LETTER

Compounding impact of deforestation on Borneo's climate during El Niño events

Sarah Chapman1, 2, Jozef Syktus3, Ralph Trancoso3, Alvaro Salazar4,5, Marcus Thatcher6, James E M Watson1, 7, Erik Meijaard6, 8, 9, Paul Dargusch1 and Clive A McAlpine1

1 The University of Queensland, School of Earth and Environmental Sciences, St Lucia QLD 4072, Australia
2 School of Earth and Environment, University of Leeds, Leeds, United Kingdom
3 The University of Queensland, School of Biological Sciences, St Lucia 4072, Australia
4 Departamento de Biología, Facultad de Ciencias, Universidad de La Serena, Casilla 554, La Serena, Chile
5 Instituto de Ecología y Biodiversidad (IEB), Chile
6 CSIRO Marine and Atmospheric Research, Aspendale VIC 3195, Australia
7 Global Conservation Program, Wildlife Conservation Society, Bronx, NY 10460, United States of America
8 Borneo Futures, Bandar Seri Begawan, Brunei
9 European Research Council Centre of Excellence for Environmental Decisions, The University of Queensland, St Lucia 4072, Australia
10 Faculty of Environmental Sciences and Natural Resource Management (MIINA), Norwegian University of Life Sciences (NMBU), Ås, Norway

E-mail: c.mcalpine@uq.edu.au

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Abstract

Both deforestation and El Niño events influence Borneo’s climate, but their interaction is not well understood. Borneo’s native forest cover decreased by 37.1% between 1980 and 2015 with large areas being replaced by oil palm and a mosaic of plantations and regrowth vegetation. The island is also affected by El Niño events, resulting in severe droughts and fires. Here, we used a high-resolution climate model to simulate and evaluate how deforestation and El Niño episodes interact during the 1980–2016 period. Simulations revealed that deforestation resulted in a warmer and drier climate with the most pronounced changes in the extensively deforested regions of eastern and southern Borneo. Deforestation-linked impacts were more pronounced under El Niño than neutral (non El Niño/La Niña) conditions. Changes in climate mainly corresponded with areas with the most deforestation. There was a significant increase in the frequency of hotter and drier climatic extremes, with the probability distribution of temperature, humidity and aridity shifting from narrow to a broadening distribution. For example, the frequency of 90th percentile of the hot temperatures (defined as average monthly temperatures >28.9 °C) during the dry season increased from 10% for neutral conditions for the 1980 forest cover to 22% for neutral conditions for the 2015 forest cover. For strong El Niño events, the frequency increased from 15.6% to 32.5%. Replacement of intact native forest with oil palm resulted in increased frequency of hot temperatures to 49% for neutral and 74% for El Niño conditions. Hotter and drier conditions are likely to increase tree mortality and forest flammability (and fire-driven deforestation). The continued reduction and fragmentation of Borneo’s forests diminishes the ability to moderate regional climate impacted by larger scale and other regional/local human climate forcings.

1. Introduction

The loss of tropical forests influences regional climate by several mechanisms including increased surface albedo and reduced evapotranspiration (Pielke et al 2011, 2016, Mahmood et al 2014, Li et al 2016a). In the tropics, the impact of albedo is generally thought to be outweighed by the reduction in evaporative cooling, resulting in higher temperatures (Li et al 2015, 2016b). Recognised local and regional-scale impacts of tropical deforestation include warmer surface temperatures and greater variation in temperatures (Alkama and Cescatti 2016, Bright et al 2017, Schultz et al 2017, McAlpine et al 2018), drought...
enhancement (Bagley et al 2014), changes in the length and intensity of the dry season (Pires and Costa 2013, Khanna et al 2017), and decreasing deep convection, deep cumulus cloud cover and total precipitation (Wang et al 2009, van der Molen et al 2011, Spracklen and García-Carreras 2015). These processes are relatively well recognised in studies of continental South America and Australia. By contrast, the key processes and consequence remain poorly understood in insular South-East Asia (SE Asia) (Stibig et al 2014). Further, there is limited knowledge of how El Niño events interact with tropical deforestation to affect the regional climate.

