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To cite this article: Taraka Davies-Barnard *et al* 2023 *Environ. Res. Lett.* **18** 024015

ENVIRONMENTAL RESEARCH
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RECEIVED
11 July 2022

REVISED
18 November 2022

ACCEPTED FOR PUBLICATION
11 January 2023

PUBLISHED
24 January 2023

LETTER

Future fire risk under climate change and deforestation scenarios in tropical Borneo

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Keywords: Borneo, fire risk, climate change

Supplementary material for this article is available online

Abstract

Fire in the tropical peatland forests of Borneo is an environmental issue interactioning with climate change and deforestation, and the consequences have local and global implications. While research has shown that fire severity and frequency are expected to increase with climate change, there is conflicting model and observational data as to the effect of deforestation on precipitation, which is a key metric for fire risk. To better understand the changes in fire risk from deforestation and climate change we ran simulations of the climate scenario RCP8.5 with and without total deforestation using regional climate model RegCM4. The output was then used for calculations of the fire weather index. We find that annual temperature change from deforestation at elevations above 500 m is 53% of the change over the 21st century in RCP8.5. Fire risk is significantly affected by both climate change and deforestation, despite some increases in precipitation from deforestation. While the multi model dry season (June–August) mean increases in fire risk are larger from elevated atmospheric carbon dioxide, the increases in maximum fire risk are larger from deforestation. The altitude is a good predictor of fire risk change, with larger increases at more densely populated lower elevations where the peatlands are concentrated and smaller increases at higher elevations. Therefore, while deforestation generally causes a smaller increase in climate-related fire risk than climate change, its local control and heterogeneous effects compared to global carbon emissions makes it critical for climate mitigation policy. These high-resolution simulations provide a guide to the most vulnerable areas of Borneo from climatic increases in fire risk.

1. Introduction

The island of Borneo (figure 1) has unique ecology, with tropical forests and peatlands that are at risk from a range of threats including land use change, climate change, and fire (Harrison *et al* 2020). Tropical peatland soils such as those found in large parts of lowland Borneo are of particular importance environmentally and are susceptible to fires during dry spells (Cattau *et al* 2016, Nikonovas *et al* 2020, Najib *et al* 2022, Imron *et al* 2022) with notable peatland burning during 1997–1998 (Page *et al* 2002) and during 2015 (Huijnen *et al* 2016).

The peatland forests of Borneo had one of the highest rates of tropical deforestation between 2001 and 2016 (Austin *et al* 2019). This deforestation, along with peatland draining, and conversion to oil plantation, is associated with increased fire frequency (Miettinen *et al* 2017, Sloan *et al* 2017, Adrianto *et al* 2020, Tan *et al* 2020). The 2015 peatland fires destroyed 0.8 Mha and emitted an estimated 227 ± 67 Tg carbon into the atmosphere (Huijnen *et al* 2016). This has consequences for ecological viability (Laurance *et al* 2012), air quality (Marlier *et al* 2015, Tacconi 2016, Ismanto *et al* 2020, Yin *et al* 2020), nutrient distribution

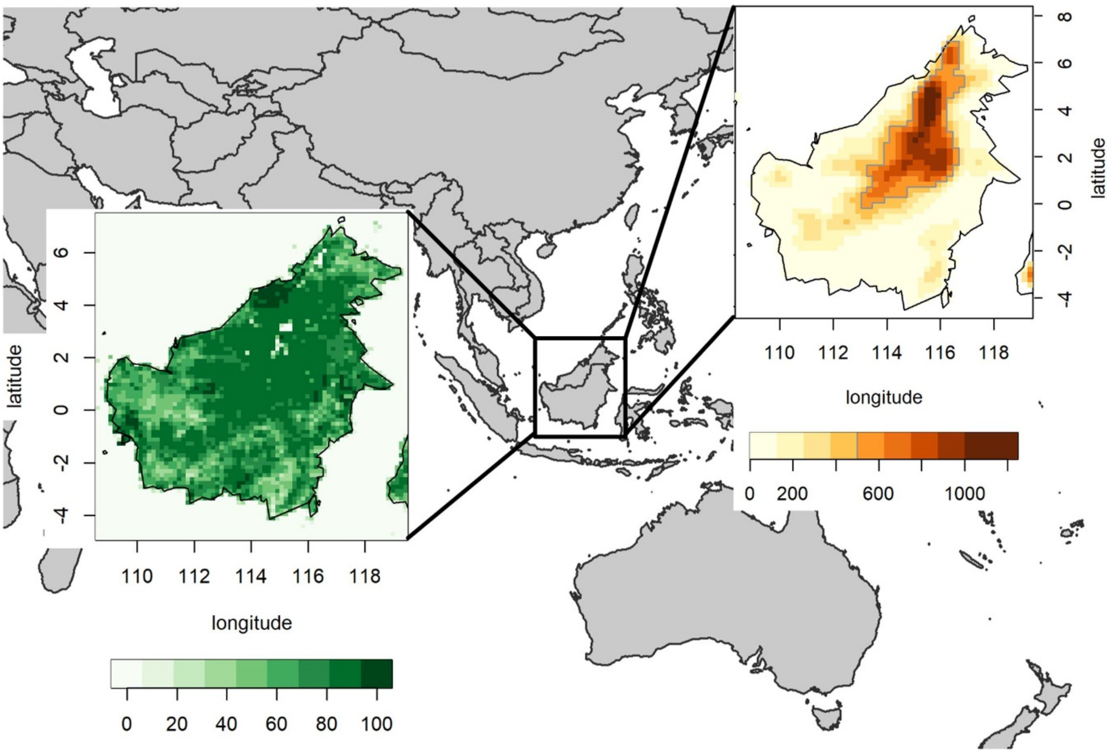

Figure 1. Location of the study area. Pull out (a) evergreen broadleaf forest in the control scenario. Converted to agricultural land in the deforestation scenario. (b) Elevation in meters. The area outlined in grey outline represents grid cells above 500 m.

