Author/s:
Wolff, NH;Masuda, YJ;Meijaard, E;Wells, JA;Game, ET

Title:
Impacts of tropical deforestation on local temperature and human wellbeing perceptions

Date:
2018-09-01

Citation:
Wolff, N. H., Masuda, Y. J., Meijaard, E., Wells, J. A. & Game, E. T. (2018). Impacts of tropical deforestation on local temperature and human wellbeing perceptions. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS, 52, pp.181-189. https://doi.org/10.1016/j.gloenvcha.2018.07.004.

Persistent Link:
https://hdl.handle.net/11343/300176

Global Environmental Change 52 (2018) 181–189

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Impacts of tropical deforestation on local temperature and human well-being perceptions

Nicholas H. Wolff[a,*], Yuta J. Masuda[b], Erik Meijaard[c,d], Jessie A. Wells[c,d], Edward T. Game[e,f]

[a] Global Science, The Nature Conservancy, Brunswick, ME, USA
[b] Global Science, The Nature Conservancy, Seattle, WA, USA
[c] ARC Centre of Excellence for Environmental Decisions, University of Queensland, Brisbane, QLD, Australia
[d] Borneo Futures, Country Woods 306, Jl.WRSupratman, Ciputat, Jakarta, 15412, Indonesia
[e] Centre for Biodiversity and Conservation Science, University of Queensland, Brisbane, QLD, Australia
[f] Global Science, The Nature Conservancy, South Brisbane, QLD, Australia

ARTICLE INFO

Keywords:
Ecosystem services
Cooling services
Human health
Heat illness
Land use change
Climate change adaptation

ABSTRACT

The combined effects of changes in climate and land cover expose millions of people to an increased likelihood of heat illness. Impacts of heat stress on health have primarily been quantified for urban environments, particularly in developed countries. Far less is known in other settings, including the effects of ongoing tropical deforestation on local temperature and its consequences for people living in these rapidly changing landscapes. Here, we explore links between deforestation and self-reported human health and well-being in the tropical landscapes of Borneo. We use extensive social surveys from nearly 500 villages throughout Kalimantan (Indonesian Borneo) that asked whether forests were important for health, and why. The most frequent answer viewed forests as important for maintaining cool local temperatures (volunteered by 28% of 4634 respondents). Using boosted regression tree analysis incorporating spatial metrics of deforestation and temperature, we found that villagers were more likely to report this cooling effect if they were from villages with higher or more variable temperatures, and in recently deforested or fragmented landscapes. Our results highlight the role of forests in regulating the local climate. This ecosystem service is highly threatened, and yet increasingly vital for avoiding heat illness and enabling adaptation to global climate change.

1. Introduction

Much has been written about how climate and environmental change are linked to extreme heat events, but these events represent just one pathway by which people can experience or be at risk of heat illness. An important yet underexplored area is how such changes operate at local scales and how they affect incidence and risk of heat illness via less extreme events. For instance, rural communities may be exposed to higher temperatures due to deforestation. Forests can remain much cooler than deforested landscapes due to shade and the role of evaporation and transpiration in reducing sensible heat (Bright et al., 2017; Ellison et al., 2017). Loss of shade alone can increase the heat index, the temperature one feels when air temperature and humidity are combined, by over 9 °C (NOAA, 2017). While these impacts may fall below the threshold of an extreme heat event, small increases in heat index may lead to subtle, indirect effects on health and well-being. For example, people will self-manage the amount of time they are exposed to heat, known as autonomous adaptation, such that the largest negative impacts may be economic costs associated with decreased productivity (Malik et al., 2010). Productivity loss may also occur from both cognitive and physical impairment, as heat exposure has been found to decrease working memory and executive function (McMorris et al., 2006), increase error in tasks (Froom et al., 1993), and increase fatigue (Gaoua et al., 2011). Temperature increases often also affect crop yields directly (Schlenker and Lobell, 2010; Schlenker and Roberts, 2009), with consequences for food security and human health. Despite the significant potential impacts of increasing temperatures from deforestation and climate change, we know very little about whether communities in and around forests are losing critical cooling services from forests, and whether they believe their health and well-being is being impacted by these changes.

To date, most research on climate change and the impact of increasing temperatures on communities has focused on the effects of extreme heat events on vulnerable populations. This body of work has found extreme heat events impact virtually every country in the world, with recent increases in frequency, severity and duration due to

---

* Corresponding author.
E-mail address: Nicholas.wolff@tnc.org (N.H. Wolff).

https://doi.org/10.1016/j.gloenvcha.2018.07.004
Received 5 December 2017; Received in revised form 5 July 2018; Accepted 8 July 2018

anthropogenic forcing (Hansen et al., 2012; Mora et al., 2017; Zwiers et al., 2010). Since the 1960s the annual global land area impacted by extreme hot summers has increased by nearly two orders of magnitude, from ~0.1% to 10% (Hansen et al., 2012). It is well established that these climate temperature signals are exacerbated by urbanization, agricultural expansion and deforestation (Kalnay and Cai, 2003), and tree planting has become an important strategy for mitigating heat island effects in many of the world's cities and towns (Bowler et al., 2010; Luber and McGeehin, 2008). While the effects of extreme heat events are global, studies quantifying their human consequences have focused on developed, higher-latitude countries primarily due to health data availability (Kjellstrom et al., 2009a; Zivin and Shrader, 2016). These results highlight the significance of heat illness, for example, in the US and Australia, where extreme heat events are now responsible for more deaths annually than all other natural hazards combined (Coates et al., 2014; Luber and McGeehin, 2008). The human impacts in less developed, low-latitude, countries may be much greater (Kjellstrom et al., 2009a), and projections suggest this discrepancy will grow even more severe (Mueller et al., 2016). Low-latitude regions are projected to experience more frequent heat extremes, and sooner, than mid-to-high latitude regions due to latitudinal differences in natural temperature variability (Harrington et al., 2016) and because current climatic conditions in many low-latitude regions already approach human thermoregulatory thresholds (Mora et al., 2017). This difference in exposure to extreme heat events between wealthy and poor regions will likely be amplified by differences in adaptive capacity (e.g. diversity of employment options, access to electricity and social services) and sensitivity (e.g. compromised health due to exposure to disease), possibly resulting in an even larger disparity in vulnerability (St. Louis and Hess, 2008; Whitmee et al., 2015) than differences in exposure alone would predict.

The effects of increasing temperatures are not limited to human health. Recent estimates suggest increased heat-related illness over the last few decades has already reduced current global labor capacity to 90%, with projected declines to 80% by 2050 (Dunne et al., 2013). These projected impacts are spatially variable (Heal and Park, 2016), with hot and humid low-latitude locations predicted to reach temperature thresholds that severely affect labor capacity decades earlier than higher latitudes. Some climate change research suggests the alarming possibility that lower latitude areas may eventually become functionally uninhabitable due to physiological limits of human adaptability to projected heat stress (Mora et al., 2017; Sherwood and Huber, 2010). Over shorter time frames, hot and humid locations such as Southeast Asia, Central America and the Caribbean could see labor capacity reduced by 11–27% due to climate change-driven increases in heat stress (Kjellstrom et al., 2009b).

The existing body of work on extreme heat events that focuses mainly on wealthier, higher-latitude countries underscores the difficulty of studying the more nuanced effects of slowly increasing ambient temperatures on human health and well-being in low-latitude, economically developing countries. These countries tend to be data poor where reliable, continuous data on human health and well-being, local temperatures, and environmental change are scarce (Kjellstrom et al., 2009b). This is especially the case in rural settings where the effects of environmental change may be most acute. Even in wealthier countries, studies have rarely linked how local environmental change, such as deforestation, affect healthy, working populations who are likely the first to experience impacts of these changes. Instead, studies have largely focused on the health impacts on vulnerable populations, or have simulated or inferred impacts of increasing temperatures of healthy populations by examining outcomes such as labor supply and productivity (Hanna et al., 2011; Zander et al., 2015; Zivin and Neidell, 2014) at national or firm-level (Dell et al., 2014; Heal and Park, 2016). In frontier areas where environmental change is driven by land use pressures (e.g. deforestation or population growth), there is little understanding of how the loss of ecosystem services provided by local environments (e.g. cooling services provided by forests (Ellison et al., 2017)) may exacerbate the effects of climate change driven warming and its associated impacts. We fill a critical gap in the literature on environmental change and heat illness risk in a low-latitude country by analyzing data on perceived effects of deforestation on the local thermal environments and its effects on human health and well-being from 500 villages in Kalimantan, Indonesia.