The SE Asian island of Borneo is a deforestation hotspot (Hansen et al 2013). Between 1973 and 2015, an estimated 18.7 Mha of Borneo’s natural forest were cleared (Gaveau et al 2016). Deforestation is expected to continue although at a slower rate (Gaveau et al 2019). The expansion of oil palm plantations is a major driver of forest loss in Borneo (Carlson et al 2012, Gaveau et al 2016, 2019). Approximately 7.0 Mha of the total plantation area in 2015 (9.2 Mha) were old-growth forest in 1973, of which 4.5–4.8 Mha (24%–26% of Borneo-wide deforestation) were planted within five years of forest clearance (3.7–3.9 Mha oil palm; 0.8–0.9 Mha pulppwood). This rapid conversion has been greater in Malaysian than in Indonesian Borneo (57%–60% versus 15%–16%). In Indonesia, a higher proportion of oil palm plantations was developed on already cleared degraded lands (a legacy of recurrent forest fires). However, rapid conversion of Indonesian Borneo’s forests to industrial plantations increased since 2005 (Gaveau et al 2016). Nonetheless, plantation expansion and associated forest conversion appear to have declined somewhat since a peak in 2012 and net forest loss has slowed, but not ceased, since 2016 (Gaveau et al 2019).

The El Niño is a major driver of seasonal and interannual climatic variability across the tropics (Rifai et al 2019). The climate of Borneo is strongly affected by El Niño (Aldrian and Dwi Susanto 2003). During El Niño conditions, the Walker circulation weakens and shifts convection eastwards, while the Hadley circulation strengthens south of the equator (Hendon 2003, Jiang and Li 2018). These processes reduce rainfall over Borneo, particularly during the dry season (May–October) with the south and southeast of the island most severely impacted (Walsh and Newbery 1999, Aldrian and Dwi Susanto 2003, Sussilo et al 2013, Supari et al 2017). Strong El Niño conditions occurred in 1997–98 and 2015 and were associated with droughts and fires, especially in the peat swamp forests of southern and eastern Borneo (Atwood et al 2016, Field et al 2016, Jucker et al 2018). The 2015 event was one of the strongest El Niño events of the past century, producing drought anomalies more extreme than prior El Niño events due to additive effects of long-term anthropogenic warming and anthropogenic land use change (Rifai et al 2019). The frequency of extreme El Niño events is likely to increase in the future (Chen et al 2016, Cai et al 2018, Wang et al 2019).

Here, we address the question: what are the climatic impacts of extensive deforestation in Borneo in recent decades? We also ask: to what extent has deforestation exacerbated the climate impact of El Niño events on Borneo?

2. Data and methods

2.1. Study region

Borneo has a moist, equatorial climate with relatively constant temperatures between 25 °C and 35 °C in lowland areas, but large annual and intra-island variation in rainfall. Rainfall is broadly determined by the two main monsoons, a southeast ‘dry’ monsoon (ca. May–October) and a northwest ‘wet’ monsoon (November–April). The southeast monsoon is driven by low pressure zones over the Asian mainland that draw south-eastern winds and generate moderate rainfall, while the northwest monsoon occurs when low pressure zones lie over Australia, creating northern winds generating heavy rain in Borneo (Mackinnon et al 1996). This creates a system of highest rainfall in western and north-western Borneo and in the central mountain areas, with drier and more seasonal conditions in eastern and especially southeastern Borneo. As a result of this variation in rainfall patterns, the island can broadly be divided into three climatic zones, depending on when the wettest period occurs: (1) a western zone in north-west Kalimantan and Sarawak; (2) a north-west and north zone; and (3) a central and south-eastern zone (Dambul and Jones 2007). Tall species-rich evergreen rain forests, dominated by canopy trees from the Dipterocarpaceae ‘dipterocarp forests’, are the island’s dominant natural vegetation. Indeed, despite their rapid loss, Borneo still sustains the region’s largest expanse of intact forest outside of New Guinea, and Borneo’s forest are an important centre of plant diversity (Kier et al 2005, Slik et al 2009). While cultivation, and localised-burning to maintain hunting areas, have been present for millennia, impacts were highly localised until recent centuries when the availability of iron facilitated the expansion of swidden cultivation (Sheil et al 2012). Industrial exploitation of the island’s forests started in earnest in the 1960 s and 1970 s, first in Malaysian Borneo and later on the Indonesian side of the island (Gaveau et al 2014).

