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LETTER

Flammable futures—storylines of climatic impacts on wildfire events and palm oil plantations in Indonesia

Shelby N Corning[1,*], **Esther Boere**[2,3], **Andrey Krasovskiy**[1], **Andrey Lessa Derci Augustynczik**[3], **Ted Shepherd**[4], **Rohit Ghosh**[4], **Florian Kraxner**[1] and **Peter Havlík**[3]

[1] Agriculture Forestry and Ecosystem Services (AFE) Group, Biodiversity and Natural Resources (BNR) Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria
[2] Department of Environmental Geography, Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands
[3] Integrated Biospheres Futures Research (IBF) Group, Biodiversity and Natural Resources (BNR) Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria
[4] Department of Meteorology, University of Reading, Reading, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: corning@iiasa.ac.at

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Abstract

Wildfire events are driven by complex interactions of climate and anthropogenic interventions. Predictions of future wildfire events, their extremity, and their impact on the environment and economy must account for the interactions between these drivers. Economic policy and land use decisions influence the susceptibility of an area to climate extremes, the probability of burning, and future decision making. To better understand how climate-driven drought events and adaptation efforts affect burned area, agricultural production losses, and land use decisions, we developed a storyline approach centered on Indonesia's 2015 fire events, which saw significant (>5%) production losses of palm oil. We explored analogous events under three warming conditions and two storylines (multi-model ensemble mean climate change and high impact). We employed a model chain consisting of CMIP6 climate modeling to quantify climate change impacts, a wildfire climate impacts and adaptation model (FLAM) to predict burned areas, and the Global biosphere management model (GLOBIOM) to predict the resultant production losses and socio-economic consequences in the oil palm sector in Indonesia and, by extension, the EU. FLAM is a mechanistic, modular fire model used to reproduce and project wildfires based on various scenario criteria and input variables, whereas GLOBIOM is a global economic land use model, which assesses competition for land use and provides economic impacts based on scenario data. We found that total burned area and production loss can increase by up to 25% and lead to local price increases up to 70%, with only minor differences beyond 2.5 degrees of warming. Our results highlight the importance of considering the interactions of future warming, drought conditions, and extreme weather events when predicting their impacts on oil palm losses and burned area. This study sets the stage for further exploration on the impacts of land management policies on local and international environments and economies in the context of global warming.

1. Introduction

Wildfires are a natural phenomenon and serve as an important component of ecosystem dynamics in much of the world. However, recent decades have seen an increase in the frequency and intensity of wildfires to an alarming degree. Regions with a history of wildfires are burning too hot and too often to fully recover, whereas regions where wildfires were previously unheard of are now catching fire at an alarming rate (Kasischke and Turetsky 2006). The increased occurrence and impact of wildfires is driven by a combination of climatic and anthropogenic factors (Pausas and Keeley 2021). The fires in turn exacerbate the climate crisis: biomass burning and resultant emissions release carbon into the atmosphere, further strengthening the effects of climate change (Baker 2022).

The main drivers behind wildfires are understood to be climate and fuel; namely, temperature, relative humidity, precipitation, wind, and biomass available to burn. These variables are driven by seasonal or annual variations in weather patterns such as El Niño Southern Oscillation (ENSO) events (Promchote *et al* 2023). Current wildfire modeling strategies often focus primarily on climatological conditions, with less explicit consideration of human activity and the influence of policies on wildfire occurrence and spread. These include semi-empirical based models such as BEHAVE (Andrews 1986) and FARSITE (Finney 1998); biogeographical models such as FireBCGv2 (Keane *et al* 2011); coupled atmosphere-fire models such as WRF-Fire (Patton and Coen 2004); deterministic models such as SPITFIRE (Thonicke *et al* 2010); and probabilistic models such as Burn-P3 (Parisien *et al* 2005).

Out of control forest fires impact not just the environment, they pose a risk to the health and safety of communities and economies on a local and global scale (O'Neil *et al* 2020, Williams *et al* 2022), including disruption of supply chains and changes to product demand and availability. To adapt to future conditions and mitigate the impacts of wildfires and climate change, modeling is a key element, which allows policy makers to explore possible strategies and compare the influence of their actions in promoting a resilient and sustainable economy, environment, and society.

Focusing on individual drivers versus the interactions of these drivers overlooks the importance of compounding that occurs with natural hazards (Khorshidi *et al* 2020). It is essential to explicitly consider the complex interactions of anthropogenic and climate drivers on local and global scales.

Indonesia provides an opportunity to explore this topic. The Indonesian landscape is characterized by forests, peatland, and agricultural land; specifically, oil palm plantations, a key contributor to the local economy and one of the largest exports of Indonesia. Its climate is heavily influenced by ENSO events. In recent decades, Indonesia has experienced more frequent and prolonged droughts, especially in the south, which have been related to a combination of anthropogenic and El Niño events.

Wildfires are a growing threat to the local environment and economy. In 2015, vast areas of Indonesia were destroyed by wildfires, especially in Southern Kalimantan and Western Sumatra (Pribadi and Kurata 2017). At this time, the country experienced an El Niño event, adding fuel to the fire through extreme drought and increased temperature.

The large scale of these fires was partly anthropogenic and partly climatic in nature. Anthropogenic activity is often the source of ignition: the root cause of most fires was the local practice of 'slash and burn' techniques, in which the land is set on fire to clear it for agricultural purposes. This practice is especially problematic on peat soils, where localized fires spread easily within the peatlands and to nearby forests due to the highly flammable nature of peatlands. Many different actors have been blamed for the management of land through the slash and burn technique, from large global corporations clearing vast areas of land to smallholder farms looking to expand their farm to make a living (Purnomo *et al* 2017).