(Ponette-González *et al* 2016), and human health (Tacconi 2016).

Peatland forests are naturally fire resistant (Siegert *et al* 2001, Page and Hooijer 2016, Miettinen *et al* 2017) and the occurrence of fires in Borneo mostly occurs in anthropogenically altered landcovers (Miettinen *et al* 2012a, Tan *et al* 2020, Vetrita and Cochrane 2020). The increase in fire frequency is primarily associated with three drivers: a drier climate caused by deforestation (Siegert *et al* 2001, Miettinen *et al* 2012a, 2012b, Page and Hooijer 2016, Vetrita and Cochrane 2020); anthropogenic ignition (Herawati and Santoso 2011); and land draining (Wösten *et al* 2008, Hoscilo *et al* 2011, Widyastuti *et al* 2020, Imron *et al* 2022). These last two are important factors, but outside of the scope of this research as most climate or fire models cannot account for them. Although relevant for fire intensity and duration, fuel load is not necessarily positively correlated with fire frequency since fires generally do not burn all available fuel and are more likely to occur in previously burned areas (Hoscilo *et al* 2011).

Changes in precipitation and other climate variables, particularly those connected with El Nino, have been shown to increase the risk of fires (Herawati and Santoso 2011, Wooster *et al* 2012, Chen *et al* 2016, Tacconi 2016, Withey *et al* 2018, Chapman *et al* 2020, Tan *et al* 2020, Najib *et al* 2022) and the associated rainfall changes and drought. Fire hotspots have been found to be 2–3 time more numerous in dry years than wetter years (Tan *et al* 2020). Climate change is expected to increase fire frequency on Borneo (Herawati and Santoso 2011), mainly due to decreases in precipitation.

Deforestation is also a major risk factor for fire, as found by numerous studies (Siegert *et al* 2001, Page and Hooijer 2016, Miettinen *et al* 2017, Adrianto *et al* 2019, 2020, Chapman *et al* 2020, Tan *et al* 2020). Simulations suggest decreased precipitation and increased wind speed are the primary drivers of increased fire risk after deforestation (Hoffmann *et al* 2003), particularly in undeveloped deforested areas (Miettinen *et al* 2017). While deforestation reduces the aboveground fuel load, via the removal of aboveground carbon, the large carbon store in the peat soil means that there is still a high fuel load, and susceptibility to burning increases with peat depth (Tan *et al* 2020). The biogeophysical changes to albedo, evapotranspiration, and roughness length can lead to an increase in temperature and reduction in precipitation: changes that would increase the fire risk.

Model and observational data on deforestation in Borneo consistently finds an increase in temperature due to deforestation, but the effect on precipitation is conflicting. Some climate model simulations (Tölle *et al* 2017, Chapman *et al* 2020) and observations (McAlpine *et al* 2018) show that precipitation reduces after deforestation, as is consistent with many global models and theories of the local and regional effects of tropical deforestation (Lawrence and Vandecar 2015). This theory posits that deforestation has a warming and drying effect due to decreased evapotranspiration

(Bonan 2008). However, there is also observational (Hanif *et al* 2016) and modelling (Findell *et al* 2006, Chen *et al* 2019) studies showing that deforestation in Borneo and other maritime climates can cause an increase in precipitation, associated with the dynamic component of the vertical moisture advection term (Chen *et al* 2019).

Since deforestation can also have heterogeneous mesoscale effects, increasing precipitation in warmer areas like cropland and decreasing it where it is cooler (Garcia-Carreras and Parker 2011), higher resolution modelling is critical to understand its effects, particularly combined with elevated atmospheric carbon dioxide levels. The climatic effect of deforestation and its implications for fire risk on Borneo is particularly relevant, as unlike the effects of global climate change, local policymakers can alter the risk through land-use policy.

It is therefore important to link high resolution climate modelling to a more holistic fire weather index (FWI), rather than simple changes in precipitation as an indication of the effect of deforestation on future fire risk. Doing this in the context of global climate change and Borneo's unique topography can strengthen our understanding of the possible outcomes of future scenarios.

An approach using a regional climate model has the potential to enhance knowledge of the relative contributions of climate change and deforestation to fire risk at a scale meaningful to local policymaking. With scenarios of total deforestation of evergreen tropical trees and representative concentration pathway (RCP) 8.5 climate change (Riahi *et al* 2011), we explore the limits of the climate effects in Borneo. Our key objective therefore is to quantify the potential extent to which future deforestation could contribute to a change in fire risk, in the context of global climate change, to aid policy makers in making well-informed land use decisions.

2. Methods

We use a regional climate model to simulate the climate under deforestation and climate change. These simulations are then used as input data for a FWI that gives an indication of fire risk.

