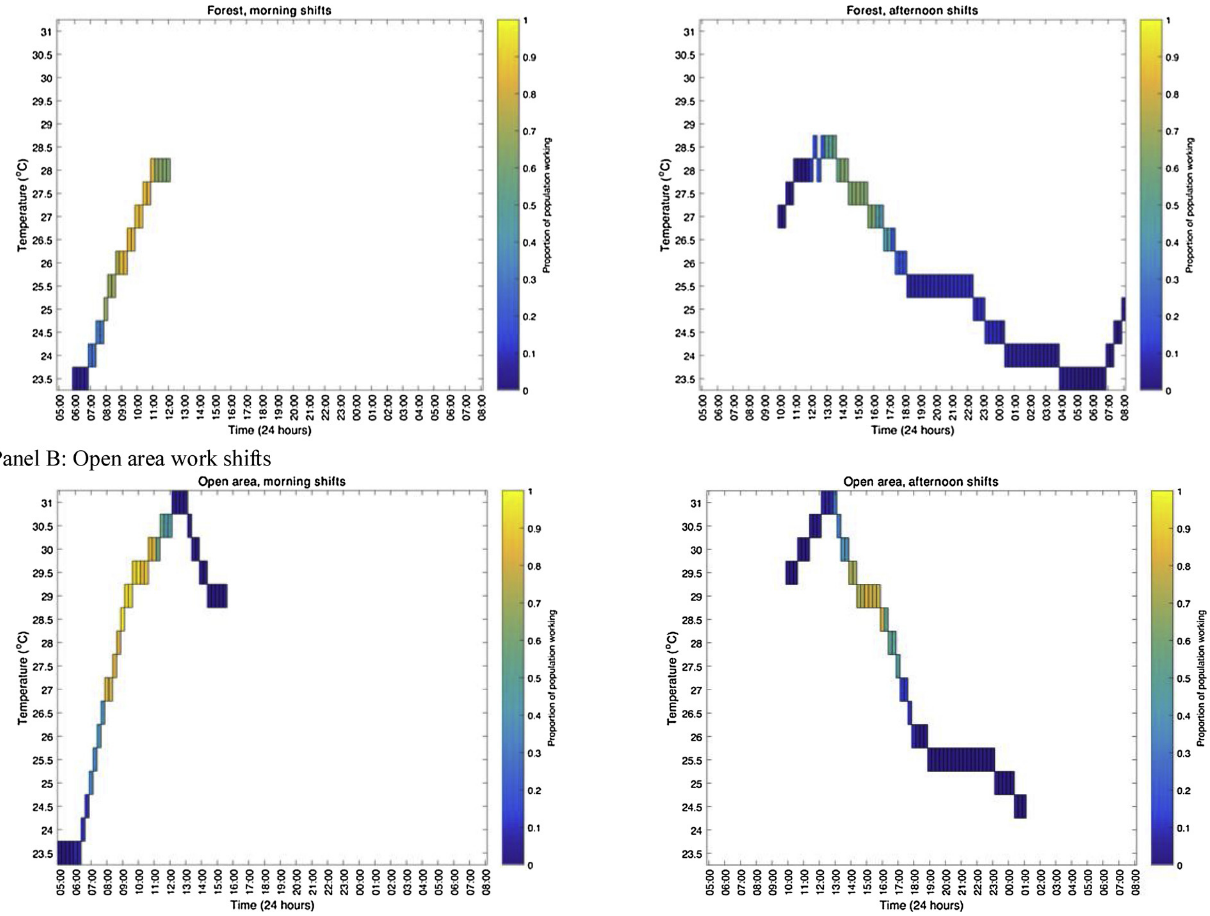

Fig. 4. Heat map of forest work and non-forest work hours.[a]
Panel A: Forest work shifts.
Panel B: Open area work shifts.
[a]Data come from a question on work shifts when working in forests and open areas in the morning and afternoon, which asked about morning and afternoon shifts, separately. Figures B4 and B5 present the individual-level work shifts for forest and open areas, respectively.