The climatic basis of fires does not necessarily relate to their ignition, but rather to their spread and continuation. This was showcased in 2015 when efforts to extinguish fires were hampered by an El Niño-induced drought period from June–October.

There is uncertainty as to how global warming will affect ENSO and wildfire events, and subsequent oil palm production impacts. Climate teleconnections, such as ENSO, concurrently influence regional climate patterns and wildfire risk. For example, Promchote *et al* (2023) utilized seasonal climate predictions to enhance palm oil yield forecasts in Thailand, underscoring the significant influence of large-scale climate patterns on regional agriculture. However, their study did not address potential wildfire risks. Therefore, our study aims to provide a broader understanding of the linkages between climate, wildfires, and agriculture. Indonesia will likely experience more intense droughts due to the combination of El Niño and global warming. This in turn is expected to increase the frequency, duration, and intensity of wildfires in Indonesia, and will likely have significant economic and environmental consequences on local, regional, and global scales.

A shock to the supply of oil palm in Indonesia caused by drought-induced fires would result in changes in global emissions; disruptions to global markets impacting prices, competition with other vegetable oils, and the local economy; and the health of the environment.

There is room to explore how such a shock might play out under different degrees of climate change. To better understand how climate-driven drought events affect burned area, agricultural production losses, and land use decisions, this study pursued a storyline approach, in which Indonesia's 2015 fire events served as the foundation of the story (providing baseline conditions) and we derived two alternative futures (storylines) from CMIP6 climate modeling. In this way, we explored analogous events using the two storylines and three warming scenarios per storyline. Novel use of a modeling chain linked the CMIP6 climate modeling, a wildfire model, and a global economic model to provide a dynamic view of how global warming and burned area correlate with palm oil production losses under different warming conditions and sets the stage to explore how policy and adaptation efforts could affect burned area and the Indonesian palm oil industry.

2. Study area and methods

2.1. Study area

Over 60% of Indonesia's 190.5 million hectares of land area are covered by forests. Nearly 70 million hectares are production forests, much of which is oil palm. Conservation and protection forests account for an additional 22 and 30 million hectares, respectively. Over 15 million hectares are covered by environmentally sensitive peatlands (Nurofiq *et al* 2020). As mentioned earlier, land is often cleared through slash and burn techniques to make room for agricultural use. Oil palm plantations and peatlands are highly flammable and represent a fire risk to nearby forests due to the high rate of spread.

Palm oil is a major export of Indonesia, with the majority of global palm oil production (83%) taking place in Indonesia and Malaysia. India is the largest consumer, followed by Indonesia itself, the European Union, and China. The European Union is the second largest importer of palm oil from Southeast Asia with a consumption of nearly 8 million tons of palm oil in 2018, which accounts for 10%–15% of their production volume (Mielke 2018). Approximately one-third of the palm oil imported by the EU is earmarked for use as biofuel. The remainder is intended mostly for the food and chemical industries.

Many studies have identified expansion of oil palm plantations and production as a key driver of deforestation. One study estimated 6 million hectares of forest loss between 2000 and 2012 in Indonesia, with an increase of primary forest loss in recent years (Margono *et al* 2014). Gunarso *et al* (2013) estimated that 43% of industrial oil palm plantations were developed at the expense of forests in Kalimantan. Similarly, Carlson *et al* (2012) estimated that the oil palm industry was responsible for 27% of total deforestation across Indonesia through 2008, 40% of which came at the expense of wetlands, which serve as a hub for biodiversity and as a more fire-resistant ecosystem.

An analysis of forests cleared for the purpose of oil palm production between 1973 and 2015 estimated that a higher proportion of oil palm was developed on pre-cleared, degraded lands—a legacy of recurrent forest fires, which could unintentionally incentivize producers to allow fires to spread. However, a rapid conversion of forested lands to industrial plantations has been observed since 2005 (Gaveau *et al* 2016). All these factors raise the risk of wildfire occurrence, spread, and impact.

Indonesia has a predominately tropical climate characterized by three rainfall patterns: monsoonal, equatorial, and local. Future projections of precipitation in this region during the comparatively dry (boreal summer) rainy season are uncertain in sign. Temperature increases and overall warmer conditions are certain; an increase in dry conditions is less certain, although plausible (Ghosh and Shepherd 2023).

Changes in ENSO are uncertain, although there is high confidence that ENSO will continue to play a dominant role in climate variability for the region. Thus, it is reasonable to assume that future El Niño events will promote droughts and fire-favorable weather (Nurofiq *et al* 2020). This is expected to have significant economic and environmental consequences with impacts for Indonesia and the biggest importing regions of palm oil, amongst others the EU.

2.2. Model chain and methods

To capture the interactions between policies, economic drivers, and climate and burned areas, a novel model chain was developed (figure 1). This chain links CMIP6 climate modeling to capture global warming impacts on weather conditions, the wildfire climate impacts and adaptation model (FLAM) (Krasovskii *et al* 2018) to predict burned areas, and the global economic land use model Global biosphere management model (GLOBIOM) (Havlík *et al* 2011, 2014) to calculate associated land use and economic. It explores how climate change impacts interact with management and policy to affect burned area and the resultant impacts on socioeconomic conditions.