Perception data provide a valid measure for evaluating effects of changes in thermal environments driven by environmental change on human health for several reasons. First, research has demonstrated that perceptions correspond with patterns of observed temperature change from objective measurements (Howe et al., 2013). In regions with a paucity of objective data (e.g. from weather stations), perceptions can provide fine-grained information on local temperature change not otherwise available (Reyes-García et al., 2016). Critically, perceptions often go beyond changes in climate, offering nuanced insight into how these changes impact physical, biological and socioeconomic systems (Hartter et al., 2012; Petheram et al., 2010; Reyes-García et al., 2016; Sánchez-Cortés and Chavero, 2011). Therefore, perception data have a rich history of being used to evaluate risks and changes in human well-being, the environment, and other topics (Bennett, 2016; Jabeen and Johnson, 2013; Meijaard et al., 2013; Renn and Graham, 2005). Perception data also play a critical role in evaluating thermal comfort and environmental conditions and their associated risks on occupational health. Thus, perception data are recognized by the International Organization for Standardization (ISO) which helps set international voluntary standards on occupational health parameters. Indeed, ISO 7730 sets standards around measuring and evaluating thermal comfort, and ISO 10551 discusses the validity of subjective judgements of thermal environments. An important first step for evaluating risk of heat illness driven by local environmental change is to measure perceived changes and risks (Balakrishnan et al., 2010; Jabeen and Johnson, 2013).

Quantitative evidence of health impacts from non-extreme heat events is still sparse. However, recent interview surveys in Kalimantan revealed widespread perceptions that temperature regulation by forests is important for human health (Meijaard et al., 2013). Here, we build on this analysis by examining the relationship of these responses with temperature and land-use patterns, as well as rates of deforestation. Our aim is to determine whether local environmental and landscape characteristics drive perceptions of temperature regulation services from intact forests. We believe quantifying relationships between environmental change and perceived risk is important for understanding the level of heat illness risk a community faces, and the drivers of work patterns, heat exposure, and other adaptation strategies. Borneo is at the epicenter of global deforestation and a region particularly vulnerable to climate change impacts (Struebig et al., 2015; Verbesselt et al., 2016). Our expansive dataset on local perceptions of ecosystem services provides a unique opportunity to explore the intersection of environmental change and human well-being and health. We place these results in the context of projected warming trends for Borneo, highlighting the potential of healthy forests for mitigating heat illness.

2. Methods

This study was motivated by the results of Abram et al. (2014) which presented a descriptive analysis of land use change and ecosystem services among forest communities throughout Borneo. Specifically, we were intrigued by the authors' finding that 35% of surveyed villagers responded that cooling services were an important health provision of forests and that these perceptions were generally related to land-use change (e.g. deforestation). A logical next step was to unpack the deforestation-related drivers of these perceptions in more detail, as a growing body of work points to cooling services provided by forests (Ellison et al., 2017; McAlpine et al., 2018; Scott et al., 2018). Yet little is known about how land use change – specifically, deforestation – affects people through increasing local temperatures, and whether and how soon local populations are affected by the loss of cooling services provided by forests. Indeed, recent research highlights how people are more resilient to heat than assumed in many projections (Hondula et al., 2015), and various factors such as regular work environments can affect acclimatization to hotter environments (Chow et al., 2016; Nikolopoulou and Steemers, 2003), indicating temporal, land use change, and local climate factors can play a role in whether local populations recognize cooling services provided by forests. Accordingly, village surveys and three spatially explicit environmental datasets were used to explore the drivers of perceptions of the role of forests in temperature regulation across our Borneo study area. We test three hypotheses on the possible relationships between the local environment and villager temperature perceptions:

H1. Local climate. People living in villages with hotter air temperature are more likely to mention temperature regulation by forests as important for their health.

H2. Landscape fragmentation. People in villages that frequently experience different environments (e.g. relative extent of intact forest versus extent of cleared forest) are more likely to mention temperature differences.

H3. Temporal change. People in villages that experienced recent forest loss are more likely to recall the temperature effects of that loss, based on the theory of availability bias (Tversky and Kahneman, 1991). Similarly, people who experienced recent high temperature anomalies are more likely to recall temperature effects.

The local climate hypothesis (H1) was motivated by the recognition that thermal thresholds influence human comfort and physiological response (Djongyang et al., 2010) and the logical conclusion that crossing these thresholds likely affects temperature perceptions. The landscape fragmentation hypothesis (H2) was motivated by recognition that high rates of deforestation in Borneo (Gaveau et al., 2016) are leading to increasing fragmentation of forest (Gaveau et al., 2014), and that these changes are affecting spatial variability of local temperature (McAlpine et al., 2018). Finally, the temporal change hypothesis (H3) was motivated by recognition that people living in areas with rising average temperatures are particularly sensitive to recent temperature change (Howe et al., 2013) and that this sensitivity may fade with time (Tversky and Kahneman, 1991).

2.1. Village surveys

Village surveys provide our primary dependent variable on perceptions of environmental protection from heat. The surveys were conducted between April 2008 and September 2009 throughout Kalimantan, Indonesia. Details of village selection criteria and survey design are described elsewhere (Meijaard et al., 2011a,b). The primary goal of the surveys was to gather information on human-orangutan interaction. Thus, villages were selected within the geographic and elevational (< 500 m) range of the Bornean Orangutan, and were near or within forests in 2008, making these villages strong candidates to identify how changes in forest cover affect everyday life. Survey villages are shown in Fig. 1. Surveys were conducted in Indonesian and responses translated to English.

The original survey collected data from 687 villages and aimed for 7–12 questionnaires per village (Meijaard et al., 2011b). We selected data based on a previous quality assessment (Wells et al., 2016), and then excluded villages that had fewer than seven responses to our focal, open-ended question about the importance of forests for health. This resulted in 477 villages and 4634 responses. Within each village, the survey team first asked the head of the village for someone who may know about local wildlife, and then identified the remaining survey participants via snowball sampling (Goodman, 1961). Following the question, “How important are forests for your and your family’s health?”, an open-ended question asked, “What is the reason for this importance of the forest for health?” Interviewers were instructed not to prompt or provide examples to respondents, so we view these responses as independent across interviews. Open-ended responses were first evaluated on the completeness and quality of responses by a native Indonesian speaker (Meijaard et al., 2013) (see *Supplemental information* (SI) for further details). Our analytic strategy did not involve identifying specific high-level themes from open-ended responses (Saldaña, 2016). Instead, our approach was to quantify the incidence of unprompted cooling services (not the typology of cooling services) from our sample population, thus providing a quantitative measure representing the prominence of forest cooling services for villagers. To do so, we recorded an indicator variable for each respondent if the open-ended response included any incidence of direct temperature regulation. Phrases, or language, about cooling services of forests in open-ended responses include responses such as, “reduces heat from direct sunlight”, “shelter from heat of the sun” and “making the air not hot” (for a list of example phrases identifying cooling services see *SI, Table S3*). Dichotomizing whether a respondent mentioned temperature regulation services ensures we do not overvalue verbose responses. We then pooled responses at the village-level by calculating the percentage of respondents per village who mentioned temperature regulation services (*SI*, *Fig. S2* presents a histogram). Aggregating responses at the village-level allows us to capture the diversity of perceptions on forest services in a village and its surrounding area. Further, this allows us to have a comparable metric across villages.