Table 2
Work habits in forests and open areas.[a]

	Forest work		Open area work		Diff[b]
	Mean	SD	Mean	SD	
AM shift (hours), typical day	3.7	1.0	3.7	1.2	0.07
PM shift (hours), typical day	4.1	2.4	2.8	1.1	1.3***
Break period (hours)	1.4	1.2	2.5	1.3	−1.1***
AM work only (%)	19	39	14	35	5.0
PM work only (%)	12	32	3.0	18	8.2***
Work all day (%)	69	46	83	38	−13***
n	95		266		

***p < 0.01, **p < 0.05, *p < 0.10.
[a] Sample sizes differed for Am shift, PM shift, and Break period because not all respondents reported working morning and afternoon shifts. For AM shifts, sample sizes were 93 and 257 for the forest work and open area work group and open area work only group, respectively. For PM shifts, sample sizes were 87 and 229 for the forest work and open area work group and open area work only group, respectively. For break period, sample sizes were 85 and 221for the forest work and open area work group and open area work only group, respectively.
[b] Differences between groups tested via a two-tailed *t*-test for continuous variables and a test on the equality of proportions for dichotomous variables.

direct sunlight, while a smaller proportion of respondents stated they would work earlier or later as a result of longer hotter days. Further, the differences between respondents in the O group and the FO group were also larger. For instance, 10% more respondents in the O group reported they would not change or adapt to increasing temperatures, and 5% more respondents stated they would stop working. Thirteen percent of respondents in the FO group stated they would work earlier or later as a result of longer hotter days.

In both future scenarios, a greater proportion of respondents in the O group reported they would not change or adapt when or how they work, while a significantly greater proportion of respondents in the FO group stated they would work earlier or later as a result of increasing

Table 3
Occupational health practices.[a]

	FO group		O group		Diff[b]
	Mean	SD	Mean	SD	
Number of breaks normally taken	1.5	1.1	2.1	1.2	−0.57***
Number of breaks on hot days	2.4	1.8	3.5	2.5	−1.1***
Shaded area easily accessible (%)	–	–	90	30	–
Wear protective clothing[c] (%)	88	32	94	23	−5.9*
Have access to water (%)	42	50	59	49	−16***
n	95		266		

***p < 0.01, **p < 0.05, *p < 0.10.
[a] Tables C1 presents regressions for these outcomes controlling for individual and household characteristics and village fixed effects.
[b] Differences between groups tested via a two-tailed *t*-test for continuous variables and a test on the equality of proportions for dichotomous variables.
[c] Includes hats, lose long sleeve shirts, and pants.

Table 4
Current and future adaptation to increasing temperatures.[a]

Current effects and adaptation	FO group		O group		Diff[b]
	Mean	SD	Mean	SD	
Adjust when to work on hotter days (%)	99	10	94	25	5.3**
How do you adjust when to work on hotter days?					
Working less (%)	71	45	59	49	12**
Working more (%)	5.3	23	4.4	21	0.9
Working earlier (%)	14	35	18	39	−4.6
Working later (%)	9.6	30	18	38	−8.1*
In the past year, due to hot days working…					
More (%)	7.4	26	12	32	−4.1
Less (%)	74	44	63	48	11**
The same (%)	18	39	25	44	−7.2
In the past year, taken on new activities as a result of hotter weather (%)	41	49	22	42	27***
Unable to work as much as you want because of heat (%)	37	48	19	39	18***
Future adaptation					
Hottest time increases by two hours would…					
not change/adapt (%)	7.0	26	14	33	−6.5*
work earlier or later (%)	45	50	28	47	16***
engage in other jobs/activities that avoid direct sunlight (%)	14	36	12	33	2.3
work less (%)	33	47	42	49	−9.5
stop working (%)	0.0	0.0	2.6	16	−2.6
other (%)	0.0	0.0	1.5	12	−1.5
Hottest time increases by four hours would…					
not change/adapt (%)	4.2	21	15	35	−10***
work earlier or later	33	48	21	41	13**
engage in other jobs/activities that avoid direct sunlight (%)	21	41	12	32	9.0**
work less (%)	40	49	47	50	−6.6
stop working (%)	1.1	10	6.0	21	−5.0**
other (%)	1.1	10	4.5	21	−3.4
n	95		266		