2.1. Regional climate modelling with RegCM4

The Regional Climate Model system RegCM-4.9.2 is a regional climate model (Giorgi *et al* 2012) that has been extensively used in Borneo and South East Asia (Juneng *et al* 2016, Cruz *et al* 2017, Gao and Giorgi 2017, Jadmiko *et al* 2017, Ngo-Duc *et al* 2017, Chung *et al* 2018, Wang *et al* 2020) and for simulations of deforestation effects in India (Lodh 2017), the Amazon (Llopart *et al* 2018) and other regions. Since this model has been used and validated in many different studies, we do not duplicate that work by including historical period simulations in this study.

The regional model runs within a smaller regional domain, at a higher resolution than most global climate models. However, since it does not simulate the entire world, it requires boundary conditions from a global model. We use initial conditions and boundary conditions (i.e. the inputs for the start of the simulation and climate variables for outside of the domain run by RegCM-4.9.2) from an ensemble of coupled model intercomparison project (CMIP5) models (Taylor *et al* 2012, Eyring *et al* 2016) using the CMIP5 protocol (Meinshausen *et al* 2011): HadGEM2-ES, MPI-ESM-MR, CSIRO-MK36, IPSL-CM5A-LR, CNRM-CM5, CanESM2. These models have been thoroughly validated in the historical period over Southeast Asia (Mehran *et al* 2014, Siew *et al* 2014, Raghavan *et al* 2018). The model scenario used here is RCP8.5 (Riahi *et al* 2011).

Within RegCM-4.92 we use the community land model land surface model CLM4.5 (Oleson *et al* 2013), which considers the surface energy balance. However, we do not use the dynamic vegetation or terrestrial carbon cycle. Therefore the results shown here are from the biophysical effects of deforestation only.

While the CMIP5 model simulations are not the latest generation, for most climate metrics (with the exception of precipitation) the versions of the models used in CMIP6 have not significantly improved for the South East Asia region compared to CMIP5 (Hamed *et al* 2022). However, the accuracy of precipitation is lower than for temperature in both CMIP5 and CMIP6 (Supharatid *et al* 2022). For Borneo in particular, while the models HadGEM2-ES, HadGEM2-AO, MIROC5, and CCSM4 are the most suitable for precipitation projections (Sa'adi *et al* 2020), only HadGEM2-ES is available for use in RegCM4 and we include the other models named above for their strengths on temperature and other projections.

Accuracy in RegCM4 saturates at a horizontal resolution of 50 km (Gao and Giorgi 2017), so we use 30 km to ensure optimum spatial resolution without unnecessary computational expense. The domain is 64 grid cells longitude, 60 grid cells latitude, with the centre at 1.3 North 113.9 East.

The model basic integration timestep is 60 seconds, 30 minutes for solar radiation, and 10 minutes for the land surface component. The domain cartographic projection is the Lambert conformal. The lateral boundary conditions scheme uses the relaxation, exponential technique. The cumulus convection scheme is Emanuel and Živković-Rothman (1999), which provides a good representation of Borneo (Juneng *et al* 2016, Ngo-Duc *et al* 2017) and the Fritsch and Chappell cumulus closure scheme.

The deforestation experiment takes Borneo from an average of 72% coverage of Tropical evergreen forest (from approximately the year 2000) to 0%.

We ran simulations as follows:

2010–2029 RCP8.5, control land cover
2010–2029 RCP8.5, deforested land cover
2081–2099 RCP8.5, control land cover
2081–2099 RCP8.5, deforested land cover

The last 15 years of each simulation was used in the calculations shown in section 3. Each simulation was run for each initial conditions and boundary conditions of the models listed above, giving a total of 24 simulations. Each simulation ensemble is averaged to a multi-model mean (MMM) used in section 3.

The anomalies are labelled as follows:

2085–2099 RCP8.5, control land cover—2015–2029 RCP8.5, control land cover: eCO_2

2085–2099 RCP8.5, deforested land cover—2085–2099 RCP8.5, control land cover: deforestation (DEFOR)

2085–2099 RCP8.5, deforested land cover—2015–2029 RCP8.5, control land cover: combined (COMBO)

2015–2029 RCP8.5, deforested land cover—2015–2029 RCP8.5, control land cover: DEFOR aCO_2

Since the background climate is different between DEFOR and DEFOR aCO_2, there is a potential for 'interaction' or 'synergy' effects. However, we analysed DEFOR and DEFOR aCO_2 and found no statistically significant differences between the two ensembles (not shown). For clarity and to avoid repetition, we show results only for DEFOR.

2.2. FWI

The FWI (Van Wagner 1987, Lawson and Armitage 2008) is a well-established measure of fire probability with a strong focus on the role of climatic changes. With its origins in site observational data, the FWI calculates diagnostics using total daily precipitation and temperature, humidity, and windspeed at midday, with the date and longitude and latitude. From those diagnostics the FWI is calculated daily. The FWI is intended for use on a continuous dataset as it calculates the water balance on an ongoing basis (Van Wagner 1987, Lawson and Armitage 2008).

We use the corresponding variables from RegCM4, averaged to the appropriate daily values, as input for FWI.

3. Results

3.1. Climate change from elevated atmospheric carbon dioxide

The elevated atmospheric carbon dioxide in the RCP8.5 scenario causes a terrestrial increase in temperature over the 21st century of 3.35 K and 3.55 K at elevations above/below 500 m respectively, in the initial conditions and boundary conditions ensemble MMM across Borneo island (figure 2(a)). The increased temperature is caused by a change to the surface energy balance caused by more heat trapped by atmospheric carbon dioxide. The annual MMM spatial range of temperature increase is 3.15–3.91 K, with slightly lower temperature increases at high elevations (figure 2(a)) where there is a higher coverage of forest. The increased temperature also extends over the sea (not shown).