First, historical and SSP585 simulation data from 38 coupled climate models in the Coupled Model Intercomparison Project 6 (Eyring *et al* 2016) were used to calculate the impact of the 2015 El Niño event on multiple climate parameters under the three global warming scenarios (+2, 3, and 4 degrees C above pre-industrial) for the two storylines. The weather variables were modified to reflect global warming conditions in a method known as the delta approach (Ruiter 2012).

Second, these modified variables were used in FLAM after its calibration to calculate burned area for all scenarios. The burned area of oil palm plantations was separated from the total burned area to further assess the impacts of fire on oil palm plantations.

Third, the burned areas were incorporated in GLOBIOM by reducing the available oil palm production area by an area equivalent to that burned.

Additional information on the climate modeling, FLAM, and GLOBIOM can be found in the Supplementary Materials.

2.3. Storyline creation

The effect of global warming in Indonesia is represented by the delta approach. In this approach, the climatic changes in relevant parameters (such as precipitation and relative humidity) under a projected degree of global warming are estimated following the physical climate storyline method developed from 38 CMIP6 models in Ghosh and Shepherd (2023). Such future climate change pattern under different global warming levels are then added (as a delta factor) on

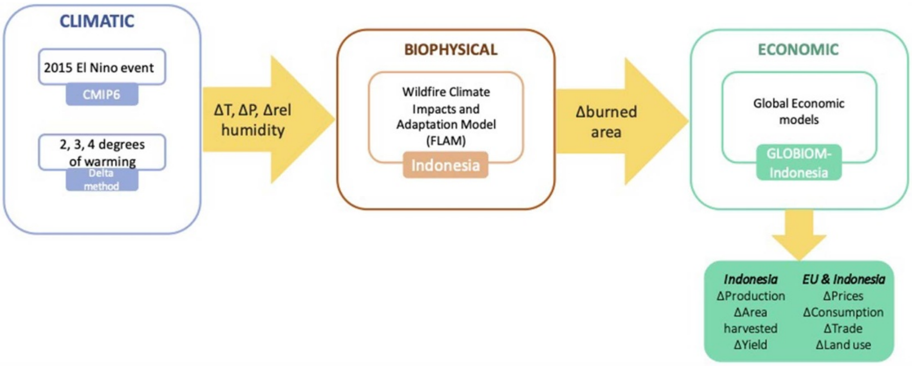

Figure 1. Schematic overview of the modeling chain.

top of the observed 2015 El Niño event to depict the 2015 El-Niño event under potential future climates in higher warming levels.

The advantages of this storyline approach compared to the traditional use of climate projections is that the fire model can be validated against 2015 observations, and the future El Niño event is physically realistic rather than being a modeled El Niño event which would be subject to model biases and could be physically unrealistic. The disadvantage is that the calculation does not allow for the possibility that El Niño events might change in amplitude or structure. However, as noted above, there is large uncertainty in how El Niño events might change, yet high confidence that they will continue to dominate internal variability. Moreover, there is barely any trend in the ENSO mode of variability over the historical period (Ghosh and Shepherd 2023, figure 2). Thus, more is gained than is lost by this approach.

This study looked at four global warming conditions: +2-, 3-, and 4-degrees Celsius, with 2015 considered to be reflective of a +1-degree scenario. Two storylines were defined: storyline 1, a multi-model ensemble mean climate change storyline (reflective of the average climate change across 38 CMIP6 climate models in the SSP585 scenario, for a given global warming level), and storyline 2, a high impact climate storyline which represent a future climate state in the CMIP6 models, where a certain potential evolution of Equatorial pacific Ocean temperature (elaborated in Ghosh and Shepherd 2023) could lead to even drier conditions over the key forest fire regions over Indonesia compared to Storyline 1 (figure 2).

Relevant (daily) weather variables modified using the delta method include the temperature and relative humidity at noon; 24-hour accumulated precipitation; and wind speed (northern and eastern components) at 10 meters.

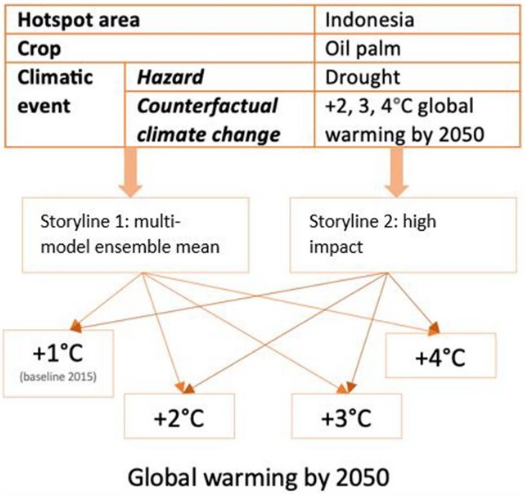

Figure 2. Storyline and scenario overview.

Results of both storylines are presented in this paper; however, because results were similar between the two storylines, the focus of this paper is on storyline 1. Further analysis and results related to storyline 2 can be found in the supplementary materials.

3. Results

Based on the model chain workflow, we first produced and analyzed modeled burned areas. This was utilized to produce and assess oil palm losses across storylines and scenarios., followed by assessment of impacts on palm oil consumption and markets. Overall, there is a clear trend between increasing temperature and increasing burned area and impacts across storylines and scenarios, especially with regards to oil palm plantations.