***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.
[a] Tables C2-C6 present regressions for these variables that control for individual and household characteristics and village fixed effects for current effects and adaptation to climate increasing temperatures.
[b] Differences between groups tested via a two-tailed *t*-test for continuous variables and a test on the equality of proportions for dichotomous variables.

temperatures.

4. Discussion

While studies projected significant potential impacts on health and productivity (Kjellstrom, 2009b), there is still a dearth of evidence on how healthy, working populations in rural communities in low-latitude countries could be affected by increasing temperatures (Kjellstrom et al., 2017; Mani et al., 2018). This is a significant gap considering temperature variability is expected to be largest in poorer, tropical countries (Bathiany et al., 2018; Harrington et al., 2016). We found increasing temperatures were already inducing adaptation - nearly our entire sample was already engaging in heat avoidance behavior when working on hotter days, typically by working less. Although working less increases leisure and is therefore not always a negative outcome, 66% of respondents stated they were unable to work as much as they would like due to hotter days. Our results are notable because micro-level behavioral adaptations are oftentimes not captured by survey data, as studies instead tend to focus on upstream adaptations, such as farming practices and inputs (e.g., Taraz, 2017), rather than when and where people work.

Our results from work shift and time use data also demonstrate the utility of measuring where and when people work, as well as complementing these data with objective temperature measurements. Our data provide important insights into heterogeneous exposure to heat. The O group spent significantly more time in hotter environments (hours spent in WBGT over 27.5 °C), which was driven in part because they tended to work a full day compared to the FO group. But individuals in the FO group were uniquely affected by increasing temperatures, as they reportedly worked less and took on new livelihood activities as a result of hotter days compared to the O group. A greater proportion of people in the FO group also stated they were unable to work as much as they wanted to due to the heat.

Although these results may seem counterintuitive, there are several possible explanations. First, individuals in the FO group may not be as acclimatized to larger intraday temperature differentials present in open areas. During our study period, ambient temperatures differed as much as 8.3 °C, and maximum globe temperatures reached 58 °C and differed as much as 14 °C compared to forested areas. Time use data indicate those working in forests can limit exposure to open areas and direct solar radiation. By dedicating a large portion of the day in forests where daytime temperatures were less variable (Fig. 2), these individuals may be more sensitive to more variable temperatures and direct solar radiation common in open areas. As a result, the FO group may be more sensitive to, or more aware of, any temperature increases that differ from their typical thermal environment. This mirrors findings about behavioral responses to thermal comfort (Chow et al., 2016; Nikolopoulou and Steemers, 2003), and may be an important consideration in adaptation strategies.

Second, the greater effect of hotter days on respondents in the FO group may reflect individual workplace preferences whereby individuals less tolerant to hotter environments have already self-selected into forest-based activities. The multi-phase sampling approach and large sample size give us confidence that our data are representative of rural, healthy working adults in and around forests for our study setting. Any respondent preferences or self-selection into workplaces is expected to be reflective of the sampling frame. Given the strong social expectations surrounding work in study villages, however, we believe this is unlikely to be a major driver of differential effects. That is, social and cultural norms would dominate any self-selection effects, and this is reflected in the division of labor and time allocations in our data. Data on occupation and time use from our data support the strength of strong social and cultural norms around occupation and place of work.