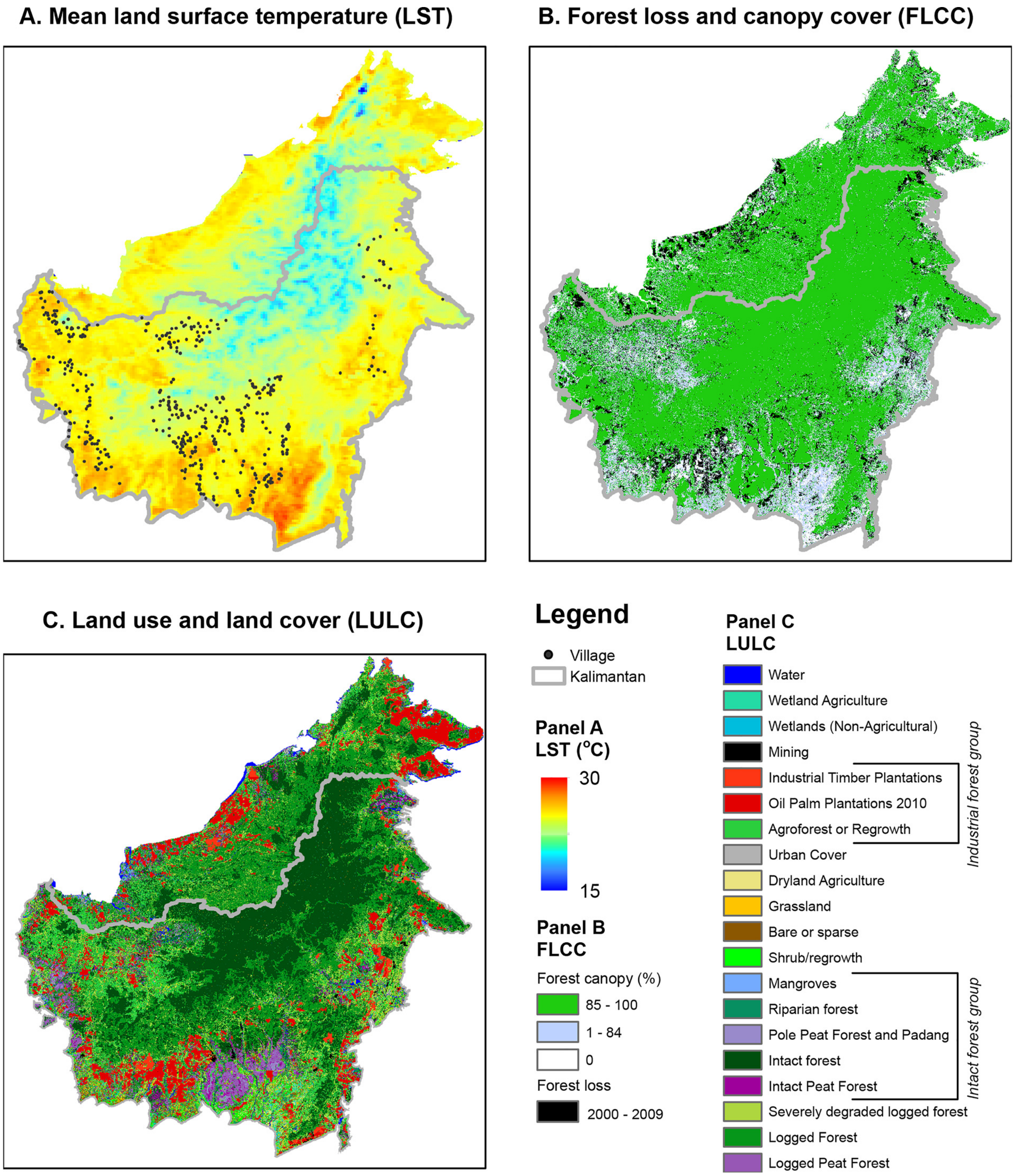
We recognize economic and demographic characteristics of the surveyed villagers likely contributes to variability of responses. For instance, richer villagers may build two-story brick houses that remain cooler than corrugated-iron roofed single-floor houses. However, survey participant selection purposefully targeted the subpopulation that was most acutely aware of forest cover and ecosystem service changes in their villages, making them ideal candidates for the hypotheses we investigate in this study. In the example above, richer villagers would likely be traders who spend little time in forest or in forest gardens, and they would most likely not have been interviewed because they know little about local wildlife. Thus, our respondents are arguably the subpopulation that is most affected by environmental changes, and, we investigated environmental and landscape drivers as potential drivers of variation in perceptions.

2.2. Landscape and environmental drivers of temperature perceptions

We used three datasets to explore potential spatial and temporal drivers of village-level temperature perceptions to test our three hypotheses. We used land surface temperature (LST) to test the importance of local climate (H1) and temporal change (H3); land use and land cover (LULC) to test the importance of landscape fragmentation (H2); and forest loss and canopy cover (FLCC) to test the importance of temporal change (H3). For each dataset, we extracted a suite of predictor variables using a 10 km buffer surrounding each village center. Prior work indicated 10 km is an appropriate scale for capturing Bornean villagers’ perceptions of their surrounding landscape (Meijaard et al., 2013). In total, we calculated 36 separate predictor variables from the three datasets (*SI, Table S5*). An overview of the datasets and the corresponding variables used in the analysis is described below.

To explore the effect of local climate on perceptions (H1), we retrieved monthly LST data from MODIS (daytime L3 0.05deg CMG V005) from https://lpdaac.usgs.gov on May 25, 2016 (Wan et al., 2015), a product that has been extensively validated against in-situ measurements (Coll et al., 2009; Wan, 2008; Wan and Li, 2008). We calculated six variables for each village, including LST mean, maximum, variability and anomaly frequency and magnitude for 2000–2009. To explore whether recent temperature change was an important driver (H3), we also calculated prior year temperature maximum and anomaly.

To explore the role of current landscape characteristics on


A. Mean land surface temperature (LST)

B. Forest loss and canopy cover (FLCC)

C. Land use and land cover (LULC)

Fig. 1. Locations of the 477 focal villages within Kalimantan, Borneo. Also shown are representative predictor variables derived from each of the three data sources.

temperature perceptions (H2), we extracted the proportional cover of 20 different LULC types in a 10 km radius of each village from a recently developed LULC map for Borneo representing conditions during 2009–2010 (Wells et al., 2016), approximately 1 year after the surveys. Full details of the data used to create the 2010 LULC Borneo map are explained in the Supplemental Methods of Wells et al. (2016). Briefly, LULC classification was predominantly based on a 2010 LULC classification (50 m resolution) developed by SarVision from 2010 ALOS PALSAR satellite imagery, using methods refined and validated by Hoekman et al. (2010). Individual variables captured the extent of the different intact forest types (padang, peat and dipterocarp forest), as well as the extent of timber and oil palm plantations, industries that drive much of Borneo's deforestation and fragmentation (Gaveau et al., 2016). In addition, we also estimated two aggregate LULC variables, giving the proportion of intact forest (of any kind) and industrial forest (includes industrial timber, oil palm plantations and agro forest). To explicitly examine landscape fragmentation, we calculated Simpson's evenness index (E) per village from the 20 LULC types. In total, 23 LULC variables were extracted.

To explore the effect of the rate of landscape change on temperature perceptions (H3), we extracted four FLCC variables from high resolution (30 m) Landsat-derived estimates of forest loss and forest canopy cover change (Hansen et al., 2013). Accuracy assessments for Hansen et al. (2013) are provided in the associated supplementary materials

Table 1
Performance of Boosted Regression Tree models. Models were developed with five-fold cross-validation, learning rate of 0.005, tree complexity of 5 and using variables summarized in *Table S5* (Base model) or Table 2 (Simplified model). For each model, performance with the training data is assessed via the correlation between observed and predicted values (training correlation, Pearson's *r*), and via the percentage of total variance accounted for by the model (% reduction in deviance). Cross-validation performance is assessed by the correlation across folds (CV correlation).