3.1. Burned areas under current and future global warming

FLAM proved adept at modeling and representing historic forest fire events in Indonesia, capturing the El Niño effect of increased burned area in 2015 (figure 3).

After calibration, FLAM was used to model burned areas in 2015 under current and future

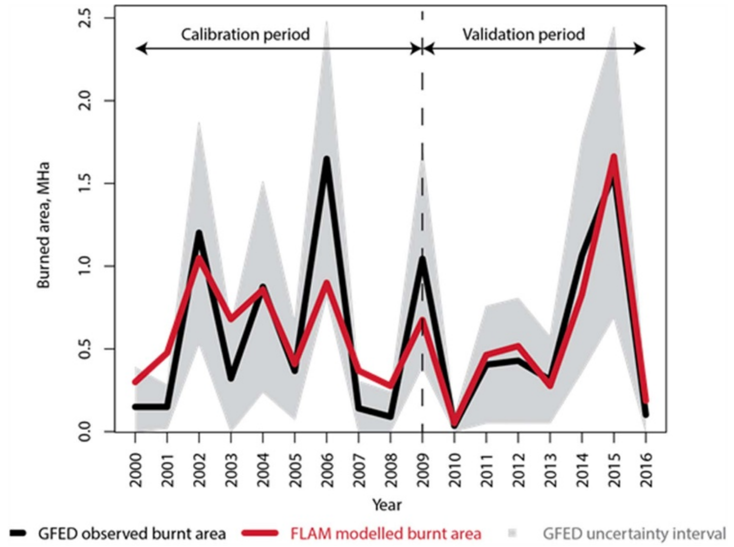

Figure 3. Annual dynamics of burned areas in Indonesia modeled by FLAM and reported by GFED. In this study modifications were made for the year 2015 (Krasovskii *et al.* 2018).

warming conditions. The total burned area for 2015 in the baseline (+1-degree) scenario was estimated at approximately 1.6 million hectares (∼1.5% of Indonesia's land area). Modeled burned area in 2015 is seen in figure 4. The numerical differences between the baseline situation and each scenario/storyline are depicted in figure 5. For the ensemble mean, total burned area increased by ∼9%, 14%, and 20% for the +2-, 3-, and 4- degree scenarios, respectively. For the high impact storyline, total burned area increased by ∼9%, 16%, and 24%, respectively.

The spatial variability of burned area is consistent across the scenarios and storylines. Differences in burned area are seen in the severity of the fire and proportion of each pixel burned, versus total number of pixels burning. Figure 6 shows the spread of total burned area in the multi-model ensemble mean storyline.

GLOBIOM estimated approximately 515 thousand of the 1.6 million hectares of burned area to be oil palm plantations. Lohberger *et al* (2017) evaluated the fire-affected areas of Indonesia for 2015 and separated out burned areas by land cover type. They estimated that plantations accounted for approximately 450 thousand hectares burned in 2015. Thus, GLOBIOM results are in line with the estimates by Lohberger *et al.*

Table 1 describes the modeled values of burned oil palm plantation area and associated production and economic impacts in 2015 for all scenarios and storylines. The burned area and production losses increase with each degree of global warming; values do not vary significantly between storylines.

Compared to total burned area (all landcover types), the oil palm burned areas increased by ∼10%, 18%, and 25% in storyline 1 and ∼10%, 18%, and 26% in storyline 2 for +2-, 3-, and 4-degrees of global warming, respectively. These values are higher than those for all landcover types, indicating that global warming may adversely affect the oil palm industry through a disproportionate increase in plantation burned area and associated economic losses.

3.2. Oil palm losses under current and future global warming

Figure 7 visualizes oil palm production loss for the historical 2015 event and projected production losses under 4 degrees of global warming in the multi-model ensemble mean storyline. The spatial distribution of the oil palm production losses remains similar in both the historic and projected events. This is a result of using 2015 as a benchmark year for burned area modeled by FLAM.

Following the drying trend, which was predicted in both storylines to be more prominent over Sumatra and Kalimantan, these islands experienced the largest losses in terms of burned oil palm area as well as in absolute production. They have also had the largest increase in oil palm cultivation over the past few decades.

Under +2 degrees global warming, total oil palm production losses are already 10% higher than the 2015 baseline event. Under four degrees of warming, this increase grows to nearly 25% higher losses than 2015. The change is particularly extreme in Sumatra, where predictions reach 31% production loss in a +4-degree world.

Burned oil palm area steadily increases with each degree of global warming. In the baseline case of 2015, burned oil palm area accounted for 2.7% of all oil palm plantation area. It increased to 2.9% in both storylines under +2-degrees, then to 3.1% and 3.4% under +3- and +4-degrees, respectively.

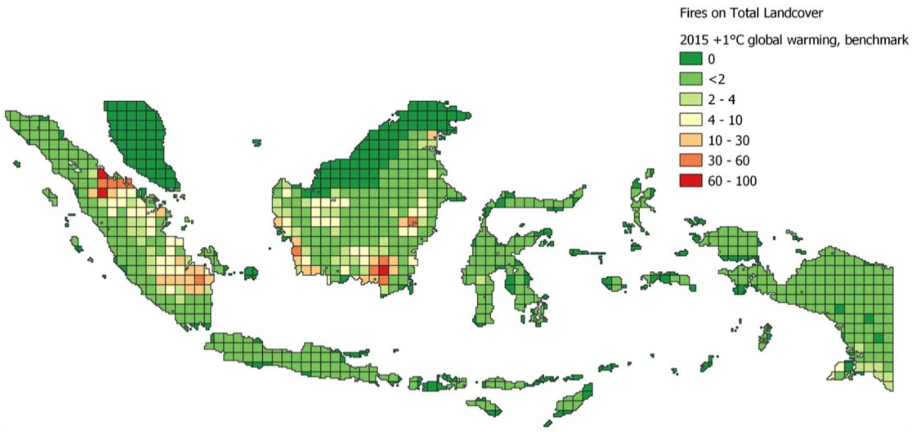

Figure 4. Total burned area in 2015 modeled by FLAM using ERA5 reanalysis weather data.