Finally, the theory of availability bias (Tversky and Kahneman, 1991) points towards another possible explanation, which essentially posits that people can more readily recall the effect of a recent experience. Using this reasoning, individuals in the FO group may be more likely to note, and act on, increasing temperatures simply because they more frequently experience the large temperature differences presented by both landscapes. Conversely, individuals who spent most of their time in open areas and did not regularly experience the cooling effect of forests may be less likely to recall the effect. It is interesting that Wolff et al. (2018) also found evidence of an availability bias in an examination of forest cooling service perceptions in villages across Kalimantan, and other recent work has highlighted this in U.S. populations (Moore et al., 2019). The implications of such a bias are potentially serious because they suggest as deforestation expands and awareness of its effects fade (Pellier et al., 2014), its contribution to heat stress and heat illness may be underappreciated until these consequences are already extreme.

Our results on stated future adaptation strategies are illuminating. They suggest individuals in the FO group may take more steps to adapt to increasing temperatures, perhaps due to the reasons stated above. In the two hour scenario, the most common overall strategy was to work earlier or later, while the most common strategy in the four hour scenario was to work less. This suggests productivity and livelihood impacts will be observed once the hottest time of day increases by more than two hours. Notably, no respondents stated migrating as an adaptation strategy in both scenarios, despite migration as an adaptation response receiving considerable attention in the academic literature (Baez et al., 2017; De Sherbinin et al., 2011; Hsiang and Sobel, 2016; Mueller et al., 2014; Rigaud et al., 2018; Thiede et al., 2017). Future research should explore stated adaptation strategies to actual adaptation behavior, as work in the U.S. suggests people's adaptive capacity may be underappreciated (Hondula et al., 2015).

We believe our findings have implications for similar rural agrarian communities in low-latitude tropical forests (e.g., communities in Southeast Asia, South America, Central Africa). First, it is likely that similar communities are already adapting to chronically hotter temperatures in common ways, such as adjusting when and how they work. Decision-makers should develop an understanding of these behavioral adaptations that are already being adopted before establishing broader adaptation strategies. Second, deforestation in tropical forests will likely result significant increases in local temperatures, and policy-makers should consider localized temperature effects of forestry activity. Finally, there is likely heterogeneous heat exposure and adaptation strategies being employed by rural community members, and accounting for this heterogeneity is likely important for identifying differential risks across the population. Some sub-populations, such as women, the elderly, and young children, may especially be at risk of heat illness from extensive heat exposure, and understanding the factors driving this risk is important. In our data, for instance, we observed that significantly more women worked only in open areas compared to forests and open areas. Despite broader lessons for rural agrarian communities in low-latitude tropical forests, our results should be cautiously applied because work shifts and breaks and other factors affecting heat exposure are likely driven by social, cultural, and economic factors that are context specific. Our time use data highlight how workplace alone does not reveal how much heat exposure an individual is likely to have. Future work should carefully consider how the gendered nature of work can affect heat exposure, heat health, and its effect on overall individual and household well-being.

The generalizability of our results may be limited to healthy, working adults in rural communities in and around tropical forests. We focused on this population because they tend to be understudied, and future work should explore heat exposure by gender, age, occupation, and other factors that are plausible determinants of heat exposure. Still, we believe our study fills a critical research gap and has implications for economic and development policies, environmental and conservation policies, public health policies, and national climate policies.

For economic and development policies, our study has three implications. First, we provide rich descriptive evidence on how work patterns of healthy, rural populations in developing economies are already adapting to rising temperatures. Extant adaptation strategies – especially those observed at the individual-level – should be incorporated into any future policies. Creative policies that directly incorporate extant adaptation strategies and the unique constraints faced by rural workers may be needed. Existing strategies to minimize risks of heat illness and productivity declines, such as increasing access to air conditioning, may not be viable for rural workers in developing economies. Other strategies, such as increasing water, rest, and shade, likely do not address the negative productivity impacts from decreasing work hours or contexts where workers are employed outside the home with limited control over such adaptations.