	Base model	Simplified model
No. villages	477	477
No. trees	1950	2200
No. predictors	35	6
Model performance		
training correlation	0.87	0.80
% total variance	69	60
CV correlation	0.43	0.43

and in Margono et al. (2014) for Indonesia and Griscom et al. (2016) for Kalimantan. Variables included absolute (km^2) and relative (proportion) loss of high canopy cover forest ($> = 85\%$ canopy cover) from 2000 to 2009 and over a more recent time frame (2005–2009). In addition to these four 'rate of loss' variables, we extracted three variables that captured canopy cover, based on criteria described in the supplementary materials of Hansen et al. (2013), during the 2009 surveys: proportion of each village with no forest (0% cover or treeless); sparse to medium cover forest (1–84%); and high cover forest ($> = 85\%$). These variables were included to augment the LULC variables and provided an alternative means for exploring the role of fragmentation (H2) in driving temperature perceptions. Importantly, canopy cover, unlike the LULC variables, captured the actual status of forest cover at the time of the surveys and doesn't necessarily distinguish between the types of trees providing the cover (e.g. secondary, primary or plantation).

We determined whether each of our three hypotheses was supported by the data, by examining features of the relationships between predictor variables and the response (*SI, Fig. S4*).

2.3. Empirical strategy

Our analyses aimed to assess support for our hypotheses regarding relationships between the local environment and villager perceptions of temperature regulation, by estimating the predictive contributions of each environmental variable, along with functional forms of their relationships with the village-level responses (% of respondents). We use Boosted Regression Tree (BRT) analysis as a robust method ideally suited to exploration of these potentially complex relationships. BRT generates an ensemble model from many regression trees (thousands), providing a robust method for quantifying relationships, predictor contributions and interactions. It has the advantage of handling nonlinear relationships and predictor correlations (Elith et al., 2008). BRT models were developed and evaluated using five-fold cross validation with the gbm (gradient boosting) functions from the 'dismo' package (Hijmans et al., 2016) in the R statistical environment (Elith et al., 2008; R Core Team, 2016). In all cases, our response is the % of villagers in each village who perceived temperature regulation by forests as important, and the predictors are the 36 variables relating to climate and landscape context, above. During fitting, predictive performance was assessed using 5-fold cross-validation (progressively testing the developing model's predictions against withheld data). Finally, model performance was assessed using the correlation between predicted and observed responses, and the total variance accounted by the model (the predictive deviance as a percentage of the null deviance). For full details of analyses, see *SI*.

3. Results

3.1. Villagers perceptions of forests role in temperature regulation

Of the 4,634 villagers from 477 villages who answered the open-ended question, the most frequent answer (expressed independently by 28% of respondents) was that forests kept the environment cool (*SI, Table S1*). See *SI, Tables S1-S3,* and prior publications (Abram et al., 2014; Meijaard et al., 2013; Wells et al., 2016) for evaluations of other reported health benefits of forests.

Looking at aggregated village-level responses, over 86% of the villages (n = 411) had at least one villager note the importance of temperature regulation services, and in over 31% of the villages at least 4 villagers (~40% of respondents) noted the importance of this ecosystem service. In 20 villages, 70% or more of respondents mentioned the role of forests in maintaining cool temperatures (*SI, Fig. S1*). Since the responses were unprompted (reasons were volunteered independently by each respondent), this gives strong evidence for the widespread perception of forests as important for temperature regulation. Other respondents may or may not have agreed with this perception – i.e. they may hold this view, but did not mention it in their open responses (implying either lower importance, or simply a focus on other reasons).

3.2. Relationships between temperature perceptions and landscape variables

Study villages are distributed throughout Kalimantan, with higher numbers in the south and southwest regions. Villages encompassed a wide range of climate and forest conditions (Fig. 1; *SI, Table S6*. For example, mean annual temperature ranged from 22.5 °C in the cooler highlands to 27.2 °C in the warmer lowlands, and the proportion of village landscapes covered by intact forest varied substantially, ranging from 1 to 97%. Histograms for key predictor variables are shown in the supplemental information (*SI, Fig. S3*).

BRT models performed very well in explaining variation in respondents' temperature perceptions among villages (87% correlation coefficient, 69% of total variance accounted by the model, Table 1). Nearly all the predictors (35/36) were retained in the final BRT model which gave the strongest predictive performance. However, 23 predictors individually contributed < 3% to the model's explained variance (SI, Table S5, Fig. S6).

The six predictors in the simplified model consisted of two variables from each of the three data classes, LST, LULC and FLCC (Table 2). The six variables each had similar contributions to the model's explained variance, ranging from 18.5% of explained variance attributed to the proportion of village area with logged forest, to 14.4% attributed to mean air temperature (Table 2). Together, the 2 LULC variables (proportion of each village landscape classified as logged forest or industrial forest, respectively) accounted for 35.7% of the model's explained variance (21% of total dataset variance), and the 2 FLCC variables (the proportion of villages with open (treeless) or sparse-to-medium canopy cover) accounted for 33.4% of the explained variance. Therefore, 69% of the variance explained by the model (or 41% of total dataset variance) related to metrics of forest conversion or degradation. Finally, the 2 LST variables (the mean and standard deviation of 2000–2009 mean air temperature) accounted for 30.9% of the explained variance. These results give support to the local climate (H1) and landscape fragmentation (H2) hypotheses. The simplified model did not include the variables most directly related to the temporal change (H3) hypothesis (i.e. more recent loss of high canopy cover, and recent temperature extremes). However, examination of individual relationships between the response and predictors indicate some support for all three hypotheses.

Relationships between temperature perceptions and either forest condition or land use are much more complex than the relationships between temperature perceptions and objective temperature measures

Table 2
The six predictor variables in the simplified model, and their relative influence. Also shown is the hypothesis each variable was intended to test: local climate (H1), landscape fragmentation (H2) and temporal change (H3). The full set of variables is given in *SI, Table S5*. ‘Village Proportion’ refers to the proportion of the land area within a 10 km radius of the village.

Variable	Units	Hypothesis	Explained variance (%)
LST (Land surface temperature)			
Standard deviation of annual maximum (2000–2009)	°C	H1	16.5
Mean of annual maximum (2000–2009)	°C	H1	14.4
FLCC (Forest loss and canopy cover)			
Open (0%) canopy cover (2009)	Village proportion	H2, H3	17.6
Sparse – medium (1–84%) canopy cover (2009)	Village proportion	H2, H3	15.9
LULC (Land use and land cover)			
Logged forest	Village proportion	H2, H3	18.5
Industrial forest group (oil palm, industrial timber, agro forest)	Village proportion	H2, H3	17.2

(Fig. 2). Nonetheless, the shapes of these relationships offered some support for our three hypotheses (*SI, Fig. S4*).

Local climate and landscape drivers also interacted in their influences on villagers’ perceptions of temperature regulation by forests. Mean air temperature and temperature variability both demonstrated strong interactions with canopy cover variables (Fig. 3). Thus, villages with higher air temperatures showed a steeper relationship between temperature perceptions (% of respondents) and the proportion of sparse-to-medium canopy cover (Fig. 3A). Villages with higher air temperature variability showed a more marked response to the proportion of open canopy cover (Fig. 3B). This indicates that people in villages with higher or more variable air temperatures are more likely to perceive temperature effects of forests, than would be expected from the additive effects of temperature and canopy cover.

4. Discussion

Perceptions that forests are important for human health because of their regulation of temperatures are frequent and widespread in Kalimantan. It is both compelling and troubling that almost a third of 4634 villagers from 477 villages independently expressed the view that forests were important for regulating temperature (maintaining cool temperatures or preventing extremes), and those who live in hotter or more fragmented or degraded landscapes appear more likely to recognize forest benefits. Our concern is that these perceptions accurately reflect the impact of recent and dramatic deforestation, and other landscape changes, occurring across Borneo. The results presented here may be indicative of widespread, underlying heat-related health issues that could balloon into a serious public health threat as global temperatures rise and forest clearing continues in the coming decades.