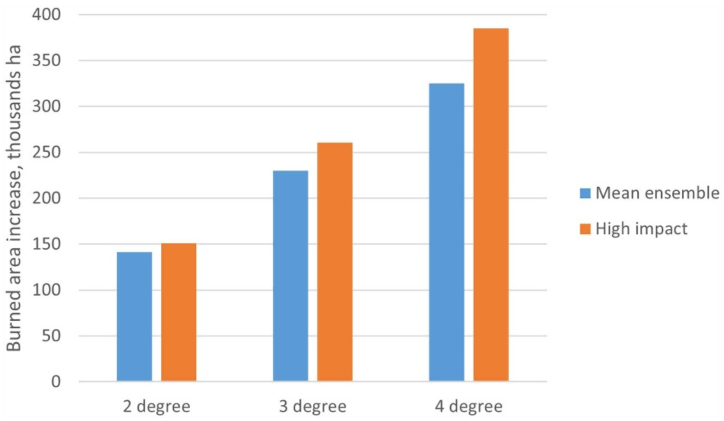

Figure 5. Increase in total burned area with respect to 2015 observed burned area.

3.3. Consumption and markets: palm oil in Indonesia

The percentage of burned oil palm area can be translated to similar losses in production and are strongly reflected in resultant price changes. The percentage change in area allocation, production, prices, calories consumed, and total consumption in Indonesia for the ensemble mean storyline as compared to the situation just before the shock that occurred in 2015 are found in figure 8.

Market shortages were predicted to occur due to wildfire-induced production decreases. These shortages resulted in prices increasing by 36% in the baseline scenario, 70.2% under +2-degrees, and up to 80.5% under +4-degrees. Pricing changes affected consumption in Indonesia (total consumption as well as calories consumed) and trade flow to other regions. Total consumption within the country decreased 5.6% in the baseline scenario, 10% under +2-degrees, and up to 11.3% under +4-degrees. Calories consumed decreased by 7.8%, 10.1%, and 11.3%, respectively, for the same scenarios. Exports also experienced a decrease: 1.9% in the baseline case, up to 2% and 2.3% under +2- and +4-degrees of global warming.

Impacts are predicted in other regions of the world, highlighting the global nature of local events. Global impacts are predicted to be of a lower magnitude than local impacts, but are still notable. An example of impacts in the European Union, one of the main importers of palm oil from Indonesia, can be found in the Supplementary Materials.

4. Discussion

In this study, we developed two storylines to explore how climate-induced fire events in Indonesia lead to economic consequences in Indonesia. This was accomplished by quantifying the impacts of the 2015 El Niño event and analogous events under +2-, 3-, and 4-degrees of global warming conditions. A model chain was employed to develop storylines and model projected weather variables. The Fine Fuel Moisture Code, derived from the fire weather index (van Wagner and Pickett 1987) and implemented in the FLAM model to evaluate the impacts of