Second, our study adds to the growing research on the economics of heat stress and climate change (Burke et al., 2016), and we echo others who called for the need to refine the social cost of carbon. Most adaptation strategies we observed have an economic cost, and such costs are likely greater for poor households that have limited pathways to adaptation and are already resource constrained. For instance, poorer households may be financially constrained to reduce number of hours worked due to hotter days, which can potentially create and perpetuate poverty traps (Barrett et al., 2016). Finally, for outdoor workers in poor rural settings such as ours, ecosystems may provide one of very few sources of adaptation that are not financially debilitating for households. While our estimates here are descriptive and not causal, our findings point to the need for research into how ecosystem services (e.g., shade from forests) can allow rural households in developing economies to adapt to rising temperatures. Ecosystem services may be especially important to adaptation when laborers operate in employer-employee dynamics outside of the home, yielding less agency in the hours and pace of their work, which can increase risks of heat-related illness (Crowe et al., 2015; Peraza et al., 2012; Quiller et al., 2017; Renton, 2009). Moreover, such services need to be an essential part of the accounting of the value of ecosystem services – something that current estimates do not necessarily capture.

For conservation and environmental policies, our results suggest the magnitude and abruptness of the temperature effect of deforestation may be worthy of more public policy attention. Heat related risks associated with global climate change have received far greater research and policy attention than the risks posed by deforestation and other land use changes for low latitude communities (e.g., IPCC, 2014; Kjellstrom, 2009b; Mora et al., 2017b). While emissions driven warming poses substantial threats to poor, agrarian villages in tropical regions, these threats will unfold slowly over many decades (Harrington et al., 2016; Mora et al., 2017b). In contrast, the impacts of deforestation are occurring now, are global in scale, and are predicted to continue at alarming rates (Hansen et al., 2013; Hughes, 2018). To put this in perspective, our results suggests the conversion of forest to more open landscapes, which often occurs over a single season (Hansen et al., 2013), can lead to a mean temperature increase of 2.6 °C. This potentially immediate temperature effect corresponds to nearly a century of warming under high emissions climate change scenarios (Rogelj et al., 2012) and exceeds by 260% the goals of the Paris Agreement which seeks to keep global temperature rise this century well below 2 °C above pre-industrial levels. For an even more startling contrast, the 8.3 °C maximum difference we observed between forest and open areas corresponds to nearly two centuries of warming (approximately year 2200) under the highest emission pathway (Rogelj et al., 2012).

Despite the temperature benefits tropical forests provide, more research is needed to quantify these cooling services. While there is some understanding of the magnitude of the temperature difference between primary forests and converted, cleared areas (Bright et al., 2017; Ellison et al., 2017; McAlpine et al., 2018), less is known about how these cooling services are affected by forest degradation. For instance, how does selective logging affect cooling services of forests? Are there forest canopy cover thresholds below which cooling abruptly declines? Do forest cooling services extend beyond the forest boundary? Nearly 40% of deforestation in Berau is driven by conversion to oil palm and fiber (e.g., Acacia) plantations (Griscom et al., 2016). Do these industrial plantations provide cooling services, and if so, how do they compare to natural forests? Finally, is it possible that some temperature related impacts could be minimized through careful spatial planning of future forest clearing and/or reforestation?

From a public health perspective, our study highlights how occupational health guidelines should differentiate between industrial agricultural work and household agricultural work in rural developing country settings. For household agricultural work, flexible work schedules and lower psychological job demand (Cantley et al., 2016) should allow people to take more frequent breaks and adopt occupational health practices. However, our results indicate improved occupational health practices are still needed for those engaging only in household agricultural work. For instance, almost half of individuals working in open areas do not have easy access to water.

Finally, our study highlights how decision-makers and researchers should carefully consider how gradual temperature increases from climate change and environmental change are affecting communities. Extreme events can provide punctuated attention and lead to policy attention, but the adverse effects of gradual but consistent changes leading to micro-level adaptations may be underappreciated. Further research is needed to disentangle the mechanisms by which these gradual changes are affecting more vulnerable populations. What infrastructure can simultaneously improve resilience while minimizing environmental damage that can exacerbate local temperatures? What are the heterogeneous impacts of these gradual changes in rural, developing country settings from gradual temperature increases? Further research on these and other questions may help illuminate sustainable resilience and adaptation policies.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gloenvcha.2019.03.005.

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