There is a reduction in precipitation both annually and in the dry season (June–August, JJA), which is largest over the highest elevation areas (figure 2(b)), but the range within the MMM is large and encompasses zero. However, changes in water balance and water related metrics follow the opposite pattern, with latent heat, humidity, and total cloud fraction all decreasing more at lower elevations, correlating somewhat with the higher temperatures (figure 3). The combination of less evaporation and a smaller reduction in precipitation means that despite the reduction in precipitation the precipitation minus evaporation increases at lower elevations (figure 3(k)), but the uncertainty extends over zero change.

There is little change to the wind speed in these simulations (figure 2(d)), with only a marginal difference between higher and lower elevations.

3.2. Climate change from deforestation

The effects of deforestation on the MMM surface temperature is 2.06 K and 1.80 K warming at elevations above/below 500 m respectively (figure 2(e)), and unlike eCO_2 temperature increases, occur only over the land. The difference between temperature change at high and low elevation is not statistically significant. The surface albedo increases (figure 3(h)) due to the difference in albedo between trees and crops. However, this albedo increase would decrease surface temperature. Therefore cooling from the increase in albedo is overcome by changes to the Bowen ratio (sensible/latent heat) (figure 3(i)) and the surface energy fluxes (figures 3(d) and (e)) and results in increased temperature, as found by previous studies of forest changes using RegCM4 (Otieno and Anyah 2012).

The MMM precipitation increases at both high and low elevations in both the annual mean (0.86 and 0.23 mm d^{-1} respectively) and dry season (0.67 and 0.16 mm d^{-1} respectively) (JJA) (figures 2(f) and 3(b)).

The evaporation signal is opposite between the high and low elevation areas, albeit with a range that encompasses zero (figure 3(c)), as is the change in latent heat (figure 3(e)). The higher increased windspeed increases evaporation at lower elevations, but at higher elevations the smaller increase in windspeed does not overcome the higher increase in precipitation, leading to contrasting results.

The wind speed increases significantly with deforestation, particularly in lower elevation coastal areas. The higher temperature of the land due to deforestation creates lower pressure as the heated air rises, creating an advection system which enhances the sea