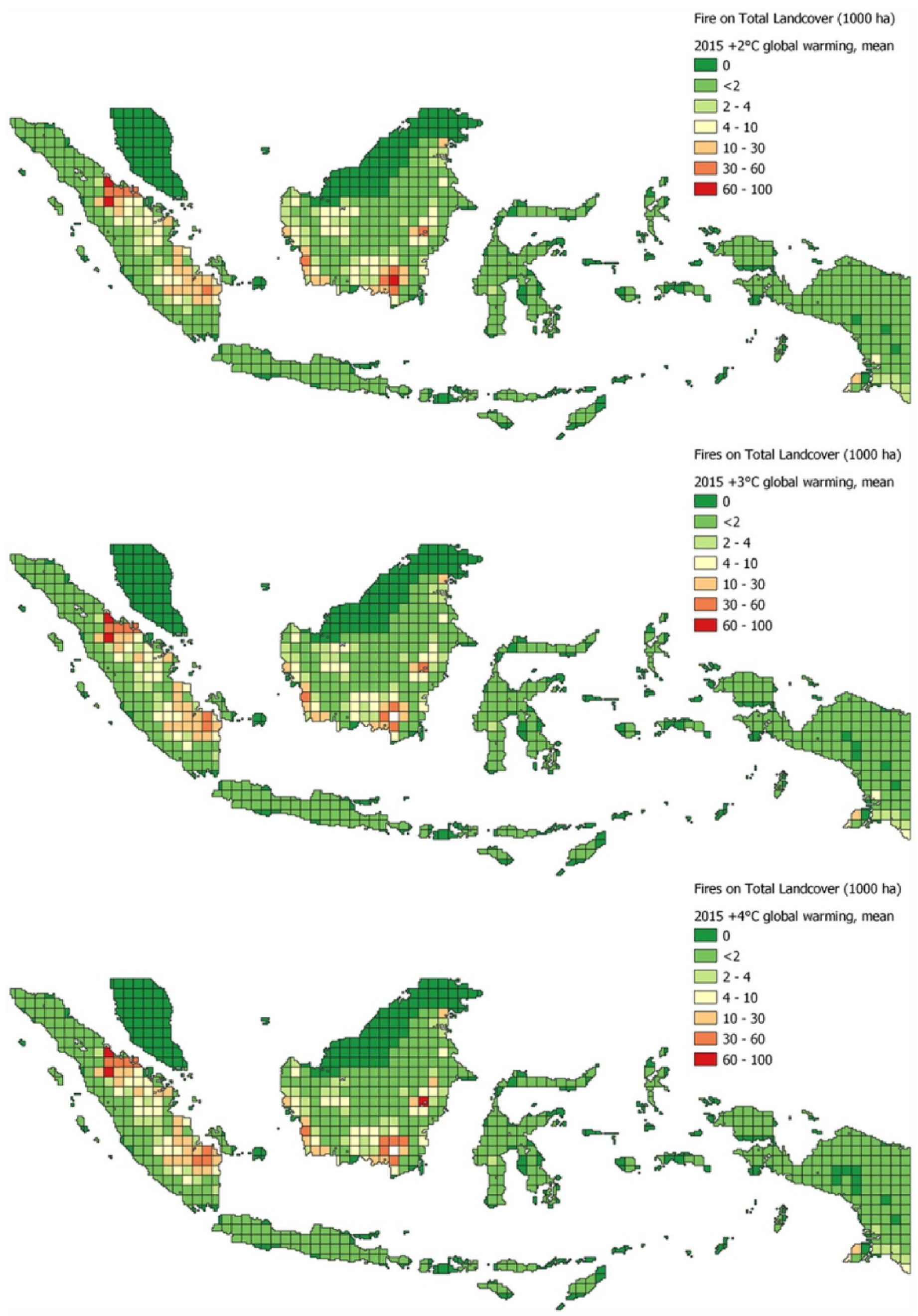

Figure 6. Total burned area for multi-model ensemble mean storyline under +2-, 3-, and 4-degrees global warming (top to bottom).

daily weather variables on fuel moisture content, has demonstrated to be a suitable mechanism for assessing fire weather under climate change conditions (Corning *et al* 2024, Yu *et al* 2024). FLAM was used to estimate the impacts of regional climate variables on total and oil palm plantation burned area, which was then used as input for the global economic model GLOBIOM, tailored to the context of Indonesia. The outputs provided insight which allowed for calculation of climate and fire-related oil palm production losses.

The largest impacts were observed in drought-prone Sumatra and Kalimantan as well as Java, which is likely to experience enhanced drought intensity in the future during similar events. Burned area and production losses related to an El Niño type event may increase between 10% and 25%, depending on the degree of global warming. The highest burned area and production losses were seen in Sumatra, where projected losses were predicted to be up to 31% more under a 4-degree global warming scenario.

Notably, there is weak sensitivity of the storyline to future precipitation changes over Indonesia, implying that predicted precipitation trends are not a significant factor in future fire risk and that warming temperatures are likely the main climate driver for wildfires in Indonesia.

Table 1. Burned area of oil palm plantations, total production losses, and associated value (cost) of damages under the historical 2015 event, and under 2, 3 and 4 degrees of global warming in the multi-model ensemble mean and high impact storylines.

			Storyline 1: ensemble mean			Storyline 2: high impact		
Variable	Region	Y2015 (+1)	+2	+3	+4	+2	+3	+4
Burned area (1000 ha)	Indonesia	515.0	567.0	606.0	645.0	568.0	610.0	650.0
	Kalimantan	203.0	218.1	227.4	236.3	219.0	229.5	243.0
	Jawa	0.7	0.8	0.9	0.9	0.8	0.9	0.9
	Papua	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sulawesi	0.7	0.7	0.8	0.8	0.7	0.7	0.8
	Sumatra	310.8	347.8	377.7	407.8	347.5	378.8	406.1
Production loss (1000 tons)	Indonesia	7154.5	7883.2	8440.4	8985.6	7886.6	8478.3	9044.9
	Kalimantan	2782.2	2991.2	3126.9	3249.0	3000.8	3149.9	3333.1
	Jawa	9.8	10.6	11.4	12.2	10.7	11.6	12.4
	Papua	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sulawesi	10.1	10.7	11.0	11.4	10.7	10.7	11.2
	Sumatra	4352.3	4870.7	5291.9	5712.9	4866.4	5306.1	5688.2
Cost of damage (USD $1000)	Indonesia	14 309	15 766	16 881	17 971	15 773	16 957	18 090
	Kalimantan	5564.4	5982.4	6253.8	6498.0	6001.6	6299.8	6666.2
	Jawa	19.6	21.2	22.8	24.4	21.4	23.2	24.8
	Papua	0	0	0	0	0	0	0
	Sulawesi	20.2	21.4	22.0	22.8	21.4	21.4	22.4
	Sumatra	8704.6	9741.4	10 584	11 426	9732.8	10 412	11 376