2.2. Land cover scenarios

We used land cover datasets for 2015 and 1980 to derive boundary conditions for the modelling experiments assessing the impact of land cover change on Borneo’s climate. Two parallel climate modelling experiments were run for the 1981–2016 period using ERA-Interim reanalysis and two alternative land cover datasets. The 1980 land cover was derived...
from the Advanced Very High Resolution Radiometer (AVHRR) satellite at 1 km spatial resolution (Hansen et al. 2013) (figure 1(a)). Land cover for 2015 was derived from (Miettinen et al. 2016), who used MODIS and Sentinel satellites to classify land cover, including oil palm plantations, at a 250 m resolution (figure 1(b)). We reclassified the land cover map of (Miettinen et al. 2016) to match the IGBP classification in which forests were represented by ‘evergreen broadleaf forest’ (which includes mangroves, peat swamp forest, lowland evergreen forest, lower montane evergreen forest and upper montane evergreen forest). Regrowth vegetation and timber plantations were classified as ‘vegetation mosaic’. For both modelling experiments, land cover and land surface characteristics outside SE Asia were set for 2015 land cover conditions.

2.3. Experimental design
We used the Conformal Cubic Atmospheric Model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to assess the impacts of deforestation on the climate of Borneo. CCAM is a global atmospheric model that simulates regional climate over a selected area using a variable resolution grid (Mcgregor and Dix 2008, Thatcher and Mcgregor 2010). The biosphere-atmosphere exchange was described using the Community Atmosphere Biosphere Land Exchange version 2.0 (CABLE). For a more detailed description of CABLE see (Kowalczyk et al. 2006). CCAM was run in stretched grid mode with a 20 km horizontal grid-spacing over SE Asia (15°N–15°S and 93–155°E). CABLE models radiation, heat, water vapour and momentum fluxes across the land-atmosphere interface. It captures the interaction among the microclimate, plant physiology and hydrology, enabling vegetation-soil full aerodynamic and radiative interactions (Kowalczyk et al. 2006). CABLE’s surface flux sub-model estimates the coupled transpiration, stomatal conductance, photosynthesis and partitioning of net available energy between latent and sensible heat of sunlit and shaded leaves (Wang and Leuning 1998). The total surface fluxes are the sum of the fluxes from the soil to the canopy air space and from the canopy to the atmosphere. This vertical flux is calculated using the Monin-Obukhov similarity theory (Raupach 1994, Kowalczyk et al. 2006).

We used CCAM at a 20 km grid-spacing over the SE Asian region to complete dynamical downscaling for the two land cover scenarios. ERA Interim reanalysis (Dee et al. 2011) was used as a boundary condition to run CCAM for the period 1980–2016. The spectral nudging was applied in the experiments using a scale-selective filter as described by (Thatcher and Mcgregor 2009). This approach allows the model to develop regional-scale features consistent with the large-scale models driven by the reanalysis and results are independent of the domain size (Thatcher and Mcgregor 2009). In our study, CCAM used a scale cut-off configuration of about 2500 km radius, corrected every 6 h above 850 hPa (~1.5 km above the surface), thereby allowing the assessment of the impact of land cover change on the surface climate. The ERA interim reanalysis was used to drive the CCAM downscaling experiments in order to compare the impact of the different land cover scenarios on the severity of El Niño events since 1980. The only difference between the two simulations was the 1980 and 2015 land cover for the SE Asian region.