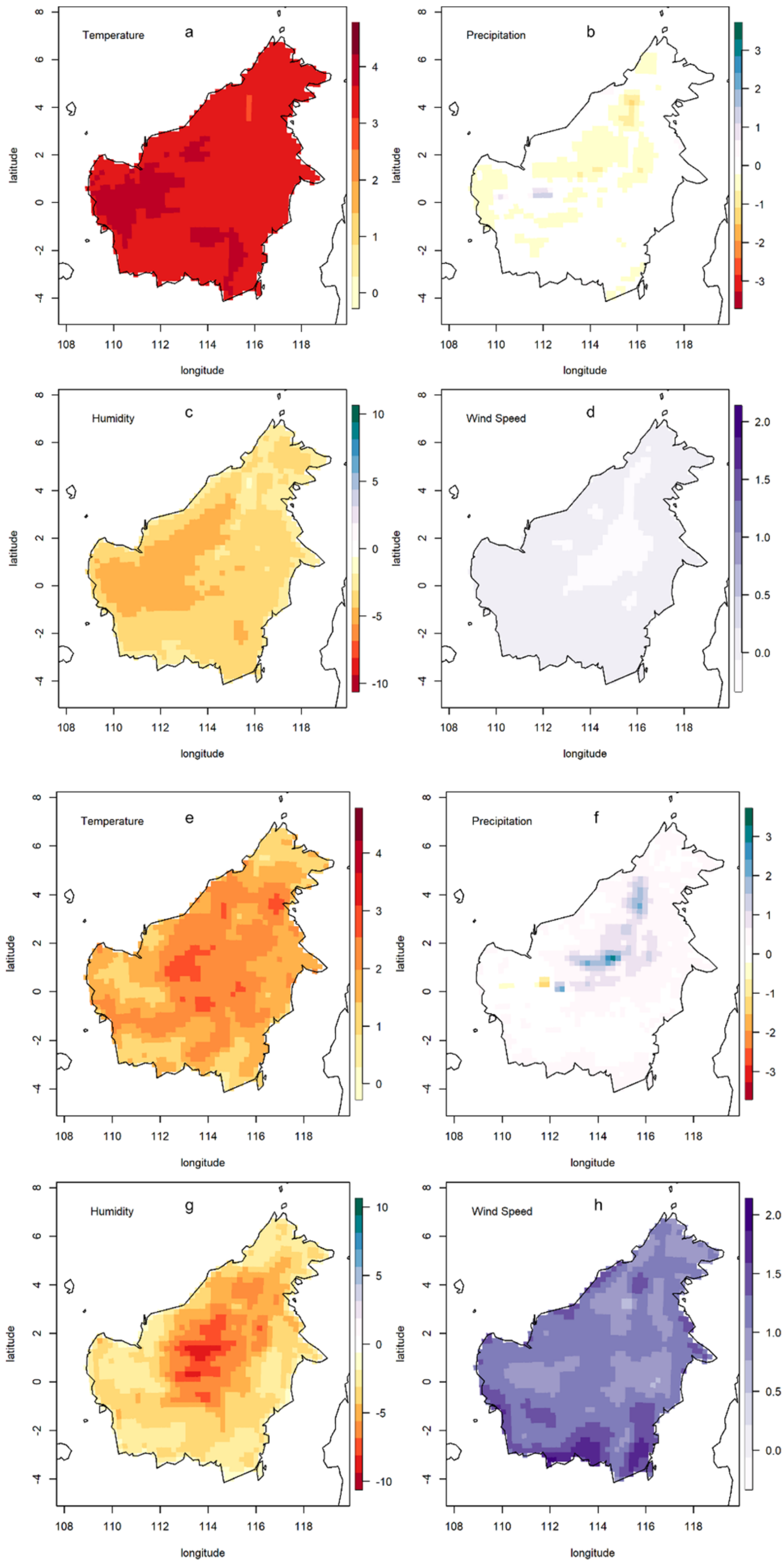

Figure 2. Annual multi model mean climate anomalies for RCP8.5 (2085–2099–2011–2025) (a)–(d) and deforestation (deforested—control) (e)–(h) and for temperature (Kelvin), precipitation (mm day^{-1}), humidity (mm day^{-1}) and wind speed (km h^{-1}).

breeze circulation from the cooler ocean areas to the hotter land. This change in wind speed is not related to large scale changes in circulation, since these are imposed by the boundary conditions and cannot change between the simulations.

3.3. Climate change from deforestation and elevated atmospheric carbon dioxide

While the COMBO effect of complete deforestation and RCP8.5 elevated atmospheric carbon dioxide is an extreme scenario that is unlikely to be realised, the

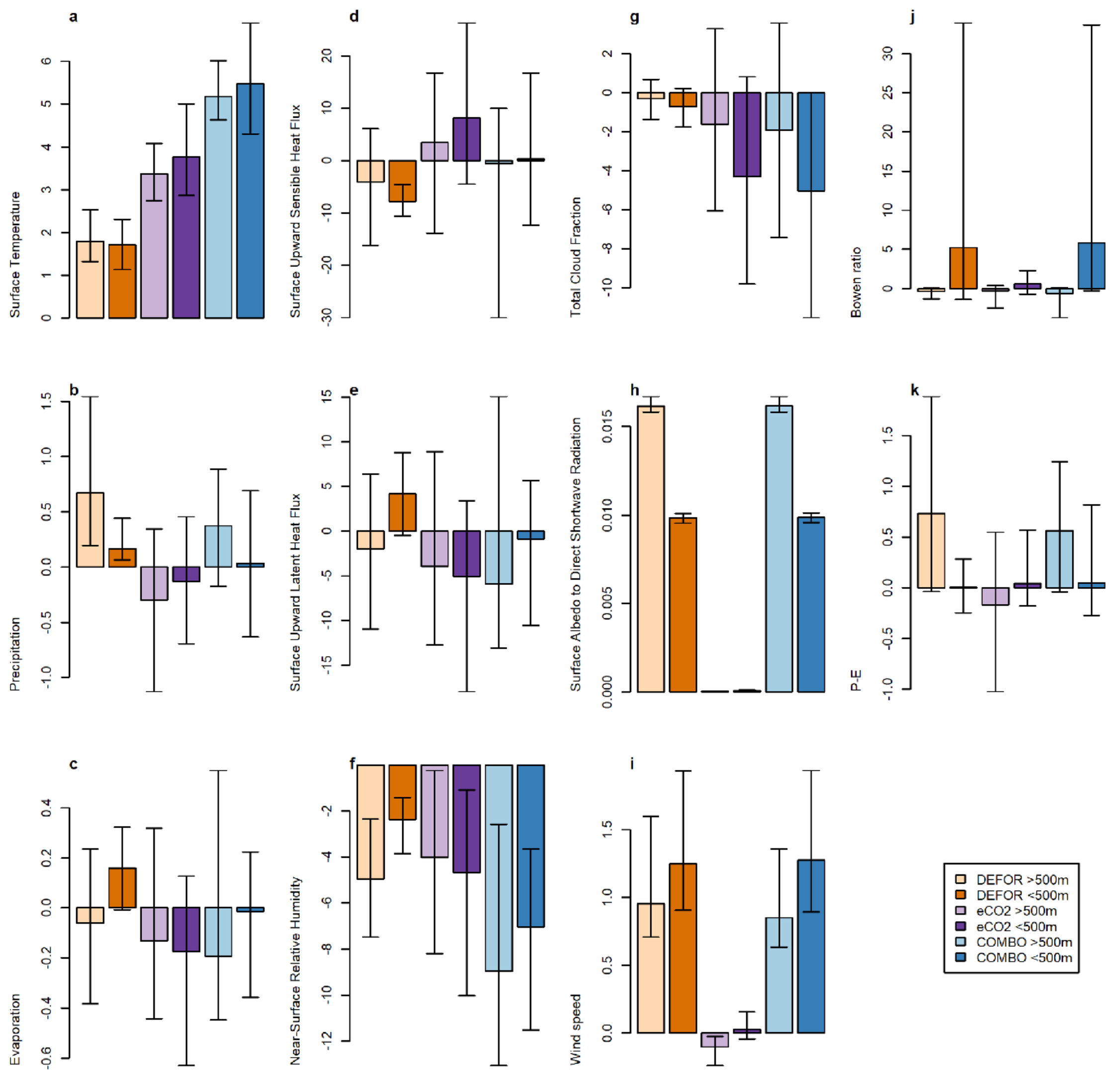

Figure 3. June/July/August multi model mean for the anomaly (control—perturbed) as described in section 2. Bars represent (columns left to right) deforestation, areas with altitude >500 m; deforestation, areas with altitude <500 m; RCP8.5 climate change effects between 2001 and 2009 compared to 2091–2099, areas with altitude >500 m; RCP8.5 climate change effects between 2001 and 2009 compared to 2091–2099, areas with altitude <500 m. Whiskers represent the ensemble minimum and maximum of each spatially averaged ensemble member.

relative contributions of DEFOR and elevated atmospheric carbon dioxide (eCO_2) are informative.