The results support each of our three original hypotheses on how local environments influence perception of temperature regulation by

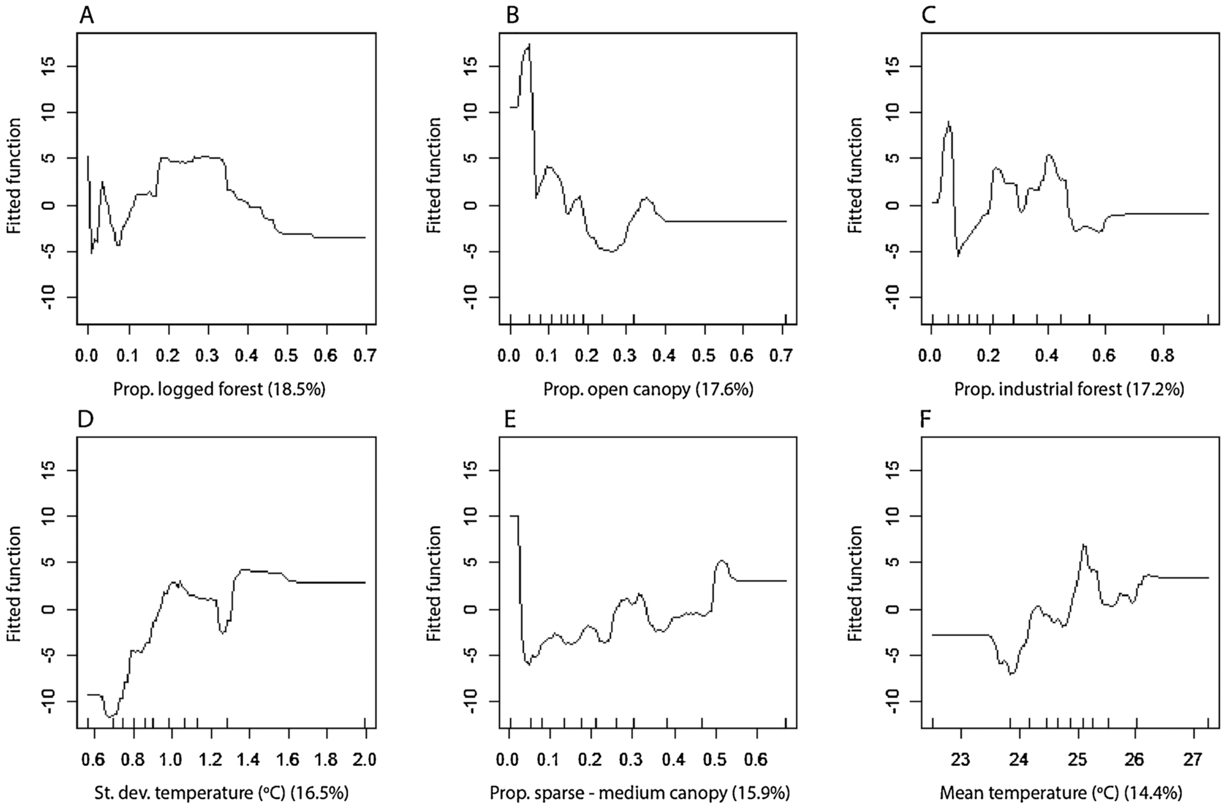


Fig. 2. Fitted relationships from the simplified BRT model for each of the six climate and landscape predictor variables (x axis) and the temperature perception response variable (y axis). Plots are sorted by contribution of each predictor (%) to the model’s explained variance. X axis units for landscape variables give the proportion of village area (within a 10 km radius), and for temperature variables, give the standard deviation and mean of the local air temperature (°C). Y axis shows the magnitude of change in the predicted value, relative to the mean prediction (zero) when controlling for the mean effect of all other variables in the model. Variables are explained in Table 2. Note that the fitted function integrates information from all regression trees in the ensemble. We have shown the fitted functions without smoothing, so that their fine-scale irregularities illustrate their stochastic variation, rather than implying extreme precision. (Fitted functions are highly robust across bootstrapped samples, reflecting the strengths of the method’s stochastic gradient boosting and cross-validation). See Table 2 for model performance metrics.

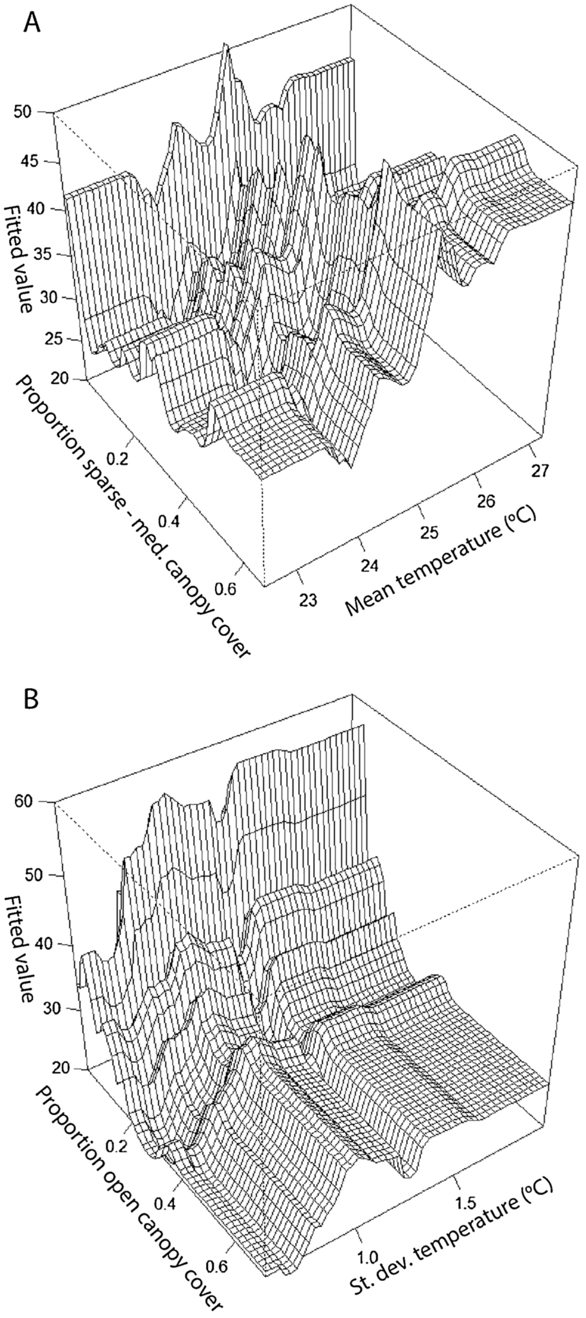


Fig. 3. Three-dimensional plot of pairwise interactions between temperature and landscape variables from simplified model. The Y axis (Fitted value) shows the predicted response (% of villagers who stated that forests are important for temperature regulation). A) Mean air temperature and proportion of village area with sparse to medium tree canopy cover; B) Air temperature variability and proportion of village area with open canopy cover.

forests (local temperature, landscape fragmentation, and temporal change). Responses were most clearly related to local temperature, with the highest percentage of responses in those villages that experience the highest and most variable temperatures. Further, temperature interacted with canopy cover variables such that perceptions of temperature regulation were greatest where higher or more variable temperatures combined with fragmented (higher proportion of sparse-to-medium cover) or open canopy forests. These interactions make intuitive sense, implying that villagers in relatively hotter locations are more likely to notice the cooling effects of high canopy cover forests, particularly when the landscape is fragmented. It is well established that trees and forests in tropical environments can cool the local and regional environment (Bonan, 2008; Bright et al., 2017): shade reduces solar radiation on the ground, and individual trees can also transpire hundreds of liters of water a day representing a cooling power equivalent to two average household central air-conditioning units per day (Ellison et al., 2017). Interestingly, evidence of cooling from temperate and boreal forests is less clear than for tropical forests due to the more complicated role of albedo in these higher latitude landscapes (Bonan, 2008, 2016; Kirschbaum et al., 2011; Zeng et al., 2017).