2.4. Statistical analysis
The focus of the analysis was on seasonal averages for the entire experiments (1981–2016) and for selected individual and composite El Niño and neutral (non-El Niño/La Niña) conditions (table 1). The monthly data generated by CCAM was split into the wet (November–April) and dry (May–October) seasons and compared between the two experiments. The data was also split into El Niño and neutral conditions to compare the effect of deforestation on climate during these conditions. El Niño conditions were defined as a series of consecutive months where the Oceanic
Nino Index (ONI) was >0.5 °C above the long-term average. When ONI was >1.5 °C the El Niño episodes were defined as strong (table 1). ONI data was derived from the NOAA ENSO dataset (NOAA 2018) (2018). The ONI is defined as a 3-month running mean of sea surface temperature anomalies over the ‘Niño 3.4’ region (5°N–5°S, 120–170°W), which is more strongly correlated with the ENSO than regions 3 and 4 individually (Bamston et al 1997). Using this definition, ENSO conditions are listed in table 1. Neutral conditions included all remaining years, apart from those identified as La Niña events (National Oceanic and Atmospheric Administration 2018).

The differences in the climatic conditions for the two different forest cover scenarios were compared for latent heat flux, screen-level relative humidity, surface temperature, rainfall, low cloud cover and an aridity index. The aridity index was calculated as potential evaporation divided by rainfall (Budyko 1974). The statistical significance of changes in climate variables with deforestation was evaluated across the entire island of Borneo using the two-tailed modified t-test of Zwiers and Storch (1995), which accounts for serial correlation in climate data.

To assess the climate impacts of the conversion of forest to oil palm and vegetation mosaic. To construct the deforested areas during the 1981–2016 period. The PDFs were constructed for the 1980 forest cover and corresponding deforested areas in 2015 comprising both oil palm and vegetation mosaic. To construct the PDFs, we used a spatial mask based on a difference in LAI > 0.6 m² m⁻² between 1980 and 2015 vegetation.

### 3. Results

#### 3.1. Climate impact of deforestation during El Niño and neutral conditions

Borneo’s forest declined by 37.1% between 1980 and 2015 (85.5%–48.4%). This loss resulted in warmer and drier conditions (figure 2). The simulated temperature increase was larger for El Niño conditions compared to neutral conditions regardless of the season. The temperature increases corresponded with the areas of greatest forest loss (figure 1).

Areas with an increase of >0.4 °C were statistically significant (p < 0.05, see figure S1). The magnitude and extent of the increase was most pronounced over southern Borneo with a temperature increase of ~1 °C (figures 2(a), (b)). During the dry season, the mean temperature change averaged over all of Borneo’s deforested areas was 0.45 ± 0.57 °C for El Niño and 0.33 ± 0.6 °C for neutral conditions. During the wet season, the impact of deforestation on temperatures was smaller 0.34 ± 0.55 °C for El Niño and 0.31 ± 0.5 °C for neutral conditions.

The impact of deforestation on simulated rainfall was less spatially coherent than that for surface temperature. A statistically significant (p < 0.05) decrease of ~10% occurred over northwest and southern Borneo (figures 2(c)–(d)). The area-averaged reduction in mean rainfall for the dry season was 4.2% for El Niño and 5.1% for neutral conditions. The reduction in the dry season was larger than during the wet season for both neutral (by 1.5%) and for El Niño (by 1.2%) years. In summary, deforestation resulted in an enhanced temperature increase and reduced rainfall during the dry season relative to changes in the wet season.

We compared the PDF distribution for strong El Niño (table 1) and neutral conditions for the two experiments consisting of the 1980 forest cover and the 2015 deforestation scenario (figure 3). Results are shown only for the dry season although the wet season showed a similar distribution (figure S2). The impact of conversion of forest to oil palm is shown in figure S3.

We first focused on latent flux which is the major driver of evaporative cooling in tropical regions (figure 3(a)), and is the dominant component of turbulent fluxes (latent and sensible heating). The key difference between forested and deforested areas was a pronounced shift towards lower values for the during El Niño conditions, reflecting diminished evaporative cooling following deforestation. The overall decrease in the mean values for all deforested areas was ~3.75 W m⁻². For oil palm during El Niño conditions, the median decrease was ~10 W m⁻². During El Niño conditions, latent heat fluxes were larger than during neutral conditions. In neutral conditions, the impact of deforestation was less but still reduced by 3.48 W m⁻².