The COMBO increase in temperature is slightly higher for the annual MMM (5.42 K and 5.35 K) for higher and lower elevations respectively (SI figure 1), than JJA MMM (5.17 K and 5.48 K respectively) (figure 3(a)). Although the annual MMM is slightly higher, the difference is well within the variability, and the signal of change for the climate variables considered here is the same.

While DEFOR accounts for 38% of the annual temperature increase at higher elevations, it is 31% at lower elevations. However, DEFOR accounts for 100% of the increase in precipitation (albeit with wide uncertainties), 99% of the increase in albedo, and 97%–100% of the increase in windspeed.

The total cloud fraction reduces in all six scenarios of varying initial and boundary conditions (figure 3(g)) in the dry season, and there is a consistently stronger effect at lower elevations. The COMBO scenario at lower elevations has the biggest reduction in total cloud fraction. However, the uncertainties are substantial and changes in cloud cover are one of the less well represented aspects in most climate models.

3.4. Changes to fire risk

The MMM maximum and mean FWI increases in the dry season (JJA) (figures 4(a) and (c)) due to eCO_2. The spatial patterns and magnitude are similar between the seasonal changes and the annual mean (not shown). The minimum MMM does not increase in line with the mean or maximum (figure 5), and in some areas reduces slightly. Thus the high end of fire risk according to the FWI increases and the spatial and temporal range of risk increases, making it more variable as well as the risk higher on average.

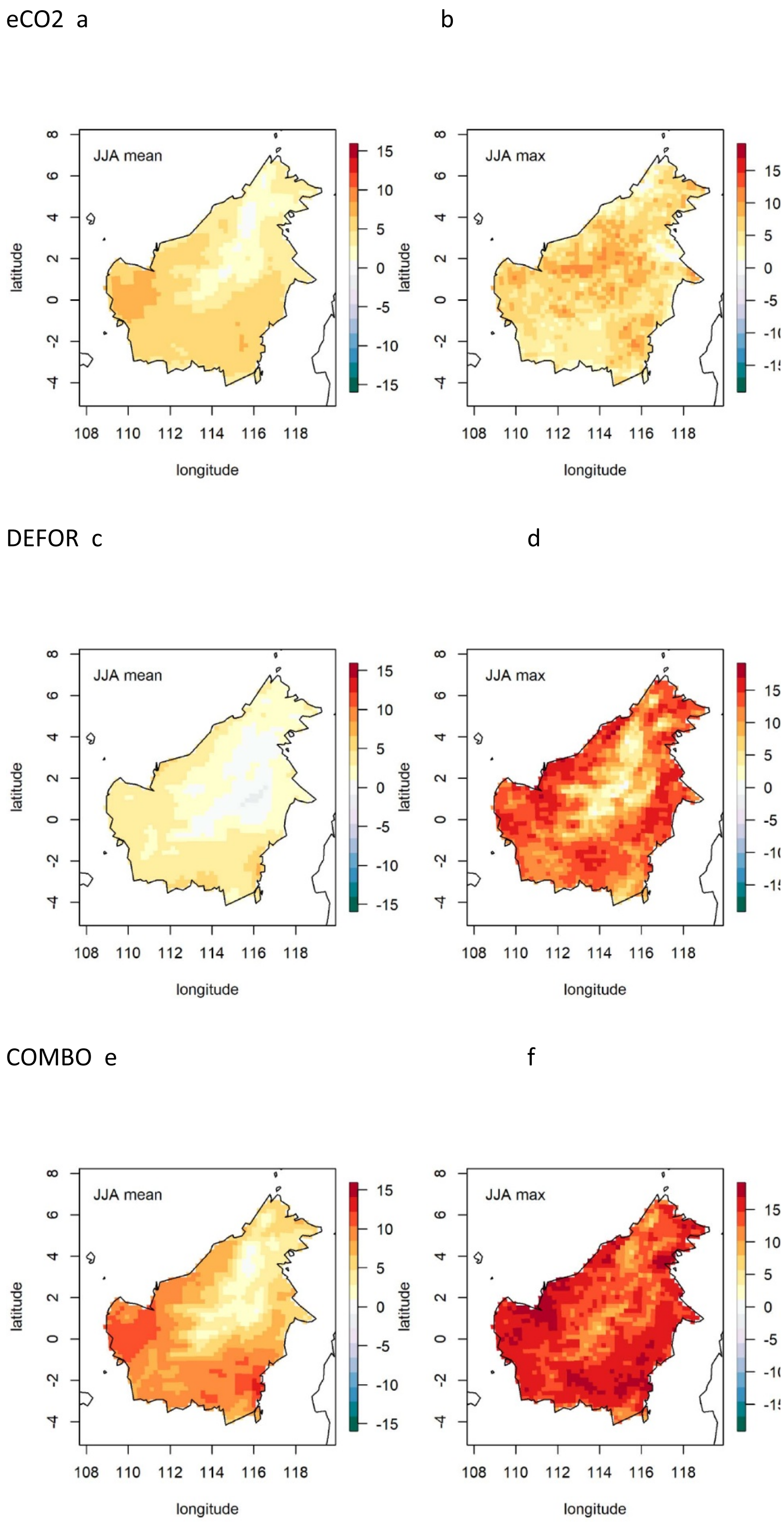

Figure 4. Multi-model mean and maximum anomaly for June/July/August of the fire weather index (FWI). Top row, eCO_2. Middle row, DEFOR. Bottom row, COMBO. Combined values above 18 or below −18 are allocated to the nearest value.