Results suggest perceptions of temperature impacts were highest in villages with low levels of converted, logged and open to medium canopy cover forests. This is consistent with the theory of availability bias (Tversky and Kahneman, 1991) which essentially posits that people can more readily recall the effect of a recent loss or change. In other words, villagers may be particularly sensitive to the temperature effect of forests during the early stages of degradation, when the canopy first starts to open (and thus more solar radiation and heat reaches the ground) and they can still easily remember how much cooler it was in intact forests.

The possibility of an availability bias affecting perceptions of temperature regulation by forest has serious implications. This human perception bias is analogous to the well documented and widespread shifting baseline syndrome (Pauly, 1995) which hinders stakeholder awareness of dwindling natural resources and thus, engagement with conservation solutions to this depletion (Clavero, 2014; Papworth et al., 2009). The danger for Borneo and other tropical forest regions is that 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. We recognize, however, the evidence supporting an availability bias is indicative, and further research is needed, particularly studies that document perception changes of a cohort through time.

More certain is our overall evidence that rural communities in Kalimantan associate the loss of forest cover with hotter temperatures. We think this is significant and indicative of an increasing risk of heat illness for those working in and around forests. The perception of a connection between forests and temperature regulation is a form of traditional or local knowledge. It is widely recognized that traditional knowledge holds detailed information on current and past environments and the dynamics that shape it (Agrawal, 1995; Barthel et al., 2010; Houde, 2007; Reyes-García et al., 2016). Improving environmental management by combining insights from traditional knowledge and western science is a priority for many governments, non-government organizations, and indigenous and local peoples (ICSU, 2002; Mistry and Berardi, 2016). Our study links local knowledge with biophysical models in order to test hypotheses about how environmental changes drives perceptions. This approach allowed us to utilize an important data set linked intimately to lived experience and traditional knowledge, and place these very local observations in the context of larger trends across the tropics. Significantly, the temperature effects we identify (along with associated health and socioeconomic risks), are likely to apply broadly wherever tropical rural communities and deforestation intersect – virtually all global tropical rainforest ecosystems including Southeast Asia, Equatorial Africa and the Amazon (Hansen et al., 2013). High rates of deforestation in many regions (Hansen et al., 2013) combined with increasing likelihood of at least 1.5 °C of warming in the coming decades (Walsh et al., 2017), underscore potential heat-related health risks throughout the tropics. The social consequences for some of the world's poorest, most vulnerable communities could be significant, driven by both direct health effects of heat illness (Whitmee et al., 2015), and through indirect disruption of economic opportunity (Malik et al., 2010).

To date, the role of forests in ameliorating local temperatures has been poorly understood in rural tropical landscapes (Bowler et al., 2010). A recent analysis comparing nine large watersheds across Borneo found watersheds with more intact forests had cooler, more stable temperatures (McAlpine et al., 2018). One of the few studies documenting this cooling effect at local scales found that primary and secondary forests in Sumatra were > 4 °C cooler than nearby young oil palm plantations (Ramdani et al., 2014). To put this in perspective, it suggests the conversion of forest to more open landscapes (possibly over a single season), has the same temperature effect as nearly a century of warming under high emissions scenarios (Rogelj et al., 2012). Clearly, the potential role for tropical forests in helping rural communities adapt to climate change needs further investigation (Ellison et al., 2017; Pramova et al., 2012).

Finally, our results point towards an opportunity to strengthen the case for forest conservation. To date, arguments for conserving tropical forests based on urgent biodiversity threats or mitigation of carbon emissions have failed to halt deforestation trends; the economic forces driving deforestation are more powerful than the perceived risks, consequences and costs of these actions (e.g. degraded habitats, future climate change) (Whitmee et al., 2015). Indeed, this disconnect between economic gains today versus costs tomorrow (or falling on other parts of society), has been nearly impossible to bridge. Yet, the connection between forest health and human health offers an additional, perhaps more locally resonant and more immediately relevant argument for avoiding forest loss. Thorough quantification of the temperature effects of deforestation on human health, and the subsequent social and public health costs of heat related illness will add significantly to the carbon, biodiversity and other ecosystem service costs that are already considered, to some extent, in policies around forest conversion. We see the potential that broad realization of the magnitude of local temperature impacts could shift cost-benefit assessments in favor of retaining more intact forests. It is also possible, that some temperature related impacts could be minimized through careful spatial planning of future forest clearing. Reforestation may enable reversal of local heat impacts associated with the loss of forests, but the extent of possible reversal is unclear. We therefore highlight the need to investigate links between landscape reforestation approaches and temperature amelioration, in light of the potential pan-tropical scale of deforestation and heat related health impacts, and the substantial global commitments made to reforestation, particularly linked to climate change mitigation.

Acknowledgements

We thank the Directorate of Forest Protection and Nature Conservation of the Indonesian Ministry of Environment and Forestry for supporting our study, and the Association of Indonesian Primatologists (FORINA) for coordinating the interview studies. We are most grateful to our many respondents throughout Kalimantan for sharing their perceptions of their environment and well-being, and thank the Adopt-an-Acre program for funding the interview surveys. We thank Roy Vagelos for his support of NHW.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.07.004.

References

Abram, N.K., Meijaard, E., Ancrenaz, M., Runting, R.K., Wells, J.A., Gaveau, D., Pellier, A.-S., Mengersen, K., 2014. Spatially explicit perceptions of ecosystem services and land cover change in forested regions of Borneo. Ecosyst. Serv. 7, 116–127.

Agrawal, A., 1995. Dismantling the divide between indigenous and scientific knowledge. Dev. Change 26, 413–439.

Balakrishnan, K., Ramalingam, A., Dasu, V., Stephen, J.C., Sivaperumal, M.R., Kumarasamy, D., Mukhopadhyay, K., Ghosh, S., Sambandam, S., 2010. Case studies on heat stress related perceptions in different industrial sectors in southern India. Glob. Health Action 3.

Barthel, S., Folke, C., Colding, J., 2010. Social–ecological memory in urban gardens—retaining the capacity for management of ecosystem services. Glob. Environ. Change 20, 255–265.

Bennett, N.J., 2016. Using perceptions as evidence to improve conservation and environmental management. Conserv. Biol. 30, 582–592.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science (80-) 320, 1444–1449.

Bonan, G.B., 2016. Forests, climate, and public policy: a 500-year interdisciplinary odyssey. Annu. Rev. Ecol. Evol. Syst. 47, 97–121.

Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc. Urban Plann. 97, 147–155.

Bright, R.M., Davin, E., O'Halloran, T., Pongratz, J., Zhao, K., Cescatti, A., 2017. Local temperature response to land cover and management change driven by non-radiative processes. Nat. Clim. Change 7, 296–302.

Chow, W.T.L., Akbar, S.N.A.B.A., Heng, S.L., Roth, M., 2016. Assessment of measured and perceived microclimates within a tropical urban forest. Urban For. Urban Green. 16, 62–75.

Clavero, M., 2014. Shifting baselines and the conservation of non-native species. Conserv. Biol. 28, 1434–1436.

Coates, L., Haynes, K., O'Brien, J., McAneney, J., de Oliveira, F.D., 2014. Exploring 167 years of vulnerability: an examination of extreme heat events in Australia 1844–2010. Environ. Sci. Policy 42, 33–44.

Coll, C., Wan, Z., Galve, J.M., 2009. Temperature-based and radiance-based validations of the V5 MODIS land surface temperature product. J. Geophys. Res. Atmos. 114.

Dell, M., Jones, B.F., Olken, B.A., 2014. What do we learn from the weather? The new climate-economy literature. J. Econ. Lit. 52, 740–798.