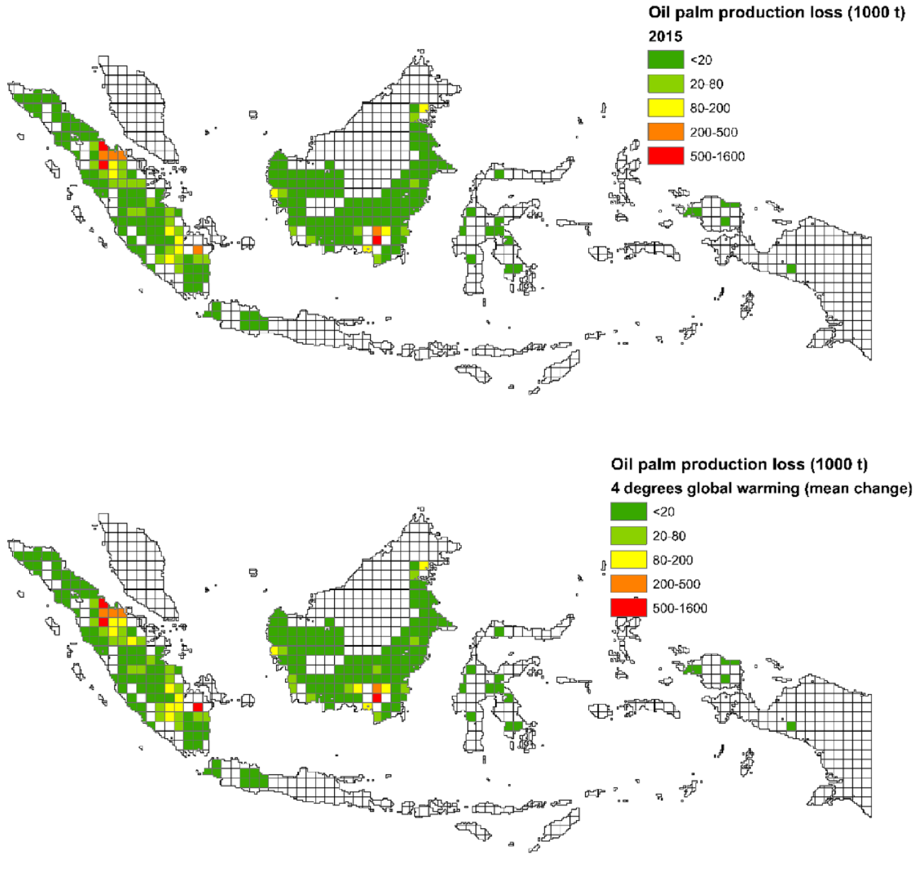

Figure 7. Oil palm production loss in the historic El Niño event in 2015 (top panel) and the mean change under 4 degrees of global warming (multi-modal ensemble, bottom panel). Units: 1000 tons.

The spread of burned area is influenced by the calibration approach used to assess suppression efficiency in FLAM. Population density is transformed into two probabilistic functions: human-caused ignition and suppression. Pixels are calibrated by identifying those with high or low suppression efficiency (probability of extinguishing a fire within one day) based on observed fires and burned area.

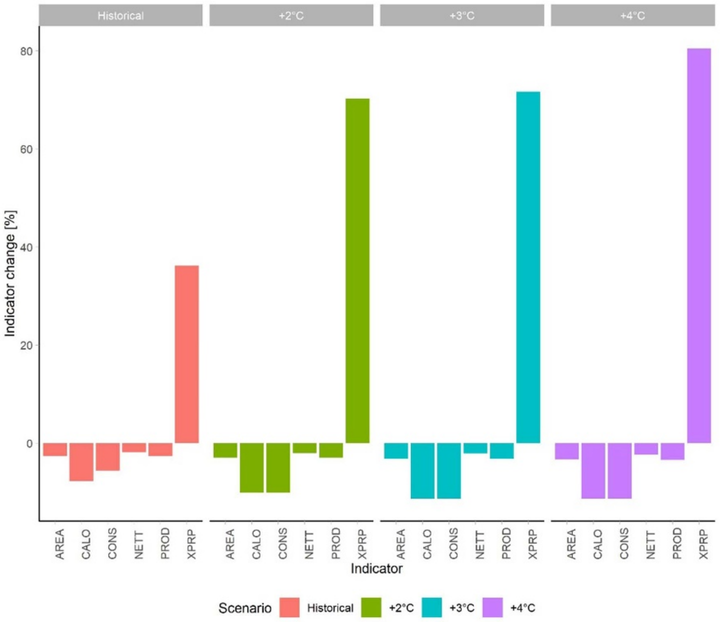

Figure 8. Percentage change in area harvested (AREA), calories consumed (CALO), total consumption in Indonesia (CONS), volume of trade (NETT), total production (PRODS), and export price (USD2000) (XPRP) under multi-model ensemble mean conditions as compared to t.

This is especially important in countries such as Indonesia, where peat fires could burn and spread for months if not immediately suppressed. Pixels with an impossibility to calibrate or where no fire could be reproduced within FLAM for various reasons were removed (Krasovskii *et al* 2018).

For natural ignition, an average of historical lightning frequencies was used for the counter-factual global warming scenarios. Climate was analyzed in parallel to ignition probability. Theoretically, drier conditions could lead to a higher total probability of fire, but there is no explicit feedback between lightning and weather in FLAM. There is still high uncertainty regarding the sensitivity of lightning-ignited wildfire occurrence to climate change (Finney *et al* 2018, Pérez-Invernón *et al* 2023). This pertains to the challenges associated with parameterizing lightning in climate models (Tost *et al* 2007, Krause *et al* 2014). While some studies project increasing risks of lightning-induced fires in Southeast Asia (Pérez-Invernón *et al* 2023), others suggest a decrease in lightning occurrences under climate change conditions (see, for example, Finney *et al* 2018) Further work needs to be done to determine how this could be better reflected in FLAM and wildfire projection models (Krause *et al* 2014).

