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LETTER

Large scale tropical deforestation drives extreme warming

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Abstract

Accelerating deforestation rates in Earth's tropical rainforests have dramatic impacts on local public health, agricultural productivity, and global climate change. We used satellite observations to quantify the local temperature changes in deforested patches of rainforests across the tropics and found local warming larger than that predicted from more than a century of climate change under a worst-case emissions scenario. We show that the most extreme warming is typically found in large patches of deforestation; the combined effects of deforestation and climate change on tropical temperatures present a uniquely difficult challenge to the long term public health, occupational safety, and economic security of tropical populations.

1. Introduction

Since 2000, over 3.5 million square kilometers of global forest cover was lost or degraded, with the most deforestation occurring in tropical rainforests [1, 2]. The IPCC issued a special report in 2019 on climate and land, highlighting the critical connections between tropical rainforests and global cycles of energy, water, and carbon [3]. This report coincided with a surge in wildfires in Brazil, Bolivia, Peru, and Indonesia in 2019 that further elevated public awareness of tropical deforestation as a climate change issue that threatens the largest land-based carbon pools and most biodiverse ecosystems on Earth [4–6]. Despite these extremely important *global* consequences, the *local* warming driven by tropical deforestation has the potential to dramatically impact communities living throughout the tropics on timescales much shorter than global climate change [7–9]. The temperature changes driven by deforestation result from modifications of the surface energy budget associated with changing albedo, soil moisture, and turbulent energy fluxes between the land and atmosphere. In the tropics, the warming signal has been shown to be dominant because of the relative importance of deforestation-induced evapotranspiration changes compared to albedo modifications in the high latitudes that can drive cooling in the annual mean [10].

Tropical deforestation is primarily driven by agricultural expansion. Forest clearing for cattle and timber in Brazil [11] and for timber in Indonesia [12, 13] has occurred for decades. More recently, the rise in tropical oil crop production—mainly soybean and oil palm—represents one of the most significant agricultural developments in history, on par in global scale and growth with the Green Revolution [14]. Rapid growth in tropical oil crop production since the early 1990s has resulted primarily from area expansion—as opposed to yield growth that was characteristic of the Green Revolution—and has been supported by global supply chains and export markets, particularly in Southeast Asia and the Amazon. Industrial-scale soybean production in the Amazon for livestock feed, vegetable oils, and biodiesel markets has led to contiguous land area expansion associated with industry agglomeration in the soy value chain [15]. In Southeast Asia, rapid growth in oil palm production for global vegetable oil, biofuel, and non-food commercial markets engages both large- and small-scale producers; however, the requirement that harvested palm fruits be processed within 48 h to preserve commercial quality has led to large contiguous areas of land clearing around mills [14]. In the Congo, tropical