Djongyang, N., Tchinda, R., Njomo, D., 2010. Thermal comfort: a review paper. Renew. Sustain. Energy Rev. 14, 2626–2640.

Dunne, J.P., Stouffer, R.J., John, J.G., 2013. Reductions in labour capacity from heat stress under climate warming. Nat. Clim. Change 3, 563–566.

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77, 802–813.

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M.v., Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: cool insights for a hot world. Glob. Environ. Change 43, 51–61.

Froom, P., Caine, Y., Shochat, I., Ribak, J., 1993. Heat-stress and helicopter errors. J. Occup. Environ. Med. 35, 720–724.

Gaoua, N., Racinais, S., Grantham, J., El Massioui, F., 2011. Alterations in cognitive performance during passive hyperthermia are task dependent. Int. J. Hyperthermia 27, 1–9.

Gaveau, D.L.A., Sloan, S., Molidena, E., Yaen, H., Sheil, D., Abram, N.K., Ancrenaz, M., Nasi, R., Quinones, M., Wielaard, N., Meijaard, E., 2014. Four decades of forest persistence, clearance and logging on Borneo. PLoS One 9, e101654.

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P., Meijaard, E., 2016. Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. Sci. Rep. 6, 32017.

Goodman, L.A., 1961. Snowball sampling. Ann. Math. Stat. 32, 148–170.

Griscom, B.W., Ellis, P.W., Baccini, A., Marthinus, D., Evans, J.S., Ruslandi, 2016. Synthesizing global and local datasets to estimate jurisdictional forest carbon fluxes in Berau, Indonesia. PLoS One 11, e0146357.

Hanna, E.G., Kjellstrom, T., Bennett, C., Dear, K., 2011. Climate change and rising heat: population health implications for working people in Australia. Asia. Pac. J. Public Health 23, 14S–26.

Hansen, J., Sato, M., Ruedy, R., 2012. Perception of climate change. Proc. Natl. Acad. Sci. 109, E2415–E2423.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science (80-) 342, 850–853.

Harrington, L.J., Frame, D.J., Fischer, E.M., Hawkins, E., Joshi, M., Jones, C.D., 2016. Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. Environ. Res. Lett. 11, 055007.

Hartter, J., Stampone, M.D., Ryan, S.J., Kirner, K., Chapman, C.A., Goldman, A., 2012. Patterns and perceptions of climate change in a biodiversity conservation hotspot. PLoS One 7, e32408.

Heal, G., Park, J., 2016. Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature. Rev. Environ. Econ. Policy 10, 347–362.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2016. Dismo: species distribution modeling. RAN - Comprehensive R Archive Network.

Hoekman, D.H., Vissers, M.A.M., Wielaard, N., 2010. PALSAR wide-area mapping of Borneo: methodology and map validation. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 3, 605–617.

Hondula, D.M., Balling, R.C., Vanos, J.K., Georgescu, M., 2015. Rising temperatures, human health, and the role of adaptation. Curr. Clim. Change Rep. 1, 144–154.

Houde, N., 2007. The six faces of traditional ecological knowledge: challenges and opportunities for canadian co-management arrangements. Ecol. Soc. 12 (2), 34. http://www.ecologyandsociety.org/vol12/iss2/art34/.

Howe, P.D., Markowitz, E.M., Lee, T.M., Ko, C.-Y., Leiserowitz, A., 2013. Global perceptions of local temperature change. Nat. Clim. Change 3, 352–356.

ICSU, 2002. ICSU Series on Science for Sustainable Development No. 4: Science. Traditional Knowledge and Sustainable Development. UNESCO p. 24.

Jabeen, H., Johnson, C., 2013. Perceptions of climate variability and coping strategies in informal settlements in Dhaka, Bangladesh. In: Joffe, H., Rossetto, T., Adams, J. (Eds.), Cities at Risk: Living With Perils in the 21st Century. Springer Netherlands, Dordrecht, pp. 149–170.

Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. Nature 423, 528–531.

Kirschbaum, M.U.F., Whitehead, D., Dean, S.M., Beets, P.N., Shepherd, J.D., Ausseil, A.G.E., 2011. Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. Biogeosciences 8, 3687–3696.

Kjellstrom, T., Holmer, I., Lemke, B., 2009a. Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. Glob. Health Action 2.

Kjellstrom, T., Kovats, R.S., Lloyd, S.J., Holt, T., Tol, R.S.J., 2009b. The direct impact of climate change on regional labor productivity. Arch. Environ. Occup. Health 64, 217–227.

Luber, G., McGeehin, M., 2008. Climate change and extreme heat events. Am. J. Prev. Med. 35, 429–435.

Malik, A., Qin, X., Smith, S.C., 2010. Autonomous Adaptation to Climate Change: A Literature Review. Institute for International Economic Policy Working Paper Series. The George Washington University, Washington, DC p.24.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., Hansen, M.C., 2014. Primary forest cover loss in Indonesia over 2000–2012. Nat. Clim. Change 4, 730–735.

McAlpine, C.A., Johnson, A., Salazar, A., Syktus, J., Wilson, K., Meijaard, E., Leonie, S., Dargusch, P., Nordin, H., Sheil, D., 2018. Forest loss and Borneo's climate. Environ. Res. Lett. 13, 044009.

McMorris, T., Swain, J., Smith, M., Corbett, J., Delves, S., Sale, C., Harris, R.C., Potter, J., 2006. Heat stress, plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine and cortisol, mood state and cognitive performance. Int. J. Psychophysiol. 61, 204–215.

Meijaard, E., Buchori, D., Hadiprakarsa, Y., Utami-Atmoko, S.S., Nurcahyo, A., Tjiu, A., Prasetyo, D., Nardiyono, Christie L., Ancrenaz, M., Abadi, F., Antoni, I.N.G., Armayadi, D., Dinato, A., Ella, Gumelar P., Indrawan, T.P., Kussaritano Munajat, C., Priyono, C.W.P., Purwanto, Y., Puspitasari, D., Putra, M.S.W., Rahmat, A., Ramadani, H., Sammy, J., Siswanto, D., Syamsuri, M., Andayani, N., Wu, H., Wells, J.A., Mengersen, K., 2011a. Quantifying killing of orangutans and human-orangutan conflict in Kalimantan, Indonesia. PLoS One 6, e27491.

Meijaard, E., Mengersen, K., Buchori, D., Nurcahyo, A., Ancrenaz, M., Wich, S., Atmoko, S.S.U., Tjiu, A., Prasetyo, D., Nardiyono, Hadiprakarsa, Y., Christy, L., Wells, J., Albar, G., Marshall, A.J., 2011b. Why don't we ask? A complementary method for assessing the status of great apes. PLoS One 6, e18008.

Meijaard, E., Abram, N.K., Wells, J.A., Pellier, A.-S., Ancrenaz, M., Gaveau, D.L.A., Runting, R.K., Mengersen, K., 2013. People's perceptions about the importance of forests on Borneo. PLoS One 8, e73008.

Mistry, J., Berardi, A., 2016. Bridging indigenous and scientific knowledge. Science 352 (6291), 1274–1275.

Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R., Counsell, C.W.W., Dietrich, B.S., Johnston, E.T., Louis, L.V., Lucas, M.P., McKenzie, M.M., Shea, A.G., Tseng, H., Giambelluca, T.W., Leon, L.R., Hawkins, E., Trauernicht, C., 2017. Global risk of deadly heat. Nat. Clim. Change 7, 501–506.

Mueller, B., Zhang, X., Zwiers, F.W., 2016. Historically hottest summers projected to be the norm for more than half of the world's population within 20 years. Environ. Res. Lett. 11, 044011.

Nikolopoulou, M., Steemers, K., 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy Build. 35, 95–101.

NOAA, 2017. National Oceanic and Atmospheric Administration. http://www.srh.noaa.gov/ama/?n=heatindex.