The changes in FWI due to DEFOR have both a larger range and more spatial heterogeneity than eCO_2, particularly for the MMM maximum (figure 4(c)). While the eCO_2 minimum FWI has both increases and decreases, the FWI for DEFOR has small decreases even in the MMM maximum. These are centred over the high elevation areas (figure 1), which benefit from increases in rainfall which ameliorate the impact of the rising temperature, humidity, and windspeed (figure 2). However, at lower elevations, despite generally the deforestation being less in the absolute sense because of previous

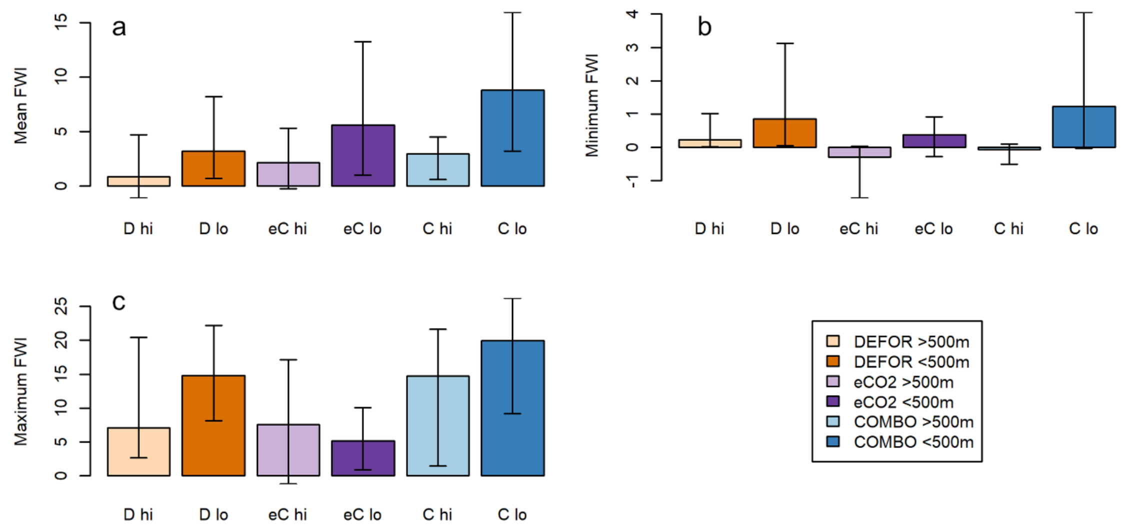

Figure 5. June/July/August FWI multi model mean (a), minimum (b) and maximum (c) for the anomaly (control—perturbed). Bars represent (columns left to right) deforestation, areas with altitude >500 m; deforestation, areas with altitude <500 m; RCP8.5 climate change effects between 2001 and 2009 compared to 2091–2099, areas with altitude >500 m; RCP8.5 climate change effects between 2001 and 2009 compared to 2091–2099, areas with altitude <500 m. Whiskers represent the minimum and maximum of the ensemble anomaly.

deforestation, the effect on the FWI risk of fire is substantial.

At lower elevations, where peatlands are concentrated, DEFOR is responsible for a larger increase in maximum FWI than eCO_2 (figure 5(c)). The maximum FWI represents a high risk of extreme events and the larger contribution to that risk comes from deforestation rather than elevated atmospheric carbon dioxide.

While the absolute risk of fire increases more at lower elevations, the relative risk increases more at higher elevations (see SI figure 2). Because of the lower initial FWI at higher elevations, the spatial pattern in percentage increase in MMM mean JJA FWI is reversed. The higher elevations have over 100% increases for eCO_2 and COMBO, but just 20%–50% increases at low elevations. Therefore while higher elevations are at lower risk overall, their increase in FWI is higher than might be expected.

The contribution to the whole island (without differentiating between higher and lower elevation) FWI is larger for eCO_2, accounting for 64% of the COMBO mean FWI in JJA, and 56% in the annual value. However, for the MMM FWI maximum in JJA, DEFOR is 74% of the increase at lower elevations and 48% at higher elevations (figure 5). Therefore the most extreme FWI values are driven by DEFOR rather than eCO_2.

4. Discussion

This study elucidates the likely climate effects of high end elevated atmospheric carbon dioxide and total deforestation in Borneo. We find that deforestation is likely to increase fire risk in future, particularly maximum fire risk, despite fluctuations or even increases in precipitation due to deforestation. This concurs with observational studies and data syntheses, which agree that deforestation drives an increase in fire occurrence (Siegert *et al* 2001, Miettinen *et al* 2012b, 2017, Page and Hooijer 2016, Adrianto *et al* 2019, Chapman *et al* 2020, Tan *et al* 2020). This work extends these existing studies by showing the effect of deforestation on fire risk is of similar importance to that from climate change, and the possibility of precipitation increases does not mitigate that.