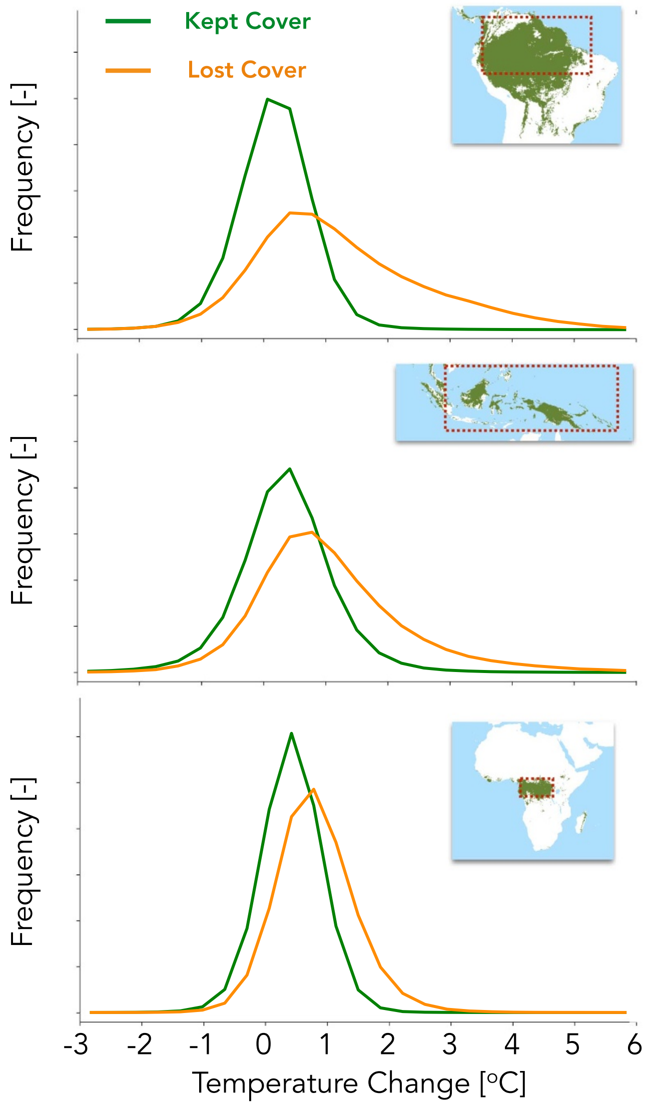

Figure 1. Frequency distributions of the change in annually average daytime temperature between 2018 and 2003 for grid cells that kept their forest cover, and grid cells where deforestation occurred. Insets show the 2003 forest cover in the three study regions designated by the dashed red lines.

deforestation for agricultural commodity production in recent decades has been driven mainly by small- and medium-scale farmers producing oil palm and cocoa [16]. Palm oil remains a staple food crop in the Congo and is not yet dominated by industrial-scale plantations and supply chains. The rise in global demand and trade for agricultural commodities produced in tropical rainforest regions will continue to lead to large-area, contiguous land clearing unless policymakers governing the forests and private companies operating in these regions make forest conservation a high priority.

Tropical deforestation has the potential to present challenges for curbing increases in local warming that will only be exacerbated by a changing climate [17]. Therefore, quantifying the local warming already induced by tropical deforestation is critical for evaluating land use and conservation policies, public health priorities, and prospects for long-term agricultural productivity throughout the tropics. In this study, we evaluate the warming due to tropical deforestation that has occurred within the first two decades of the 21st century and demonstrate that industrial-scale deforestation activity has already contributed to extreme local warming throughout the tropics. Section 2 describes the degree of local warming that has occurred within Earth's three major tropical rainforests, and section 3 articulates the relationship between the temperature change within individual contiguously deforested patches and their area. In section 4, we discuss how these findings may impact agricultural productivity and public health throughout the tropics in the context of global warming.

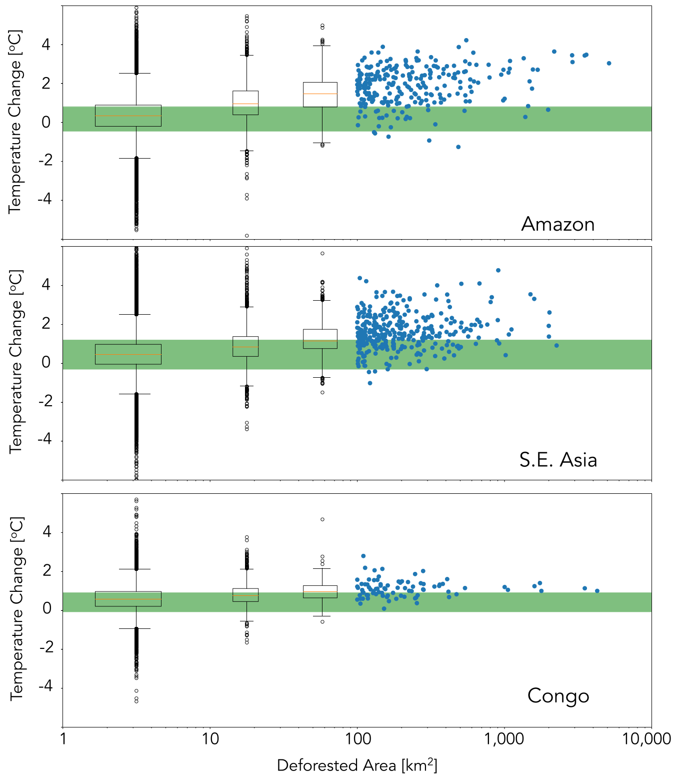

Figure 2. Annually averaged mean temperature changes within each patch of contiguous deforestation as a function its area for the three domains shown in figure 1. For the box plots, orange lines show the mean values, boxes show the interquartile range, whiskers show the 90th percentile values, and circles show the outliers. The box plots show accumulated data for patches between 1–10, 10–33, and 33–100 km^2, respectively. Blue dots represent all contiguously deforested patches larger than 100 km^2. The green shading shows expected mean values drawn from a Gaussian distribution with mean and standard deviation associated with each region's *forested* distribution (figure 1).