Our study showed a clear link between climate change, fire occurrence, burned area, and oil palm production losses, especially during El Niño events. The anthropogenic component cannot be overlooked, with humans often the source of deforestation, oil palm cultivation, and fire ignition. Under normal conditions, human-caused fires pose a risk of spreading; in conditions induced by global warming, such as those as modeled in this study, the likelihood of fires spreading is drastically higher, as witnessed in the 2015 fire season.

Impacts are not isolated to loss of forest area, increased emissions, and environmental degradation. There are notable and significant consequences in the socioeconomic realm, as shown by this study's modeling chain. Extreme weather events, especially under global warming conditions, pose a serious problem for oil palm production, both in terms of area suitable for plantations as well as production losses due to wildfires. Economic impacts are seen in increased local and global costs of products due to decreases in available supply, leading to decreases in local consumption, exports, and related revenue. This poses many problems for local economies, with internal supplies seeing a markedly higher price increase, decreased consumption, and less revenue (internally and abroad). This has the potential to destabilize fragile local economies as well as promote further conversion of other lands to use as plantations.

The results of this study are helpful to understand the many potential impacts of climate-induced fires on the oil palm sector in Indonesia. They can be used as a guidance for decision- and policymakers to better understand the interconnected impacts and consequences of local actions in the context of climate change.

Future directions of this study could focus on how mitigation options impact production losses and forest fire risk and spread, from both socio-economic and environmental perspectives. Furthermore, socioeconomic interventions—such as a ban on all oil palm plantation expansion in Indonesia and reductions in EU demand for palm oil (for example resulting from the implementation of the EU Deforestation Regulation)—could be integrated into the storylines to show their impact on land cover and land use change and the resultant change to burned area and production losses. Similarly, there are several environmental policies under discussion: the rewetting of peatlands, fuel reduction through the creation of fire breaks/buffer zones, and a ban on conversion of forested area into oil palm plantations.

There are many potential adaptation options, such as improved fire monitoring and ignition identification strategies to increase suppression efficiency; land cover conversion policies to promote fire-resilient landscapes; and the creation of fire breaks/buffer zones in fire hotspot areas to reduce the spread and impact of wildfires in the event of a burn.

There should also be more focus on environmental impacts of these policies under global warming and climate change. This includes analyzing the impacts of current and potential policies on biodiversity indicators, changes in forested area, and the availability of various environmental services. Recent improvements to the FLAM and GLOBIOM models prove it is also possible to calculate potential changes in green house has emissions.

5. Conclusions

Oil palm plantations are a driver of land use conversion (deforestation and peatland drainage) and threaten ecosystems through biodiversity loss, soil erosion, waste, air pollution, and water quality issues. The conversion to plantations raises wildfire risk, both in terms of ignition and out-of-control spread. While many developed countries have enacted policies to reduce land conversion within their own borders, this often results in shifting production from within their borders to other parts of the world. With world consumption of oils and fats increasing in recent years, the demand for palm oil will likely grow as well, driving further deforestation in countries such as Indonesia. It is important to consider not just national but also international policies.

Climate change will almost certainly increase the instability and risk of wildfires and resultant shocks to economic systems, such as those witnessed in the oil palm sector of Indonesia in 2015. Understanding the threat of natural hazards and climate change cannot be understood nor remedied by focusing on individual drivers. As this study showed, consideration of all factors (climate change, extreme weather, policy, and agricultural practices) is necessary to understand their compounding impact on society and the environment, as well as the complex interactions of our decisions. Policies related to local and global use of palm oil and other biofuels should consider the unintended consequences of increased usage, even for sustainable purposes. Sustainable decision making must account for all potential impacts, and recognize when a well-intended policy could have negative long-term consequences due to global and system interactions.

Further, this study supports the premise that decision and policy makers must consider short- and long-term effects on multiple systems in their work, and provides a framework to assess the impacts of future decision-making. It provides a foundation upon which to further explore policy impacts on socio-economic and environmental themes in Indonesia in the context of forest fires, oil palm plantations, and global warming, and lays the groundwork for further exploration on this topic. Consultation with country experts and researchers can ensure that all options and their impacts are explored, such as through model coupling and feedback of results.

Continuing research will explore two socioeconomic adaptations (a policy in the EU reducing demand for the share that is intended for biofuel use and another policy banning deforestation in Indonesia for the purposes of oil palm plantations) and one environmental adaptation option (a policy on forest conservation and peatland restoration) to assess how various policies may alter predictions of burned areas and economic losses.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11517813 (Corning *et al* 2024).

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Author contributions

Paper writing by S C with contribution from E B, A K, A L, T S and R G E B, A K and A L developed software, processed data, and provided results. T S and R G analyzed and provided climate data. F K and P H conceptualized research.

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Conflict of interest

The authors declare no conflict of interest.

ORCID iDs

Shelby N Corning https://orcid.org/0009-0001-5277-5380
Andrey Krasovskiy https://orcid.org/0000-0003-0940-9366
Andrey Lessa Derci Augustynczik https://orcid.org/0000-0001-5513-5496
Ted Shepherd https://orcid.org/0000-0002-6631-9968
Rohit Ghosh https://orcid.org/0000-0001-9888-7292

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