The impact of deforestation on relative humidity was also most pronounced during El Niño conditions (figure 3(b)), with a mean decrease of 4%
Figure 2. Impact of deforestation (difference between 2015 and 1980 land covers) on surface temperature (°C) and rainfall (%) during the dry (MJJASO) and wet seasons (NDJFMA). (a) Temperature difference in El Niño conditions; (b) temperature difference in neutral conditions; (c) rainfall difference in El Niño conditions; and (d) rainfall difference in neutral conditions.

and a change in the PDF from a narrow distribution of high humidity values (~90.4 ± 1.7%) to a broader distribution. Mean values for deforestation were ~86.4 ± 2.5%. As expected, relative
Humidity had higher values during neutral conditions compared to El Niño conditions but showed a similar reduction following deforestation.

The main impact of deforestation was the increase in temperatures during El Niño conditions (figure 3(c)), with a mean increase of 0.35 °C. The temperature distribution for the forest showed a narrow peaked PDF centred on 28.0 °C. Following deforestation, mean temperatures increased by 0.33 °C for neutral conditions. For oil palm, the mean temperature increase was higher for both El Niño (0.45 °C) and neutral (0.46 °C) years. For all deforested areas, the PDF shifted to hotter temperatures with temperatures exceeding 28.5 °C increasing in frequency. This increased frequency of high temperatures during El Niño conditions was particularly pronounced for oil palm (figure S3).

While the area-averaged mean temperature changes were relatively modest, changes in the frequency of hot temperatures were proportionally large. To illustrate this, we computed the changes in the 90th percentile in the frequency of hot temperatures (defined as average monthly temperatures >28.9 °C for the 1980 forest cover during neutral conditions) resulting from deforestation. The impact of deforestation on the frequency of hot temperatures during neutral conditions increased from 10% to 22%. For strong El Niño events, the frequency increased from 15.6% to 32.5%. The increase in the frequency of hot temperatures was larger for the wet season. For strong El Niño events during the wet season, the frequency increased from 39.2% to 61.5%. For the 95th percentile, the changes are even more pronounced. The impact of the conversion of forest to oil palm had a larger impact on the frequency of hot temperatures (figure S3). For neutral conditions, following the conversion of forest to oil palm, the frequency of 90th percentile increased from 11.4% to 48.6%. For strong El Niño events, the frequency increased from 22.9% to 74.3%.

The key impact of deforestation on rainfall during El Niño conditions was the reduction in mean rainfall by 4.2%. This reduction was stronger (5.1%) during neutral conditions. The mean rainfall was approximately 1.0 mm day⁻¹ lower during El Niño conditions than during neutral conditions. There also was a reduction in the number of days with rainfall between 2–5 mm day⁻¹ following deforestation during El Niño conditions (figure 3(d)). The impact of conversion to oil palm on rainfall was stronger with a mean reduction of 9.0% for El Niño and 6.0% for neutral conditions (figure S3).

The hotter and drier conditions (figures 3(b)–(c)) resulted in a large reduction in low cloud cover during the dry season (figure 3(e)). The impact of deforestation on low cloud cover was particularly pronounced with a broad distribution for the
Figure 4. Impact of deforestation (difference between 2015 and 1980 land covers) for: (a) latent heat flux, (b) relative humidity, (c) low cloud cover and (d) aridity index during the dry season (MJJASO). Results are shown for the strong El Niño conditions (left column), neutral conditions (middle column), and difference between El Niño and neutral conditions (right column).