2. Deforestation impacts on local warming

Using 1 km^2 resolution data [18] from the MODIS-Aqua satellite, we calculated the annually averaged daytime temperature differences between 2003 and 2018 without any spatial averaging that is characteristic of other contemporary deforestation studies [19, 20]. This satellite passes over the equator at 1:30 PM local time; we use the annually averaged temperature value at each grid cell to characterize daytime tropical temperatures in both 2003 and 2018. Hansen *et al* [1] present global data at 30 m^2 spatial resolution for (i) percentage forest cover in 2000, (ii) the year during which the majority of deforestation within each grid cell took place (if any), and (iii) a binary value to indicate whether the satellite has registered any forest cover gain during the observation interval. After re-gridding these data to the MODIS 1 km^2 resolution using a linear interpolation, we analyzed only grid cells in the Amazon, Congo, and Southeast (S.E.) Asia (see insets in figure 1) where the forest cover in 2003 was greater than 75%. Deforestation of over 50% of the 30 m^2 grid cells within a particular 1 km^2 MODIS pixel was required for our analysis to classify a particular pixel as 'deforested'. While this method likely neglected some extremely small patches of deforestation that occurred early in the satellite record, our results were found to be insensitive to small modifications in our classification scheme. ‘

Although the deforestation dataset provides information as far back as 2000, 2003 is the first full year of MODIS-Aqua coverage. In addition, the El Niño Southern Oscillation was close to neutral during 2003 and 2018, so these years are ideal to study the impacts of local land use change without including large scale temperature variability driven by the tropical oceans. Even without local climate impacts of a strong El Niño event, interannual temperature variability is a feature of the climate system; we expect a spread in local land surface temperatures that closely mirrors the variability in tropical sea surface temperatures that regulate the regional climate. Indeed, in grid cells that retained more than 75% forest cover between 2003 and 2018 the temperature changes are between −1 and +2 °C nearly everywhere (figure 1).

As noted above, we calculated the temperature changes in all grid cells as the difference of annual mean daytime temperatures. The MODIS satellite detects top-of-canopy temperatures where forest is present, and land surface temperature where forest is not present. The canopy air temperatures in tropical forests have been found to be 2 °C–5 °C warmer than the two-meter air temperatures beneath the canopy [21–23]. By contrast, an analysis of tower data taken

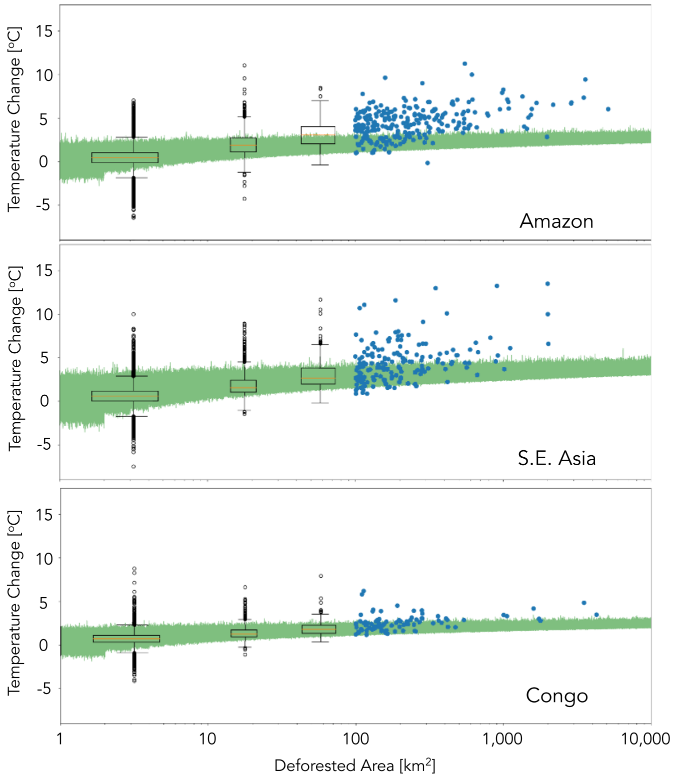

Figure 3. Same as figure 2, but for the annually averaged *maximum* temperature change within each patch of deforestation. Green shading shows expected maximum temperature changes from a random draw of maximums from a Gaussian distribution with the mean and standard deviation associated with each region's forest distribution from figure 1.

over a tropical pasture during the GOAMAZON campaign [24] (not shown) demonstrates that land surface temperatures that are measured by the MODIS satellite are generally 2 °C–6 °C warmer than the local two-meter air temperature. We are primarily interested in the two-meter air temperature experienced by humans and crops; because both of our available temperature measurements are roughly equally biased towards warmer values that are strongly correlated with two-meter air temperature, we do not expect our estimates of two-meter air temperature *differences* between forested and deforested regions to be meaningfully biased. The potential for biasing estimates of two-meter air temperature change driven by deforestation when using available satellite measurements has been investigated in other studies and found to be negligable [25].