Papworth, Sk., Rist, J., Coad, L., Milner-Gulland, Ej., 2009. Evidence for shifting baseline syndrome in conservation. Conserv. Lett. 2, 93–100.

Pauly, D., 1995. Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol. Evol. (Amst.) 10, 430.

Pellier, A.-S., Wells, J.A., Abram, N.K., Gaveau, D., Meijaard, E., 2014. Through the eyes of children: perceptions of environmental change in tropical forests. PLoS One 9, e103005.

Petheram, L., Zander, K.K., Campbell, B.M., High, C., Stacey, N., 2010. 'Strange changes': indigenous perspectives of climate change and adaptation in NE Arnhem Land (Australia). Glob. Environ. Change 20, 681–692.

Pramova, E., Locatelli, B., Djoudi, H., Somorin, O.A., 2012. Forests and trees for social adaptation to climate variability and change. Wiley Interdiscip. Rev. Clim. Change 3, 581–596.

R Core Team, 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramdani, F., Moffiet, T., Hino, M., 2014. Local surface temperature change due to expansion of oil palm plantation in Indonesia. Clim. Change 123, 189–200.

Renn, O., Graham, P., 2005. Risk Governance: Towards an Integrative Approach. White Paper No. 1, Written by Ortwin Renn With an Annex by Peter Graham. International Risk Governance Council, Geneva, Switzerland p. 157.

Reyes-García, V., Fernández-Llamazares, Á., Guèze, M., Garcés, A., Mallo, M., Vila-Gómez, M., Vilaseca, M., 2016. Local indicators of climate change: the potential contribution of local knowledge to climate research. Wiley Interdiscip. Rev. Clim. Change 7, 109–124.

Rogelj, J., Meinshausen, M., Knutti, R., 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nat. Clim. Change 2, 248–253.

Saldaña, J., 2016. The Coding Manual for Qualitative Researchers, third edition. SAGE, Los Angeles.

Sánchez-Cortés, M.S., Chavero, E.L., 2011. Indigenous perception of changes in climate variability and its relationship with agriculture in a Zoque community of Chiapas, Mexico. Clim. Change 107, 363–389.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010.

Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc. Natl. Acad. Sci. 106, 15594–15598.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Äijälä, M., Artaxo, P., Carslaw, K.S., Chipperfield, M.P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T., Reddington, C.L.S., Rizzo, L.V., Swietlicki, E., Vignati, E., Wilson, C., 2018. Impact on short-lived climate forcers increases projected warming due to deforestation. Nat. Commun. 9, 157.

Sherwood, S.C., Huber, M., 2010. An adaptability limit to climate change due to heat stress. Proc. Natl. Acad. Sci. 107, 9552–9555.

St. Louis, M.E., Hess, J.J., 2008. Climate change: impacts on and implications for global health. Am. J. Prev. Med. 35, 527–538.

Struebig, Matthew J., Wilting, A., Gaveau, D.L.A., Meijaard, E., Smith, Robert J., Abdullah, T., Abram, N., Alfred, R., Ancrenaz, M., Augeri, Dave M., Belant, Jerrold L., Bernard, H., Bezuijen, M., Boonman, A., Boonratana, R., Boorsma, T., Breitenmoser-Würsten, C., Brodie, J., Cheyne, Susan M., Devens, C., Duckworth, J.W., Duplaix, N., Eaton, J., Francis, C., Fredriksson, G., Giordano, Anthony J., Gonner, C., Hall, J., Harrison, Mark E., Hearn, Andrew J., Heckmann, I., Heydon, M., Hofer, H., Hon, J., Husson, S., Khan, Anwarali, Faisal, A., Kingston, T., Kreb, D., Lammertink, M., Lane, D., Lasmana, F., Liat, Lim B., Lim, Norman, T.-L., Lindenborn, J., Loken, B., Macdonald, David W., Marshall, Andrew J., Maryanto, I., Mathai, J., McShea, William J., Mohamed, A., Nakabayashi, M., Nakashima, Y., Niedballa, J., Noerfahmy, S., Persey, S., Peter, A., Pieterse, S., Pilgrim, John D., Pollard, E., Purnama, S., Rafiastanto, A., Reinfelder, V., Reusch, C., Robson, C., Ross, J., Rustam, R., Sadikin, L., Samejima, H., Santosa, E., Sapari, I., Sasaki, H., Scharf, Anne K., Semiadi, G., Shepherd, Chris R., Sykes, R., van Berkel, T., Wells, K., Wielstra, B., Wong, A., Fischer, M., Metcalfe, K., Kramer-Schadt, S., 2015. Targeted conservation to safeguard a biodiversity hotspot from C limate and land-cover change. Curr. Biol. 25, 372–378.

Tversky, A., Kahneman, D., 1991. Loss aversion in riskless choice: a reference-dependent model. Q. J. Econ. 106, 1039–1061.

Verbesselt, J., Umlauf, N., Hirota, M., Holmgren, M., Van Nes, E.H., Herold, M., Zeileis, A., Scheffer, M., 2016. Remotely sensed resilience of tropical forests. Nat. Clim. Change 6, 1028–1031.

Walsh, B., Ciais, P., Janssens, I.A., Peñuelas, J., Riahi, K., Rydzak, F., Vuuren, D.Pv., Obersteiner, M., 2017. Pathways for balancing CO2 emissions and sinks. Nat. Commun. 8, 14856.

Wan, Z., 2008. New refinements and validation of the MODIS Land-Surface Temperature/Emissivity products. Remote Sens. Environ. 112, 59–74.

Wan, Z., Li, Z.L., 2008. Radiance-based validation of the V5 MODIS land-surface temperature product. Int. J. Remote Sens. 29, 5373–5395.

Wan, Z., Hook, S., Hulley, G., 2015. In: DAAC, N.E.L. (Ed.), MOD11C3 MODIS/Terra Land Surface Temperature/Emissivity Monthly L3 Global 0.05Deg CMG V006 [Data Set]. NASA EOSDIS LP DAAC.

Wells, J.A., Wilson, K.A., Abram, N.K., Nunn, M., Gaveau, D.L.A., Runting, R.K., Nina, T., Mengersen, K.L., Meijaard, E., 2016. Rising floodwaters: mapping impacts and perceptions of flooding in Indonesian Borneo. Environ. Res. Lett. 11, 064016.

Whitmee, S., Haines, A., Beyrer, C., Boltz, F., de Souza, Capon A.G., Dias, B.F., Ezeh, A., Frumkin, H., Gong, P., Head, P., Horton, R., Mace, G.M., Marten, R., Myers, S.S., Nishtar, S., Osofsky, S.A., Pattanayak, S.K., Pongsiri, M.J., Romanelli, C., Soucat, A., Vega, J., Yach, D., 2015. Safeguarding human health in the Anthropocene epoch: report of the Rockefeller Foundation–Lancet Commission on planetary health. Lancet 386, 1973–2028.

Zander, K.K., Botzen, W.J.W., Oppermann, E., Kjellstrom, T., Garnett, S.T., 2015. Heat stress causes substantial labour productivity loss in Australia. Nat. Clim. Change 5, 647–651.

Zeng, Z., Piao, S., Li, L.Z.X., Zhou, L., Ciais, P., Wang, T., Li, Y., Lian, X., Wood, E.F., Friedlingstein, P., Mao, J., Estes, L.D., Myneni, Ranga B., Peng, S., Shi, X., Seneviratne, S.I., Wang, Y., 2017. Climate mitigation from vegetation biophysical feedbacks during the past three decades. Nat. Clim. Change 7, 432–436.

Zivin, J.G., Neidell, M., 2014. Temperature and the allocation of time: implications for climate change. J. Labor Econ. 32, 1–26.

Zivin, J.G., Shrader, J., 2016. Temperature extremes, health, and human capital. Future Child 26, 31–50.

Zwiers, F.W., Zhang, X., Feng, Y., 2010. Anthropogenic influence on long return period daily temperature extremes at regional scales. J. Clim. 24, 881–892.