Deforestation had a significant impact on the moisture balance resulting in a drier climate (figure 3(f)). We assessed this impact using the aridity index, which is the ratio of potential evapotranspiration to precipitation with higher values indicating a drier climate. During El Niño conditions, the aridity index increased from an area-averaged mean of 0.11–0.26. The distribution shifted from low clustered values to a much flatter and broader distribution following deforestation. There was a similar change during neutral conditions with an increase in the mean value of 0.008–0.19 following deforestation. Conversion to oil palm resulted in even greater aridity changes from 0.10 to 0.35 for El Niño conditions and 0.08–0.26 for neutral conditions. Conversion to oil palm had a stronger impact
on the climate than the conversion to vegetation mosaic.

Figure 4 shows the spatial distribution and magnitude of change in selected climate variables during the dry season for the 2015 and 1980 land cover simulations. The impact of deforestation on latent heat flux was most pronounced over southern and eastern Borneo where the deforestation was most severe (figure 4(a)). In these regions, the impact was more pronounced during strong El Niño conditions compared to neutral conditions with a reduction of more than 10%. Deforestation resulted in widespread and substantial reduction in relative humidity of 2%–8% over lowland regions of Borneo (figure 4(b)), with a stronger reduction over southern and eastern Borneo for El Niño conditions. There was a similar widespread reduction in low cloud cover over lowland regions for both El Niño and neutral conditions (figure 4(c)). The reduction for El Niño compared to neutral conditions was strongest for southeast coastal regions, while the changes elsewhere were more variable and localised. The aridity index increased over the deforested areas of south and southeast Borneo for both El Niño and neutral conditions (figure 4(d)), with the strongest decrease associated with El Niño conditions.

3.2. The 2015 El Niño event
To illustrate the impact of deforestation on regional climate during the recent strong 2015 El Niño events, we evaluated the simulated changes in surface temperatures and rainfall. Deforestation resulted in higher temperatures and lower rainfall during this event than what would have occurred without deforestation. Over most of Borneo, surface temperatures were higher over deforested areas (figures 5(a)–(b)). Temperature changes greater than 0.2 °C were statistically significant (p < 0.05) for both the dry and the wet seasons. The strongest temperature increase of ~1 °C occurred in both seasons in southern Borneo and corresponded to areas of largest deforestation. The PDF of the seasonal temperature shows a substantial shift in the frequency of hot temperatures with an area-averaged mean increase of 0.33 °C for the dry season and 0.36 °C during the wet season. Overall, the number of days with temperatures greater than 29 °C increased during the 2015 El Niño for both seasons.

Rainfall was also affected by deforestation, although the spatial impact differed by season (figures 5(c)–(d)). In the dry season, rainfall decreased in northern Borneo by up to 20%, while it increased in the coastal areas of southern Borneo (figure 5(c)). In the wet season, rainfall was reduced over the southern coastal areas by up to 20%, while rainfall increased in northern coastal locations (figure 5(d)). The PDFs showed a general shift to lower rainfall. The area-averaged mean decrease in rainfall for both seasons was >4.0%. Interestingly, deforestation resulted in more extreme rainfall with an increase in frequency of both low and high rainfall amounts (see lower panel figures 5(c)–(d)).

4. Discussion
Our study shows the conversion of Borneo’s native forests to oil palm and a mosaic of timber plantations and regrowth vegetation, compounds the impacts of El Niño events, resulting in a hotter, drier climate. We found that temperature increased over deforested areas by 0.39 °C and rainfall declined 4.6% during the dry season, though in some deforested areas rainfall reductions were over 15%. This is consistent with evaluation of climate station observations (Thirumalai et al 2017, McAlpine et al 2018). We found that the climate impacts were most pronounced in southern and eastern Borneo where deforestation was most extensive. The impacts were also stronger during El Niño conditions (compared to neutral conditions) as a consequence of reduced evaporative cooling and associated changes in relative humidity and low cloud cover. The combined impact was a reduction in the moisture balance, with the aridity index more than doubling after deforestation, and tripling after conversion to oil palm. The frequency of climatic extremes was also greater under El Niño conditions. Our results are consistent with previous modelling and observational studies of the impact of tropical deforestation (Alkama and Cescatti 2016, Perugini et al 2017, Duveiller et al 2018). For example, a review by (Perugini et al 2017) showed tropical deforestation is associated with regional warming of 0.6 ± 0.74 °C and declines in rainfall.