In contrast to the grid cells that retained forest cover between 2003 and 2018, figure 1 shows that the frequency distribution of temperature changes in grid cells that have experienced deforestation between 2003 and 2018 is skewed towards extreme warming in each of the three geographic domains. This extreme skew towards warming is most obvious in the Amazon, where 12% of deforested grid cells were 3 °C (5.4 °F) warmer in 2018 than 2003. Fewer than 1% of points that retained forest cover experienced warming of this magnitude. The spatial pattern of tropical deforestation is partially driven by the accessibility of different regions to industrial equipment. However, compositing deforested points by elevation [26] showed no meaningful difference in the frequency distributions of temperature changes between deforested points above and below 200 m (not shown).

The impact of deforestation becomes more obvious in areas that experienced the most extreme warming between 2003 and 2018. Of all grid cells in S.E. Asia that have warmed more than 5 °C (9 °F), 65% have experienced deforestation, despite the fact that the grid cells deforested in these 15 years occupy less than 11% of the region's total area. In the Amazon, 60% of the grid cells that have warmed by 5 °C have been deforested between 2003 and 2018, while they account for less than 4% of the region's total area. This amount of warming is equivalent to more than a century of greenhouse-gas induced climate change in a worst-case emissions scenario [27]. Furthermore, the impacts of deforestation and climate change will likely add linearly, as they are the result of two fundamentally different modifications of Earth's surface energy budget. Warming of this magnitude could contribute to creating 'uninhabitable zones' in the tropics that have been postulated even without considering the impact of deforestation on local temperature change [28].

3. Role of contiguous patch size on warming

Tropical deforestation can drive local daytime temperature increases equivalent to those associated with worst-case greenhouse gas emissions scenarios on a far shorter timescale. Recent work has argued that the warming within a 50 km radius of tropical deforestation can be large enough to bias estimates of greenhouse gas-induced warming [29]. What is responsible for the extreme warmings observed throughout the tropics? We examined temperature changes within individual contiguously deforested patches using a flood-fill algorithm that iterates recursively through the land cover dataset to determine deforested grid cells that share at least one boundary. While this method allows us to isolate individual patches of deforestation for analysis, it makes no distinction between different patch shapes. For example, a long, thin line of deforestation following a river's path is counted the same as a more symmetrical shape with the same area. However, our approach allows for explicit identification of industrial scale clear-cuts in a way that large-scale averaging of satellite data does not [19, 20, 30].

Figure 2 shows annual mean temperature changes within contiguously deforested patches as a function of their area; the width of the green shading is defined by the standard deviation of temperature changes in regions that *retained* forest cover (see figure 1). Although small deforested patches between 1 and 9 km^2 show temperature changes nearly identical to those found in regions that retained forest cover, the interquartile range of warming in patches between 33 and 100 km^2 in the Amazon lies completely outside the likely range defined by the forested distribution, indicating that anomalous warming is expected from even these relatively small clear-cut areas. The mean within-patch warming increases as the contiguously deforested area increases; in all regions we find that most large (>100 km^2) patches have mean warming that exceeds the range experienced by the forested regions. In both the Amazon and S.E. Asia, the average within-patch temperature change regularly exceeds 2 °C for contiguous deforested areas larger than 100 km^2, a change in regional climate that would take decades of anthropogenic climate change to realize [31]. The short timescale of deforestation would give surrounding forest ecosystems little time to acclimate to the extreme warming associated with large contiguous patches of deforestation. Modelling studies have demonstrated that extreme warmings comparable to those found in the large patches shown in figure 2 have the potential to trigger large scale ecosystem die backs driven by alterations to the moisture budget in large tropical rainforest basins [32].

We have established that the average local warming within contiguously deforested patches scales with their area, but the *maximum* local warming that occurs in a given patch exhibits an even stronger relationship with the area of contiguous deforestation. Figure 3 shows the maximum annually averaged within-patch warming as a function of contiguously deforested patch area. The maximum of a set of randomly distributed points is expected to increase with the size of the set. To calculate the range of expected maximum temperature changes without the impacts of deforestation, we took a series of random draws from Gaussian distributions with mean and standard deviation values identical to those of the forested distributions from each region shown in figure 1. The number of draws corresponded to the area of the patch; a higher number of draws will generally lead to a higher maximum value. Once maximums from each series of draws were calculated, the process was repeated 100 times to generate the spread of maximum values shown in figure 3.