The scenarios considered here are preventable by good governance. Although RCP8.5 remains the global trajectory of climate change despite the impact of the covid 19 pandemic (Friedlingstein *et al* 2022, Ray *et al* 2022), efforts at all levels to prevent climate change are ongoing. And while the recent rate of Borneo deforestation is high, there are protected forest areas (Austin *et al* 2019) and increasing understanding of the local and global significance of tropical forests (Alisjahbana and Busch 2017, Pendrill *et al* 2019, Surahman *et al* 2019). However, these high-end scenarios show the differing spatial patterns of change, and help deepen our understanding of the environmental impacts of both climate change and deforestation.

While focussing on the primary climate effects from these changes allows the largest impacts to be assessed, there are some limitations to the methodologies considered here. In the RegCM4 model used here, the climate impact of deforestation may be underestimated due to an absence of a terrestrial carbon cycle. The carbon released by deforestation, from both aboveground biomass but also the changes in soil carbon are not included, but Asian tropical forests are some of the most carbon dense ecosystems in the world (Gibbs *et al* 2007). If we assume a density of between 151 and 250 t C ha^{-1} (Gibbs *et al* 2007) and a loss of all above and belowground carbon over a forested area of 540 000 km^{-2} similar in scale to that modelled here, that result in a loss of around 8–14 Gt C. This would account for approximately an additional 0.005 °C of warming globally assuming a high climate sensitivity (Gillett *et al* 2013). Therefore, it is unlikely to be a significant local contribution when considering the 1.86 K contributed by the biogeophysical climate effects of deforestation or the 3.64 K from elevated atmospheric carbon dioxide levels primarily from fossil fuel burning.

The six sets of initial conditions and boundary conditions give significant variability of the results of one model (RegCM4), including opposite signals of change for both eCO_2 and DEFOR for surface radiative fluxes (latent and sensible heat), and evaporation. For context, the global average model surface temperature change range in RCP8.5 at the end of the 21st century is around 5 K (Solomon *et al* 2007) and the surface temperature range in this sample of models for Borneo is around 2 K. Therefore although the uncertainties are substantial, they are in line or slightly lower than the wider CMIP5 ensemble.

The ensemble range of FWI is large, with the spatial means encompassing no change or even a decrease in some cases (figure 5). This emphasises the uncertainty of the climate only effects on fire risk due to a combination of structural uncertainty in the climate models as well as the FWI. However, it is notable that for lower elevations the mean FWI increases in the whole ensemble. This increase in fire risk is critical as it represents the areas most vulnerable to deforestation due to proximity to urban areas which might make the areas more attractive for oil plantation use, which is the single largest driver of deforestation in the Kalimantan region of Borneo (Austin *et al* 2019).

Although these are idealised model simulations, and exact values cannot be taken as realistic, the overall trajectory is a useful comparison. The land cover representation for deforestation is a conversion from tropical evergreen forest to C3 rainfed crops and captures the main biogeophysical effect of deforestation. However, deforestation results from a range of drivers (Austin *et al* 2019, Susandi *et al* 2019) that lead to new land covers with differing properties. In particular, deforestation in Borneo has been driven by conversion to grassland and oil palm plantation (Austin *et al* 2019). Grassland has similar biogeophysical surface characteristics to cropland, but oil palm plantation has an albedo closer to forest. However, albedo change is not the driver of the climate changes in the deforestation scenario (figure 3), and the reduced evapotranspiration that drives the temperature change is uncertain in oil plantations, which use more water than forests but have 15%–20% higher evapotranspiration (Fan *et al* 2019). However, the presence of oil palm plantation, particularly the presence or absence at low densities, is strongly correlated with higher fire risk in observational data analyses (Sloan *et al* 2017).

The FWI used here gives an indication of the change in fire risk due to changes in climate, but that is one aspect of the risk. Some research suggests that anthropogenic drivers of fire are a larger contributor to fire risk than climatic risks (Cattau *et al* 2016), and the FWI does not account for the change in fuel load or land cover. A study of Borneo fire risk points to rainfall as the primary risk factor, but slope and population density are the next most important (Sze *et al* 2019). The FWI tells us about the underlying risk, but needs to be understood in the context that it is not the only source of risk.

It is also important to note that approximately 30% of the deforestation shown in this deforestation scenario has already occurred (Tang *et al* 2019) and would need afforestation efforts to avoid (Humpenöder *et al* 2014). Further, while there are protected areas of Borneo, only around 12% of these are sufficiently topographically diverse to provide analogous climates under a RCP8.5 scenario due to the fragmented nature of the protected areas (Scriven *et al* 2015).

5. Conclusions

The data uncertainties around precipitation change due to deforestation and its key role in fire risk make it an important climate variable. However, this analysis shows that even if precipitation increases as a result of deforestation, the fire risk in the most populated areas of Borneo still increases from deforestation. Since deforestation increases the risk of fire there is potential for a positive feedback loop with negative consequences for both the natural environment, the climate, and the viability of human activities on the deforested land.

Forest preservation and peatland restoration is already a key part of Indonesia's climate policy (Alisjahbana and Busch 2017, Surahman *et al* 2019), and these results reinforce its importance. The biggest single threat climatically to the sensitive ecology of Borneo is from elevated levels of atmospheric carbon dioxide. However, the risk from deforestation is also considerable and crucially, it is locally controllable in a way that global carbon dioxide levels are not.

Data availability statement

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

Acknowledgments

All authors acknowledge funding from the KaLi Project, funded by the UKRI Global Challenges Research Fund, Grant No. NE/T010401/1.

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