The results consistently show that the impact of conversion of forests to oil palm was proportionally larger compared to vegetation mosaic. In our experiments, oil palm was defined as a uniform plant functional type representing closed-canopy plantations 15 years in age. It is not dynamic and cannot capture variations across the oil palm growth cycle. A comparison of our results, representative of all Borneo’s large scale oil palm, with location-specific observation studies show a smaller temperature increase (area average of 0.47 °C over all model grid cells with oil palm plantations) than the increase of 2 °C–3 °C for young oil palm plantations (Manoli et al 2018, Fowler et al 2011).

Our results have limitations arising from using a single model and generalised land cover characteristics. We sought to overcome these limitations by using realistic land cover scenarios based on synthesis of satellite data and relatively high resolution (20 km) climate experiments nudged by ERA Interim reanalysis and using the advanced land surface model CABLE. A further limitation is that the CCAM does...
not incorporate the carbon cycle (Sheil 2014). All climate models have limitations. None have satisfactorily resolved, or even simulated, all the key processes involved in land-cover feedbacks including aerosols, cloud dynamics, and the determination of rainfall (Stevens and Bony 2013, Ljungqvist et al 2016, Lohle 2017, Marotzke et al 2017), with these remaining important research themes (Fröhlich-Nowoisky et al 2016, Ceppi et al 2017, Sheil 2018). Despite such limitations, our study has been successful in capturing observed trends and thus reveals our best assessment of the likely impact of deforestation on Borneo’s climate.

The climate impacts of deforestation were especially pronounced during strong El Niño events. Strong El Niños occurred in 1997–98 and 2015 and were associated with severe droughts and fires (Langner and Siegert 2009, Taufik et al 2017). Borneo’s forests are increasingly susceptible to fires when the dry season average rainfall is less than 4 mm day$^{-1}$ (Field et al 2016). Droughts, timber cutting and forest fragmentation increase the likelihood of forest dieback, flammability and repeated fires (Siegert et al 2001, van Nieuwstadt and Sheil 2005, Corlett 2016, Brando et al 2019). The decreased rainfall of between 4.5–5 mm day$^{-1}$ in southern and eastern Borneo...
observed in our simulations is close to the threshold conducive to forest fires identified by Field et al (2016). Deforestation can make remnant forest more vulnerable to fires due to the opening of the canopy and increased drying within the forest (Langner et al 2007, Staal et al 2015). The changes in climate could impact agricultural production, especially affecting drought-sensitive crops including oil palm (Oettli et al 2018, Tani et al 2020), which may displace such crops to the wetter parts of the island, driving further deforestation. The deforestation-driven climate changes could thus drive further deforestation. Furthermore, we see from detailed modelling studies elsewhere that extensive forest loss risks tipping whole continental rain forests from wet to arid (Lovejoy and Nobre 2018) while some theoretical advances and observations suggest the feedbacks involved may be much stronger than recognised and thus more likely to switch (Makarieva and Gorshkov 2007, Lawrence and Vandecar 2015, Boers et al 2017, Sheil 2018). The implications of such tipping points for an island such as Borneo are uncertain, but the 20% decline in rainfall already observed indicate the feedbacks are strong (McAlpine et al 2018). This could be particularly pronounced during El Niño years, with our results showing that the extensive deforestation of Borneo, particularly in southern and eastern regions, had increased the severity of the 2015 El Niño event, resulting in hotter and drier climate with more frequent heat extremes. Climate change projections indicate a likely hotter and drier climate with more frequent heat extremes. Particularly in southern and eastern regions, had increased the severity of the 2015 El Niño event, resulting in hotter and drier climate with more frequent heat extremes.

Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ORCID iDs
Jozef Syktus https://orcid.org/0000-0003-1782-3073
Ralph Trancoso https://orcid.org/0000-0002-9697-7005
Clive A McAlpine https://orcid.org/0000-0003-0457-8144

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