The maximum temperatures in the largest deforested patches far exceed those expected from the random draws, and in some places exceed 10 °C (18 °F). Correlations between maximum within-patch warming and the logarithm of deforested area range between 0.34 (Congo) and 0.44 (S.E. Asia). We found that mean elevation and within patch elevation variance were both poor predictors of the spread in within patch temperature changes in the largest clear cuts. Some of this spread can be explained by the fact that the flood-fill algorithm implemented in this study does not account for distinctions in patch shape. However, our analysis strongly suggests that the skew that characterizes the temperature change frequency distributions in deforested regions (figure 1) is driven by the prevalence of large clear-cuts. In both S.E. Asia and the Amazon, more than 25% of all grid cells deforested between 2003 and 2018 are concentrated in patches larger than 100 km^2; these extensive patches contain 76% and 84% of the deforested grid cells that have warmed by more than 5 °C, respectively. The reasons for the relationship between extreme warming and contiguous deforested patch size involve land-atmosphere feedbacks that are beyond the scope of this study; however, the results detailed in figures 2 and 3 have profound implications for land management, public health, and sustainable development policy in the tropics.

4. Human impacts of local warming

Global warming is already forcing the tropics out of its natural envelope of temperature variability; future greenhouse gas emissions will only make the warming more extreme [33]. Increasing temperatures from local land use changes will greatly magnify the impacts of global warming on people, ecosystems, and societies in the tropics that are on the front lines of global climate change. Crop yields will be compromised by extreme warming, particularly for commodities other than mature oil palm that has canopy cover [34]. Studies have shown that soy bean yields decrease in tropical countries by ~10% with a 4 °C warming, and 20% with a 6 °C warming, even when the effects of CO_2 fertilization are accounted for [35, 36]. The relationships between local temperature changes and the size of contiguous deforested area presented here fall well within these bounds and suggest that industrial clearing of tropical rainforests could reduce these regions' capacities to produce agricultural commodities in a warming world. Apart from crop health, recent work has documented the impacts of extreme temperatures on farmworker wellbeing in the United States [37]. While the findings may not be completely transferable to tropical regions, they suggest that the deforestation-induced warming identified in this study could be extremely dangerous to those engaged in outdoor labor in large industrial clear-cuts.

The deforestation-induced warming identified in this study greatly compounds population impacts of climate change. Thirty percent of the world's population is already exposed above lethal heat event thresholds [38]. There are more than 200 million people in forested areas of Central Africa, Southeast Asia, and the Amazon Basin [39], and a growing proportion of the population will be exposed to deadly heat conditions with global warming alone [38]. Combined heat exposure from deforestation, global warming, and internal heat generated from physical labor among outdoor working populations in agriculture, forestry, and other prevalent sectors in the tropics may cause additional morbidity through heat-related illnesses, traumatic injuries [40, 41], and kidney injury and disease [42–44]. In addition to the very young, old, and those with underlying health conditions, otherwise healthy working populations in tropical industrializing settings may have limited adaptive capacity and lack immediate access to healthcare, electricity, and water [45], thereby impeding recovery from heat exposure and a return to productivity [46]. Furthermore, if working populations decrease work hours and pace to maintain health in the setting of both continued deforestation and climate change, reductions in productivity with heat exposure will be even more dramatic than those projected under climate change alone [47]. Health and productivity trade-offs from large patches of deforestation may cause ripple effects in communities where well-being is contingent upon outdoor labor [48].

Tropical deforestation, particularly industrial scale clear cutting, has the potential to alter local climate as much as decades or centuries of global warming under worst case emissions scenarios. In the context of a warming climate, these compounding temperature changes associated with land use are of paramount importance and deserve policy attention for those concerned about the health and well-being of local populations, the integrity of ecosystems, and the sustainable development of the tropics. Several ongoing efforts, such as the United Nations Decade of Ecosystem Restoration focusing on accelerating the Bonn Challenge's goal to restore 350 million hectares of degraded and deforested land by 2030, provide promising pathways for increasing the resilience of local populations to warming driven by tropical deforestation. Evaluating and modifying global supply chains that require tropical deforestation to remain profitable is another critical strategy to reduce the environmental impacts of deforestation on the people in the tropics most vulnerable to and least responsible for anthropogenic climate change.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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